The International Journal of Life Cycle Assessment (2023) 28:800–812
https://doi.org/10.1007/s11367-023-02182-w

BUILDING COMPONENTS AND BUILDINGS

Carbon footprint of reinforced concrete columns with and without supplementary cementitious materials

Gisela Cordoba[1] · **Edgardo Fabián Irassar**[1]

Received: 2 June 2022 / Accepted: 3 May 2023 / Published online: 19 May 2023

Abstract

Purpose The construction sector consumes a large quantity of natural resources and generates a great deal of carbon dioxide emissions and wastes, affecting its sustainability. Replacing Portland cement with supplementary cementitious materials (SCM) could reduce the environmental impact. This paper examines the carbon footprint of reinforced concrete columns. It focuses on the influence of increasing the steel cross-section and reducing the clinker factor by replacing Portland cement with SCM.

Methods Eighteen concrete mixtures were selected and classified according to the specified compressive strength at 28 days of curing using binary and ternary blended cements. Columns were designed consisting of such concretes and employing different reinforcing steel cross-sections. The life cycle assessment was conducted on ISO 14040 standard. The embodied carbon dioxide (ECO_2) of the reinforced concrete columns was determined.

Results The results show that the higher the compressive strength of concrete, the lower the carbon footprint of the columns. Concretes with a high volume of SCM replacement and low compressive strength at 28 days do not show the lowest carbon footprint since it requires a greater volume of material to withstand the bearing capacity. The carbon footprint of the columns increases as the steel section increases. Furthermore, increasing the compressive strength of concrete is less beneficial for reducing the carbon footprint of the column when the steel cross-section is increased.

Conclusions Portland cement is the component material of concrete that contributes the most to the concrete carbon footprint, and steel has the highest ECO_2/tonne. Replacing Portland cement with SCM reduces ECO_2 at one point of the life cycle and may increase the material volume and ECO_2 at another. The lowest carbon footprint of compressed reinforced concrete elements is achieved for the higher-strength concretes and the minimum steel cross-section.

Keywords Building materials · Concrete · Blended cement · Supplementary cementitious materials · Life cycle assessment · Carbon footprint

1 Introduction

In 2015, the United Nations approved the 2030 Agenda for Sustainable Development, which set out a 15-year plan to achieve the 17 Sustainable Development Goals. These goals mean increasing access to clean drinking water and sanitation; improving urban planning and public transport; providing affordable and adequate housing resilient infrastructure; and reducing energy consumption for heating and cooling as well as emissions that contribute to climate change. Infrastructure must be provided and improved for this purpose, new buildings constructed, existing ones modernised, strength and durability enhanced, construction operations optimised and more efficient building materials used. Strategies and approaches must be based on regional aspects to achieve these goals simultaneously, particularly Goal 12, which addresses the sustainable management and efficient use of natural resources (OECD 2020), especially for high-volume used materials.

In 2017, world consumption of materials reached 92 Gt (UN Economic and Social Council 2019), mostly non-metallic ones (mainly building materials and fossil fuels)

Communicated by Vanessa Bach

✉ Gisela Cordoba
gcordoba@fio.unicen.edu.ar

Edgardo Fabián Irassar
firassar@fio.unicen.edu.ar

[1] Department of Civil Engineering and Surveying at Engineering Faculty, Universidad Nacional del Centro de La Provincia de Buenos Aires, CIFICEN (UNCPBA-CICPBA-CONICET), Av. Del Valle, 5737 (PC 7400) Olavarría, Buenos Aires, Argentina

(OECD 2020). According to the United Nation's Sustainable Development Goal 12 projections, the growing use of non-metallic minerals in infrastructure and construction led to an increase in the per capita 'material footprint' from 5 to 9 tonnes between 2000 and 2017 in developing countries (United Nations 2015). By 2060, the use of non-metallic materials is expected to grow to 82 Gt, most of the growth occurring in the short term, driven by the increasing demand for investment in construction and inadequate large-scale recycling of these materials (OECD 2019).

There is a close correlation between economic growth and investment, infrastructure and construction. This leads to the fast development of industrial, urban and transport infrastructure, which promotes the use of large volumes of materials. Renewing existing buildings may also result in large volumes of such construction materials eventually reaching landfills if not properly managed (Cancio Diaz et al. 2017; OECD 2019, 2020).

The construction industry is responsible for ~ 11% of total greenhouse gas (GHG) emissions. To progress towards meeting Sustainable Development Goals, it is necessary to reduce emissions rapidly by 2030 (Adams et al. 2019). Concrete is the most commonly used construction material within this infrastructure (Cancio Diaz et al. 2017; Kourehpaz and Miller 2019; OECD 2020), which can be defined as a mixture of cement, aggregates and water, and may contain chemical admixtures, fibres and other cementitious materials (ACI Committee 130 2019). Currently, the trend for reducing GHG emissions in the construction industry is to use supplementary cementitious materials (SCMs), which reduce the clinker factor for less energy-intensive materials (filler, natural pozzolans, calcined clays), industrial by-products (fly ash, slag) or waste from demolition (Cancio Diaz et al. 2017; UN Environment Programme et al. 2018; Gettu et al. 2018). However, the estimations show that the replacement of OPC by SCM is insufficient if not accompanied by a reduction in the volume of materials used and the construction and demolition waste generated. Also, the construction material lifespan should be increased (Global Cement and Concrete Association 2021; Watari et al. 2022).

In recent years, various codes for the design of reinforced concrete structures have included the concept of concrete sustainability. According to the American Concrete Institute (ACI), the owner may include requirements to increase sustainability. However, it also establishes that 'the strength, serviceability, and durability requirements shall take precedence over sustainability considerations' (American Concrete Institute 2019). The initiatives proposed by the ACI to reduce the carbon footprint of concrete include using SCM and higher-strength concrete, using alternative fuels for cement production and increasing the durability and resilience of structures, among others (American Concrete Institute 2022). On its part, in 2010, the Fédération Internationale du Béton (*fib*) included performance requirements for sustainability in its Model Code for Concrete Structures (Fédération Internationale du Béton 2010). According to that, 'the purpose of design for sustainability is to reduce impacts on the environment, society and economy by evaluating and verifying the performance' of either a concrete mix, a structural component or the structure as a whole. In addition, the fib published a bulletin on green structures in 2012 (Glavind et al. 2012). This guideline was developed to provide valuable tools for owners, users, designers and producers of concrete to reduce the environmental impact of concrete structures throughout their entire service life (Glavind 2011; Glavind et al. 2012). Regarding concrete composition, it also suggests reducing the clinker factor by replacing OPC with SCM and reducing the cement content per m^3 of concrete as effective alternatives to minimise the environmental impact of concrete (Glavind 2011).

On the other hand, the concept of 'dematerialisation' has been introduced as a measure of material efficiency and refers to the reduction in the amount of materials used and waste generated to produce a unit of economic output (Zhang et al. 2018). The complete dematerialisation of the construction industry is unlikely as building materials are consumed in large volumes (Allwood et al. 2011; Irassar et al. 2020). However, exploring the substitution of materials, improving their performance and analysing the trade-offs are essential to reduce the environmental impact (Allwood et al. 2011). The reduction of materials required to produce an economic unit can be translated into the life cycle assessment (LCA) (Finkbeiner and Bach 2021). Energy use and GHG emissions are lowered as the volume of structural elements is reduced (Miller et al. 2015a; Kourehpaz and Miller 2019; Hawkins et al. 2020). Therefore, dematerialising the construction industry contributes to its simultaneous decarbonisation.

Therefore, this paper examines the carbon footprint and the volume of materials required to build reinforced concrete columns made with ordinary Portland cement and blended cements. Life cycle assessment is used as a methodology to quantify the ECO_2. The study is focused on the influence of increasing the steel cross-section per column and reducing the clinker factor by replacing Portland cement with supplementary cementitious materials on the volume of materials used and their carbon footprint for constant performance (axial load and bending moment to be withstood).

2 Methodology

This study is conducted on ISO 14040 (International Standard Organization 2006). The methodology is divided into four phases: (1) *goals and scope definition*, where the purpose, functional unit and system boundaries are established; (2) *life* *cycle inventory (LCI)*, in which relevant data is collected from inputs and outputs of the system; (3) *life cycle impact assessment (LCIA)*, for which potential environmental impacts are assessed; and finally (4) *interpretation*, which identifies and explains the issues and limitations of the study, examines the results, reaches conclusions and offers recommendations (Abd Rashid and Yusoff 2015).

2.1 Functional unit

Three functional units were taken for this study: one unit volume measurement of concrete and steel (1 m^3), an ordinary column subjected to axial load only and an ordinary column subjected to axial load and one-direction bending moment, using different concrete mixtures, specified compressive strength and different ratios of reinforcing steel-to-concrete cross-sectional areas to build the columns. A three-storey building for healthcare use was taken to estimate the axial load and the bending moment to which the structural elements are subjected. Flat slabs, concrete walls and reinforced concrete beams and columns comprise the structural elements. The stairwell and concrete walls support the lateral wind load. A constant slab thickness of 20 cm and rectangular beams of 30 cm × 40 cm are adopted. The columns considered functional units belong to the first floor and bear loads of the upper levels and the continuous beam on which the second-floor slab leans. This paper is not intended to discuss the design of concrete elements, nor is it the aim of this study to deal with the calculation and structural design of reinforced concrete structures. Therefore, only the dimensions of the columns are provided.

Eighteen concrete mixtures made of ordinary Portland cement (OPC) and blended cements, natural silica sand (NSS) and crushed fine aggregate (CFA), coarse crushed aggregate (CCA) and tap water were selected. Blended cements had replacement levels between 12 and 34% by mass. The SCMs included were limestone filler (LF), granulated blast furnace slag (GBFS), fly ash (FA), calcined kaolinitic clay (KC) and calcined illitic shale (IC). The proportion of the concrete mixtures is reported in Table 1.

The cross-sectional area of the reinforcing steel and the concrete of the columns were calculated following the Argentine Code 'CIRSOC 201' (Instituto Nacional de Tecnología Industrial 2005) for an axial load of 900 kN and/or a bending moment of 32 kNm. The calculation method of the CIRSOC 201 code is based on that established by the ACI 318 Building Code (American Concrete Institute 2019). Columns subjected to axial load and bending moment were pre-dimensioned in axial load only, and their cross-section ability to resist the bending moment was verified using the axial load-bending interaction diagrams. If the section does not verify the combined load action, it is possible to increase the steel-to-concrete cross-section ratio (ρ) or the column cross-section while maintaining constant ρ. The present study analyses the increase in cross-section required for the column to verify under the combined action of loads for ρ varying between 0.01 and 0.04 for a concrete strength class of 25, 30 and 35 MPa, considering as reference the column built with concrete of strength class 30 MPa and without SCM.

Table 1 Life cycle inventory

Material	kg CO_2 e/t
Ordinary Portland cement (OPC)*	912
Coarse crushed aggregate (CCA)**	46
Crushed fine aggregate (CFA)**	46
Natural silica sand (NSS)**	14
Limestone filler (LF)*	35
Granulated blast furnace slag (GBFS)*	47
Fly ash (FA)*	35
Calcined kaolinitic clay (KC)***	205
Calcined illitic shale (IC)****	253
Tap water***	9
Reinforcing steel*	1990

Value taken from *Jones (2019), **Flower and Sanjayan (2007), ***Vizcaino et al. (2015), ****Cordoba et al. (2020), *****Presa (2016)

2.2 System boundaries

The environmental impact of the raw material is considered from 'cradle to the building site gate'. For industrial by-products (GBFS and FA), the environmental impact of preparing and grinding the material for use in blended cement is considered. Transportation of materials was not part of the study.

The limitations of the study are listed below:

- Only columns are considered. Other solicitations (shear, bending moment in both directions, slender, torsion) and structural elements (beams, slabs, foundations) are not taken into account, nor is the study of changes in column shape (circular columns, slender columns) included.
- Due to the prevalent interest in GHG emissions, only the parameter of embodied carbon dioxide (ECO_2) is considered (energy use, material consumption, water use, land use and other categories are omitted).
- The study does not consider the admixtures used for concrete mixtures due to data access limitations.
- The present study did not analyse the influence of transporting the concrete composite materials.
- Casting, use, demolition or deconstruction stages are not considered. Therefore, concrete durability and insulation properties are not analysed.

2.3 Life cycle inventory (LCI)

The environmental impact information was taken from the literature and validated the information from industrial producers located in the city of Olavarría, Buenos Aires, Argentina. The data is detailed in Table 1.

2.4 Life cycle impact assessment (LCIA)

Firstly, concrete mixtures are classified according to their specified compressive strength (f'_c) at 28 days in four strength classes (C25, C30, C35 and C45). f'_c is obtained for medium–low quality control during concrete manufacturing, as in developing countries. According to the formula stated in the CIRSOC 201 Code (Instituto Nacional de Tecnología Industrial 2005), the average compressive strength at 28 days (f'_{cm3}) is required to be greater than f'_c plus 5 MPa ($f'_{cm3} = f'_c + 5$ MPa). f'_{cm3} is the compressive strength at 28 days reported by the authors of the papers from which the concrete mix compositions were extracted, determined in all cases experimentally, and as an average of three or more specimens.

Secondly, the cross-sectional area of the reinforcing steel and concrete is determined for a given ρ and the different concrete strength classes in 2.70 m high columns. The ρ employed ranged from 0.01 to 0.04, ensuring that $\rho_{\text{máx}} = 0.08$ is not exceeded if splices of longitudinal reinforcement are required. The required steel section is taken by multiplying ρ and the concrete cross-section (American Concrete Institute 2019), which does not consider the diameters and numbers of commercial steel bars that meet the minimum ρ.

Finally, the carbon footprint of concrete mixtures and columns is analysed. Once the volume of materials required to build the concrete columns has been calculated and the LCI has been compiled, the environmental impact of columns for each type of cement, strength class and ρ is assessed. To evaluate the carbon footprint of concrete mixtures, one made of 350 kg/m^3 of ordinary Portland cement, w/c = 0.50 (M1) and strength class C30, is considered the reference concrete mixture since it is the most commonly used ready-mix concrete in Argentina (Cordoba et al. 2023) and the USA (Miller et al. 2015b). To compare the columns' carbon footprint, the one made of M1 and $\rho_{\text{min}} = 0.01$ is taken as the reference.

3 Results

3.1 Concrete mixes and steel

Mixture proportions, its average compressive strength at 28 days, the replacement percentage of OPC by SCM and the references from which the data was obtained are detailed in Table 2. Eighteen mixtures were selected, nine

Table 2 Concrete mixture proportion

Mix	Concrete mix proportion (kg/m^3)										f'_{cm3} (MPa)	% SCM replacement (by mass)	Strength class
	OPC	CCA	CFA	NSS	LF	GBFS	FA	KC	IC	Water			
M1	350	1000	840	-	-	-	-	-	-	175	36	0	**C30**
M2	308	1000	834	-	42	-	-	-	-	175	35	12	
M3	287	1000	831	-	63	-	-	-	-	175	35	18	
M4	280	1000	831	-	-	70	-	-	-	175	35	20	
M5	277	1000	830	-	38	35	-	-	-	175	37	21	
M6	263	1050	-	805	-	-	-	87	-	175	37	25	
M7	255	1000	826	-	60	35	-	-	-	175	37	27	
M8	246	1000	827	-	34	70	-	-	-	175	35	30	
M9	230	1000	825	-	50	70	-	-	-	175	35	34	
M10	350	1050	-	807	-	-	-	-	-	175	32	0	**C25**
M11	281	840	1000	-	-	71	-	-	-	140	33	20	
M12	281	900	900	-	40	40	-	-	-	140	33	22	
M13	263	1050	-	788	-	-	-	-	87	175	30	25	
M14	259	900	900	-	79	22	-	-	-	130	31	28	
M15	314	1055	202	606	55	-	-	-	-	165	43	15	**C35**
M16	308	935	-	800	77	-	-	-	-	170	41	20	
M17	327	1020	198	593	41	-	41	-	-	176	41	20	
M18	341	1000	204	611	60	-	-	-	-	170	50	15	**C45**

Mixture references: M1–M5, M7–M9 (Menendez 2006); M6, M10, M13 (Cordoba et al. 2020); M11, M12, M14 (Falconara 2014); M15–M17 (Perrone et al. 2012); M18 (Giaccio et al. 2001) corresponding to C30 strength class, five to C25, three to C35 and one to C45. Two of the chosen mixtures are made of OPC cement, while the others are made of binary and ternary blended cements, with replacement percentages by mass varying between 12 and 34. M1 (OPC) was considered the reference mix.

Table 3 shows the ECO_2 per m^3 of material for the concrete mixtures and steel (considering a steel density of 7.85 t/m^3). The carbon footprint per m^3 of concrete is reduced with the increasing level of SCM replacement by any SCM used. Within the C30 strength class, and with respect to the M1 mix (OPC), replacement levels between 12 and 34% allow reducing the carbon footprint of the mixes between 9.2 and 25.9%. Comparing C25 mixes with respect to M1 (OPC, C30), it is found that all the concrete mixes allow reducing the carbon footprint between 6.2 and 20.1%, for mixtures between 0 (M10) and 28% (M14) replacement of OPC by SCM.

The C35 mixes reduce the carbon footprint between 10.2 and 16.7% for replacement levels of OPC by LF between 11 and 20%. It is observed that for similar replacement levels in the C30 concrete mixes, the reduction is comparable. This is because of the SCM used: in the C35 mixes, only LF was used, while in the C30 mixes, GBFS was also employed, which has a higher ECO_2/t.

The carbon footprint of the C45 concrete mix (M18, OPC-LF) is 7.0% lower than that of M1. It had a 15% replacement of OPC by LF. This lower reduction compared to lower strength class mixes is because M18 had a higher cement content per m^3. However, it is possible to reduce the carbon footprint for a relatively low replacement level and higher cement content per m^3 of concrete.

Finally, the carbon footprint of steel is almost 40 times that of M1. This is due to the high energy intensity of steel production, whereas, except for Portland clinker, the production of concrete component materials does not consume a large amount of energy, and the production process is relatively simple.

3.2 Columns under axial load only

3.2.1 Required volume of materials to withstand the axial load and bending moment

Table 4 shows the cross-sections and volumes of concrete and steel required to shape the columns bearing an axial load of 900 kN for the different concrete strength classes and ρ. For a C25, an increase in ρ from 0.01 to 0.04 increased the required steel cross-section by 286% while reducing the concrete cross-section by 31%. However, for C45, an increase

Table 3 ECO_2 per m^3 of material for the concrete mixtures and steel

Concrete mixtures			
Concrete mixture	ECO_2/m^3 (kg/m^3)	OPC replacement level (%)	ECO_2 reduction compared to M1 (%)
M1 (OPC)	405.2	0	-
M2 (OPC-LF)	368.1	12	9.2
M3 (OPC-LF)	349.5	18	13.7
M4 (OPC-GBFS)	344.2	20	15.1
M5 (OPC-LF-GBFS)	341.1	21	15.5
M6 (OPC-KC)	318.7	25	21.4
M7 (OPC-LF-GBFS)	321.7	27	20.6
M8 (OPC-LF-GBFS)	314.2	30	22.5
M9 (OPC-LF-GBFS)	300.1	34	25.9
M10 (OPC)	380.2	0	6.2
M11 (OPC-GBFS)	345.3	20	14.8
M12 (OPC-LF-GBFS)	343.4	22	15.3
M13 (OPC-IC)	322.7	25	20.4
M14 (OPC-LF-GBFS)	323.8	28	20.1
M15 (OPC-LF)	345.1	15	14.8
M16 (OPC-LF)	337.6	20	16.7
M17 (OPC-LF-FA)	363.8	11	10.2
M18 (OPC-LF)	376.8	15	7.0
Steel			
		ECO_2/m^3	
Steel		15,621.5	

Table 4 Size of the concrete columns and volume of materials involved for columns under axial load only

Quantity of steel	Concrete strength class	Column cross-section (cm^2)	Steel cross-section (cm^2)	Concrete volume (m^3)	Steel volume (m^3)
$\rho = 0.01$	C25	676	6.76	0.181	0.0018
	C30	625	6.25	0.167	0.0017
	C35	529	5.29	0.141	0.0014
	C45	441	4.41	0.118	0.0012
$\rho = 0.02$	C25	625	12.50	0.165	0.0034
	C30	529	10.58	0.140	0.0029
	C35	484	9.68	0.128	0.0026
	C45	400	8.00	0.106	0.0022
$\rho = 0.03$	C25	529	15.87	0.139	0.0043
	C30	484	14.52	0.127	0.0039
	C35	441	13.23	0.115	0.0036
	C45	400	12.00	0.105	0.0032
$\rho = 0.04$	C25	484	19.36	0.125	0.0052
	C30	441	17.64	0.114	0.0048
	C35	400	16.00	0.104	0.0043
	C45	400	16.00	0.104	0.0043

in ρ from 0.01 to 0.04 increased the steel section by 363% and only allowed a 12% reduction in the concrete section. Nevertheless, this significant increase in steel cross-section represented less than a 3% increase in the total volume of the column for any of the strength classes. The difference observed between C25 and C45 is attributed to the high compressive strength of the steel (f_y). Although steel is placed in reinforced concrete constructions to support tensile stress, when the bars are placed in the same direction as the compressive stress, they cooperate with concrete to bear the compressive load. In concretes of lower compressive strength ($f'_c = 25$ MPa), the reduction of the concrete cross-section was more pronounced since a relatively small increase of the steel cross-section contributed to bearing a larger load. However, as f'_c increases (the case of C45 concrete), the gap between f'_c and f_y becomes narrower, so the increase in steel cross-section was less advantageous. Therefore, in terms of material volume, increasing ρ for concretes of relatively low-strength classes is effective, whereas it is convenient to keep ρ as low as possible for concretes of high-strength classes.

On the other hand, when the concrete strength class was reduced from C30 to C25, the volume of the reinforced concrete column under axial load increased between 8 and 18%, depending on ρ. In contrast, when the strength class was increased from C30 to C35, the volume of the structural element was reduced by 9 to 15%, while for C45 strength class, the volume of material required was reduced by 9–29% compared to C30 since, for $\rho = 0.03$ and 0.04 and C45 concrete, the column had to be built with the minimum cross-section (20 cm side).

In a reinforced concrete structure, columns represent a relatively small volume, less than 15%. According to estimations made by López (2020), columns represent between 6.5 and 13.9% of the total volume of the structure, depending on the strength class of the concrete (the higher the concrete strength class, the lower the share). By increasing the strength class of the concrete from C30 to C45, it would be possible to reduce the total volume of the structure by up to 4% without optimising any of the other structural elements. Therefore, the use of high-strength class concretes becomes one strategy for the forthcoming dematerialisation of the construction industry, as it has been proven that it is also possible to reduce the volume of slabs and beams by increasing the compressive strength of concrete and using post-tensioned elements (Hawkins et al. 2020; MPA The Concrete Centre 2022).

3.2.2 Carbon footprint for varying steel to concrete cross-section ratio (ρ)

Figure 1 shows the ECO$_2$ per column for the different ρ and concrete strength class. To analyse the influence of increasing ρ on concretes of different strength classes, the reference mixes adopted were M10 (OPC) for C25, M1 (OPC) for C30, M15 (OPC-LF) for C35 and M18 (OPC-LF) for C45. Generally, for a given ρ, increasing the concrete strength class reduces the ECO$_2$ of the columns. Only in the case of $\rho = 0.04$, when using C45 concrete, the carbon footprint is higher than when using C35. This is explained by the fact that the columns with C35 and C45 must be built with the minimum section of 20 cm side, and M18 (C45) has a 9% higher ECO$_2$/m^3 than M15 (C35) (Table 3).

Naturally, the contribution of steel to the column carbon footprint increased with the increase of ρ. The higher the carbon footprint, the larger the ρ. The contribution of the

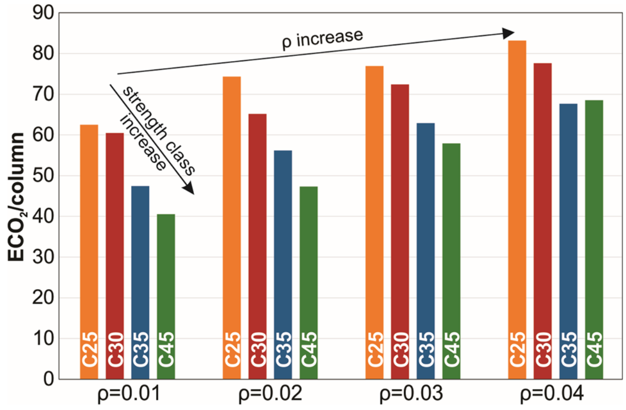

Fig. 1 ECO_2 of columns under axial load only with different ρ and concrete strength class

steel to the ECO_2/column ranged between 28.0 and 30.3% for $\rho = 0.01$, between 44.0 and 46.7% for $\rho = 0.02$, between 54.4 and 57.0% for $\rho = 0.03$ and between 61.6 and 64.1% for $\rho = 0.04$. This is explained by the fact that, although the steel cross-section is relatively small compared to that of concrete and the increase in steel volume was less than 3% for all ρ (Sect. 3.2.1), the ECO_2/m^3 of steel are 32 to 43 times higher than those of the concrete mixes studied. Therefore, the reduction in the volume of the column cannot offset the increase in the ECO_2 of the steel.

Consequently, on the one hand, for the same concrete strength class, the higher the ρ, the higher the carbon footprint of the columns. On the other hand, within the same ρ, the higher the concrete strength class, the lower the carbon footprint of the columns. Meanwhile, the carbon footprint of the column with $\rho = 0.03$ and C45 is lower than that of the column with $\rho = 0.01$ and C25. This is attributed to the fact that the reduction in the column volume due to the simultaneous use of a larger steel section and a higher concrete strength class is sufficient to neutralise the increase in ECO_2 associated with the steel. Likewise, the lowest carbon footprint is obtained for the column with the minimum steel cross-section ($\rho = 0.01$) and the highest strength class of those studied (C45). This is the result of minimising the volume of material with the highest ECO_2/m^3 and significantly reducing the volume of material by employing a concrete with higher strength class.

3.2.3 Carbon footprint for varying concrete strength class and supplementary cementitious materials content

Figure 2 shows the percentage of OPC replacement by SCMs (right-hand axis), the reduction of ECO_2 of M2–M18 mixtures with respect to the reference mixture (M1) and the reduction of ECO_2 of columns built with M2–M18 compared to that made with M1.

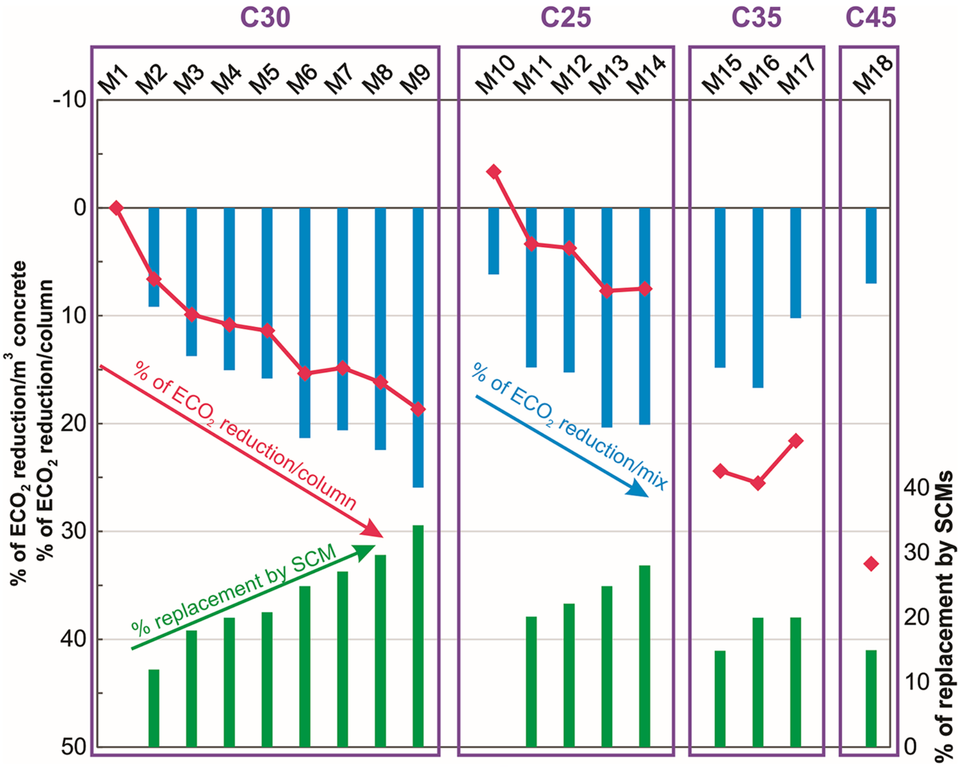

Fig. 2 Reduction of the ECO_2 per m^3 of concrete and per column for concretes with SCMs for columns under axial load only

Regarding the concrete mixtures (blue bars, Fig. 2), an increase in the replacement level of OPC by SCMs reduced the carbon footprint of the mixture. Furthermore, the higher the concrete strength class, the lower the carbon footprint decrease.

Concerning the concrete columns with $\rho = 0.01$ (red line, Fig. 2), for those with C30 mixtures, the carbon footprint decreased in the same proportion as M2–M9 mixtures due to the OPC replacement by SCM increase (green bars, Fig. 2). This correlation is found since the M1 mixture was considered to shape the reference column. Analysing the columns built with C25 concretes, the reduction in the carbon footprint of the columns was significantly lower than that calculated for the corresponding concrete mixtures. For M10 (OPC), the carbon footprint of the columns was 3.3% higher than the corresponding to M1. This is because the decrease in the cement content per m^3 of concrete was not enough to offset the increase in the volume of materials required to maintain the bearing capacity.

In contrast, the highest decreases in the carbon footprint were attained for columns built with C35 and C45 concretes. For M15–M17 mixtures, the carbon footprint decreased between 10.2 and 16.7% compared to the reference (M1), whereas for the corresponding columns, the carbon footprint decreased between 21.6 and 25.5%, more than the reduction calculated for the mixture. Out of those made with blended cements, the M18 mixture had the lowest reduction in the carbon footprint compared to M1 (7.0%). However, the column built with M18 allowed a significant carbon footprint saving of 33.0% compared to the one made with M1. The higher saving achieved in columns built with C35 and C45 mixtures is explained by the combined effects of the OPC replacement by SCMs (Table 3) and the reduction in the volume of materials (Table 4) to shape the columns as a result of the higher concrete strength class.

3.3 Columns under axial load and one-direction bending moment

3.3.1 Required volume of materials to withstand the axial load and bending moment

Table 5 shows the cross-sections and volumes of concrete and steel required to shape the columns bearing an axial load of 900 kN and a bending moment of 31.8 kNm, for the different concrete strength classes and ρ. For a C25, an increase in ρ from 0.01 to 0.04 increased the required volume of steel by 246.9% while reducing the total volume of the column by 38.3%. However, for C35, an increase in ρ from 0.01 to 0.04 increased the volume of steel by 306.3% and allowed a 23.4% reduction in the concrete volume. Yet, as with columns under axial load only, the notable increase in the required volume of steel represents less than 3% of the total column volume for any of the strength classes. Hence, when columns are subjected to the combined action of axial load and bending moment, the increase of ρ is more sensitive for concretes of relatively low-strength class concrete than for those of high-strength class.

On the other hand, when the concrete strength class was reduced from C30 to C25, the volume of the reinforced concrete column under axial load and bending moment increased between 8.5 and 16.0%, depending on ρ. In contrast, when the strength class was increased from C30 to C35, the volume of the structural element was reduced by 14.8 and 8.2% for $\rho = 0.01$ and 0.02, and it was not modified for $\rho = 0.03$ and 0.04 since a smaller column cross-section is not able to withstand the bending moment.

Table 5 Size of the concrete columns and volume of materials involved for columns under axial load and bending moment

Quantity of steel	Concrete strength class	Column cross-section (cm^2)	Steel cross-section (cm^2)	Concrete volume (m^3)	Steel volume (m^3)
$\rho = 0.01$	C25	784	7.84	0.210	0.0021
	C30	676	6.76	0.181	0.0018
	C35	576	5.76	0.154	0.0016
$\rho = 0.02$	C25	625	12.50	0.165	0.0034
	C30	576	11.52	0.152	0.0031
	C35	529	10.58	0.140	0.0029
$\rho = 0.03$	C25	529	15.87	0.139	0.0043
	C30	484	14.52	0.127	0.0039
	C35	484	14.52	0.127	0.0039
$\rho = 0.04$	C25	484	19.36	0.125	0.0052
	C30	441	17.64	0.114	0.0048
	C35	441	17.64	0.114	0.0048

3.3.2 Carbon footprint for varying steel to concrete cross-section ratio (ρ)

Figure 3 shows the ECO_2 of columns with different ρ and concrete strength class. The reference mixes adopted for the different strength classes were M10 (OPC) for C25, M1 (OPC) for C30 and M15 (OPC-LF) for C35.

For a given ρ, increasing the concrete strength class reduced the carbon footprint of the columns. For ρ = 0.01, increasing the strength class of concrete from C25 to C35 reduces the carbon footprint by 28.8%; for ρ = 0.02, a reduction of 17.3% is possible; for ρ = 0.03, 10.2%; and for ρ = 0.04, 10.3%. The smaller reduction obtained as ρ increases is attributed to the fact that such an additional steel section does not reduce the cross-section required to withstand the bending moment, making it less effective to increase the strength class of the concrete.

Analogous to the columns under axial loading only, the increase in ρ leads to an increased carbon footprint. For C25, increasing ρ from 0.01 to 0.04 provided an increment in carbon footprint of 14.7%, while for a C35, that was 44.3%. Additionally, the carbon footprint of the column with $\rho = 0.03$ and C35 is smaller than that of the one with $\rho = 0.01$ and C25, and the minimum carbon footprint is found for the column with $\rho = 0, 01$ and C35.

3.3.3 Carbon footprint for varying concrete strength class and supplementary cementitious materials content

Figure 4 shows the percentage of OPC replacement by SCMs (right-hand axis), the reduction of ECO_2 of M2–M17 mixtures with respect to the reference mixture (M1) and the reduction of ECO_2 of columns built with M2–M17 compared to that made with M1 for columns subjected to axial load and bending moment.

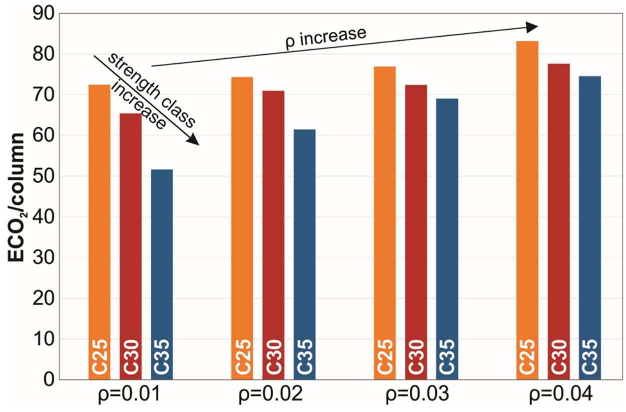

Fig. 3 ECO_2 of columns under axial load and bending moment with different ρ and concrete strength class

For those columns built with C30 mixtures and $\rho = 0.01$ (red line, Fig. 4), the carbon footprint decreased in the same proportion as M2–M9 mixtures, as for the columns under axial load only. For columns built with C25, the carbon footprint reduction of the columns was significantly lower than that calculated for the corresponding concrete mixtures, only being able to reduce the carbon footprint of the columns with M13 and M14 within this strength class. The carbon footprint of M10 (OPC) was 10.8% greater than that of M1, and those of M12 and M13 were 3.6% and 3.2% higher, respectively. In the same way as for columns under axial load only, it is because the decrease in the carbon footprint per m^3 of concrete is not enough to neutralise the increment in the carbon footprint due to the increase in the volume of material required.

In the case of columns made with C35, the reduction of the carbon footprint was within the same range as for columns under axial loading only (21.1–25.0% lower), showing that for both simple compression and compression + bending, increasing the strength class allows to efficiently reduce the volume of material required and the carbon footprint.

3.4 Curing influence on concretes with SCM

Table 6 shows the compressive strength of some of the concrete mixes at 90 days of curing. Concrete mixtures made with OPC and with OPC + LF and mixtures with ternary blended cements and higher substitution levels of LF (M1–M3, M5, M7–M9 (Menendez 2006)) increased their compressive strength to a lesser extent with the prolonged curing time. In contrast, those concrete mixtures made with cements with SCM with pozzolanic properties and low content of LF (M4 (Menendez 2006), M6 and M13 (Cordoba et al. 2020) and M17 (Perrone et al. 2012)) increased their compressive strength more significantly, allowing to upgrade the concrete strength class. This increase in the strength class would lead to a greater eco-efficiency of columns under axial load. That is possible due to the reduced volume of structural elements, getting the combined benefit of saving Portland clinker and lower use of materials.

4 Discussion

It is possible to reduce the carbon footprint of reinforced concrete columns by upgrading the concrete strength class and its SCM content. Increasing the steel section within the same concrete strength class leads to a higher carbon footprint. However, it is possible to lower the carbon footprint of the column made with $\rho = 0.01$ and C25 by employing simultaneously higher ρ and a higher strength class concrete. Therefore, it is essential to consider not only the carbon footprint of materials per unit weight or

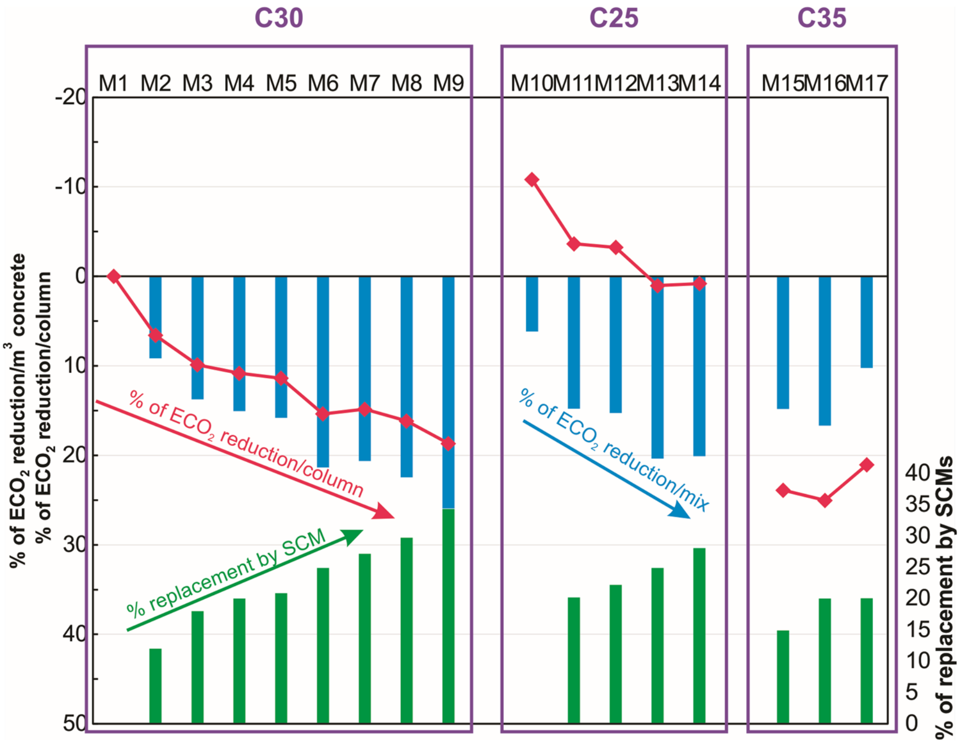

Fig. 4 Reduction of the ECO_2 per m^3 of concrete and per column for concretes with SCMs for columns under axial load and bending moment

volume but also the volume of material required to build compressed structural elements.

Concretes with a relatively high strength class contain higher cement content per m^3 of concrete, as well as a lower replacement level of OPC by SCM (Table 2). Although OPC presents a considerably larger carbon footprint than the one associated with SCM production, its replacement can decrease the specified concrete compressive strength at 28 days. Hence, reducing the carbon footprint by lowering the clinker factor using SCMs is not always enough to offset the increased volume of materials required to maintain the bearing capacity.

This study has shown that using materials with a lower carbon footprint per unit volume does not always reduce the carbon footprint of the structural element, nor minimising the volume is always the most sustainable solution in terms of CO_2 equivalent emissions. If materials with a low carbon footprint are used, it would be relevant to measure whether the volume of materials involved is simultaneously reduced. If the volume of materials required increases, it would be necessary to analyse whether the effect of this increase is compensated by the lower carbon footprint per unit volume or whether it is more advantageous to use materials with a higher carbon footprint per unit volume, which

Table 6 Compressive strength and strength class of concretes at 28 and 90 days of curing

Concrete mixture	f'_{cm3} (MPa)	Strength class, according to f'_{cm3}	f'_{c90} (MPa)	Strength class, according to f'_{c90}
M1 (OPC)	36	30	39	30
M2 (OPC-LF)	35	30	38	30
M3 (OPC-LF)	35	30	38	30
M4 (OPC-GBFS)	35	30	41	35
M5 (OPC-LF-GBFS)	37	30	39	30
M6 (OPC-KC)	37	30	47	40
M7 (OPC-LF-GBFS)	37	30	38	30
M8 (OPC-LF-GBFS)	35	30	39	30
M9 (OPC-LF-GBFS)	35	30	38	30
M13 (OPC-IC)	30	25	38	30
M17 (OPC-LF-FA)	41	35	47	40

reduce the total volume. Then, high-strength concrete can be more sustainable than low-strength concrete (Aïtcin 2007; UN Environment Programme et al. 2018; Kourehpaz and Miller 2019; American Concrete Institute 2022). Moreover, the positive impact of using SCM as a replacement for Portland cement could be maximised through an increase in the strength class of the concrete by reducing the water-to-binder ratio, obtaining a concrete with a lower clinker factor content and a high-strength class (Mehta 1991; Damineli et al. 2010; Cyr 2013; Day et al. 2013).

There are further benefits related to implementing these strategies that were not measured in this study but are worth highlighting. Due to the availability of non-metallic minerals, construction and building materials are not considered to contribute to mineral resource scarcity (Habert et al. 2010; Silva et al. 2020). However, they represent 93.2% of the building's mass (Silva et al. 2020), and according to projections, the consumption of non-metallic materials will increase in the forthcoming decades (OECD 2019). The use of higher-strength concretes may contribute to reduce the thickness or cross-section of structural elements (Kourehpaz and Miller 2019; Hawkins et al. 2020) and thereby diminish the volume of natural resources for their construction (UN Environment Programme et al. 2018). Thus, reducing the cross-sections of structural elements would allow buffering the effect of the increase in non-metallic materials consumption. In addition, depending on the sources of non-metallic minerals and the geolocation of the production/extraction sites, reducing the volume of materials leads to savings in their transportation and associated emissions.

Regarding the use of SCM as a replacement for Portland cement, it should be emphasised that in addition to the clear reduction of the carbon footprint, it contributes to reducing the use of energy (electricity and fuels) and non-renewable raw materials and, when it comes from industrial by-products, contributes to the circular economy model and to reducing the volume of waste (Tait and Cheung 2016; Gettu et al. 2018; Kourehpaz and Miller 2019; Habert et al. 2020). On the other hand, SCMs with pozzolanic activity generally do not contribute to compressive strength at early ages (Cyr 2013; Juenger and Siddique 2015), but they contribute to concrete compressive strength at ages beyond 28 days (Wild et al. 1996; Dhandapani and Santhanam 2017). Furthermore, most standards and regulations are prescriptive, defining cements by the composition of the SCMs. Cements are classified according to the compressive strength of mortars with a given composition, ignoring the physical effects of including SCMs or modifying the mortar or concrete mixes composition. The durability-related parameters are not assessed in this study, as traditional methods for LCA impact evaluation do not involve performance parameters. However, it is well known that denser concretes (higher compressive strength) are accompanied by enhanced durability since both properties are closely linked to the pore size and connectivity of the pore network (Mehta 1991; Cyr 2013). In this regard, the transition towards the use of performance-based standards would lead to explore other opportunities for designers of structures and building materials to reduce the environmental impact (John et al. 2019). Hence, it provides engineers and architects with the flexibility to extend the concrete design age beyond 28 days (when feasible), enabling a reduction in the volume of materials involved to build some structural elements and, consequently, increasing the eco-efficiency of concrete (The Concrete Centre 2020; Habert et al. 2020).

5 Conclusions

Building materials exhibit environmental advantages and disadvantages related to the examination level considered in the methodology. For this study of reinforced concrete columns, the following conclusions can be drawn:

- As it is well known, using SCMs in blended cements reduces the carbon footprint per tonne of cement and m^3 of concrete.
- To increase the specified compressive strength (f'_c) of concrete, high cement content per m^3 of concrete is generally required. Thereby, it increases the carbon footprint of a concrete mixture.
- For ordinary reinforced concrete columns subjected to axial load only and axial load and bending moment, increasing the reinforcing steel cross section increases the carbon footprint for a given concrete strength class. This is because, although the increase in the steel cross-section reduces the volume of the column, the reduction in the amount of materials used is not enough to offset the increase in CO_2 equivalent emissions associated with the steel.
- For reinforced concrete columns, increasing the f'_c permits to reduce the steel and concrete cross sections and the volume of the material reduces the carbon footprint.
- The use of high volumes of SCM can reduce the f'_c at 28 days, increasing the required materials and carbon footprint of reinforced concrete columns.
- If SCM are used simultaneously with an increased concrete f'_c, the combined benefit of reducing the embodied carbon dioxide per m^3 of concrete and the volume of columns leads to a significant reduction in the carbon footprint of such structural elements.
- SCMs with pozzolanic activity usually do not contribute to the initial strength of concrete. However, they increase the ultimate compressive strength (> 56 days). Therefore, amendments to standards and policies are needed to extend the concrete design age when possible to promote the use of this type of SCM.

Summarising, using materials with a low carbon footprint does not always reduce the carbon footprint of the structural element, nor minimising the volume is always the most sustainable solution. Therefore, finding a solution that balances the use of materials with a low carbon footprint and a decrease in the required materials volume is necessary. However, this study has been limited to the calculation of concrete columns, being essential to include in subsequent studies the optimisation of the shape of the concrete columns and the combination of other stresses and to integrate these criteria with the existing analyses carried out by other authors on beams, slabs and other structural elements in order to fully evaluate a complete structure.

Lastly, it would be essential to complete a life cycle assessment of reinforced concrete structures considering the use and final deposition stages of the concrete as well as the transportation of the materials, to comprehensively analyse the entire lifespan and examine the effect of the concrete durability, especially those incorporating SCM.

Acknowledgements The authors would like to acknowledge Professor Norma Ércoli and Dr. Eng. Antonela Di Salvo Barsi for their advice on the dimensioning of the columns with a structural approach; the Comisión de Investigaciones Cientificas (CIC) de la Provincia de Buenos Aires and the Faculty of Engineering of the Universidad Nacional del Centro de la Provincia de Buenos Aires (UNCPBA) for financing the development of this research; and the reviewers of this paper for substantially improving the results and analysis.

Data availability All data generated or analysed during this study are included in this published article.

Declarations

Competing interests The authors declare no competing interests.

References

Abd Rashid AF, Yusoff S (2015) A review of life cycle assessment method for building industry. Renew Sustain Energy Rev 45:244–248

ACI Committee 130 (2019) Report on the role of materials in sustainable concrete construction

Adams M, Burrows V, Richardson S (2019) Bringing embodied carbon upfront

Aïtcin P-C (2007) Binders for durable and sustainable concrete, First edit. Taylor & Francis, Abingdon, UK

Allwood JM, Ashby MF, Gutowski TG, Worrell E (2011) Material efficiency: a white paper. Resour Conserv Recycl 55:362–381. https://doi.org/10.1016/j.resconrec.2010.11.002

American Concrete Institute (2019) ACI 318, Building code requirements for structural concrete

American Concrete Institute (2022) Sustainability of concrete. In: https://www.concrete.org/topicsinconcrete/topicdetail/sustainability%20of%20concrete?search=sustainability%20of%20concrete. Accessed 1 Aug 2022

Cancio Diaz Y, Sanchez Berriel S, Heierli U et al (2017) Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies. Dev Eng 2:82–91. https://doi.org/10.1016/j.deveng.2017.06.001

Cordoba G, Paulo CI, Irassar EF (2023) Towards an eco-efficient ready mix-concrete industry: advances and opportunities. A study of the Metropolitan Region of Buenos Aires. J Build Eng 63:105449. https://doi.org/10.1016/j.jobe.2022.105449

Cordoba G, Zito SV, Sposito R et al (2020) Concretes with calcined clay and calcined shale: workability, mechanical, and transport properties. J Mater Civ Eng 32:4020224. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003296

Cyr M (2013) Influence of supplementary cementitious materials (SCMs) on concrete durability. In: Eco-efficient concrete. Elsevier, pp 153–197

Damineli BL, Kemeid FM, Aguiar PS, John VM (2010) Measuring the eco-efficiency of cement use. Cem Concr Compos 32:555–562. https://doi.org/10.1016/j.cemconcomp.2010.07.009

Day KW, Aldred J, Hudson B (2013) Concrete mix design, quality control and specification, fourth edition

Dhandapani Y, Santhanam M (2017) Assessment of pore structure evolution in the limestone calcined clay cementitious system and its implications for performance. Cem Concr Compos 84:36–47. https://doi.org/10.1016/j.cemconcomp.2017.08.012

Environment Programme UN, Scrivener KL, John VM, Gartner EM (2018) Eco-efficient cements: potential economically viable solutions for a low-CO2 cement-based materials industry. Cem Concr Res 114:2–26. https://doi.org/10.1016/j.cemconres.2018.03.015

Falconara S (2014) Carbonatación en hormigones con adiciones minerales en la pampa húmeda (“Concrete carbonation with mineral admixtures in the Wet Pampa”)

Fédération Internationale du Béton (2010) Model code for concrete structures. Lausanne, Switzerland

Finkbeiner M, Bach V (2021) Life cycle assessment of decarbonization options—towards scientifically robust carbon neutrality. Int J Life Cycle Assess 26:635–639. https://doi.org/10.1007/s11367-021-01902-4

Flower DJM, Sanjayan JG (2007) Greenhouse gas emissions due to concrete manufacture. Int J Life Cycle Assess 12:282–288. https://doi.org/10.1065/lca2007.05.327

Gettu R, Pillai RG, Santhanam M, et al (2018) Sustainability-based decision support framework for choosing concrete mixture proportions. Mater Struct 51. https://doi.org/10.1617/s11527-018-1291-z

Giaccio G, Milanesi C, Violini D, Zerbino R (2001) Hormigones elaborados con cemento fillerizado (“Concretes made with filler cement”). In: 14° Reunión Técnica Asociación Argentina de Tecnología del Hormigón. pp 81–88

Glavind M (2011) Green Concrete Structures Struct Concr 12:23–29. https://doi.org/10.1002/suco.201000022

Glavind M, Asprone D, Bleiziffer J, et al (2012) fib Bulletin 67. Guidelines for green concrete structures. fib. The International Federation for Structural Concrete

Global Cement and Concrete Association (2021) Roadmap for Net Zero Concrete

Habert G, Bouzidi Y, Chen C, Jullien A (2010) Development of a depletion indicator for natural resources used in concrete. Resour Conserv Recycl 54:364–376. https://doi.org/10.1016/j.resconrec.2009.09.002

Habert G, Miller SA, John VM et al (2020) Environmental impacts and decarbonization strategies in the cement and concrete industries. Nat Rev Earth Environ 1:559–573. https://doi.org/10.1038/s43017-020-0093-3

Hawkins W, Orr J, Ibell T, Shepherd P (2020) A design methodology to reduce the embodied carbon of concrete buildings using thin-shell floors. Eng Struct 207:110195. https://doi.org/10.1016/j.engstruct.2020.110195

Instituto Nacional de Tecnología Industrial (2005) CIRSOC 201 Reglamento Argentino de Estructuras de Hormigón

International Standard Organization (2006) ISO 14040 - environmental management - life cycle assessment - principles and framework. ISO/TC 207/SC 5 Life cycle Assess.

Irassar EF, John VM, Tobón JI et al (2020) Ciudades sostenibles y resilientes. Rev Cem Concreto 7:78–90

John VM, Quattrone M, Abrão PCRA, Cardoso FA (2019) Rethinking cement standards: opportunities for a better future. Cem Concr Res 124:105832. https://doi.org/10.1016/j.cemconres.2019.105832

Jones C (2019) Inventory of Carbon and Energy (ICE) Database. In: https://circularecology.com/embodied-carbon-footprint-database.html. Accessed 27 Jan 2020

Juenger M, Siddique R (2015) Recent advances in understanding the role of supplementary cementitious materials in concrete. Cem Concr Res 78:71–80. https://doi.org/10.1016/j.cemconres.2015.03.018

Kourehpaz P, Miller SA (2019) Eco-efficient design indices for reinforced concrete members. Mater Struct 52:1–15. https://doi.org/10.1617/s11527-019-1398-x

López AE (2020) Impacto económico y medioambiental del diseño de estructuras en edificios de hormigón armado (Economic and environmental impact of the design of reinforced concrete building structures)

Mehta PK (1991) Durability of concrete - fifty years of progress? ACI Symp Publ 126:1–32. https://doi.org/10.14359/1998

Menendez G (2006) Aplicación del diseño de experimentos en la formulación de cementos compuestos (“The application of experimental design in the development of blended cements”). Universidad Nacional del Centro de la Provincia de Buenos Aires

Miller D, Doh JH, Mulvey M (2015a) Concrete slab comparison and embodied energy optimisation for alternate design and construction techniques. Constr Build Mater 80:329–338. https://doi.org/10.1016/j.conbuildmat.2015.01.071

Miller SA, Horvath A, Monteiro PJM, Ostertag CP (2015b) Greenhouse gas emissions from concrete can be reduced by using mix proportions, geometric aspects, and age as design factors. Environ Res Lett 10:. https://doi.org/10.1088/1748-9326/10/11/114017

MPA The Concrete Centre (2022) Comparison of embodied carbon in concrete structural systems

OECD (2020) Environment at a glance. OECD Publishing, Paris

OECD (2019) Global Material Resources Outlook to 2060. OECD

Perrone F, Rodriguez F, Violini D et al (2012) Hacia el logro de un hormigón más sustentable: optimización del diseño de hormigones con ceniza volante y filler calcáreo (“Towards a more sustainable concrete: optimisation of fly ash and lime filler concrete design”). In: V Congreso Internacional y 19° Reunión Técnica Asociación Argentina de Tecnología del Hormigón. pp 407–414

Presa C (2016) Consumo energético del ciclo integral del agua en usos urbanos (Energy consumption of the comprehensive water cycle in urban uses). https://ecodes.org/archivo/proyectos/archivo-ecodes/pages/especial/consumo-energetico-ciclo-integral-agua-usos-urbanos/index.html. Accessed 20 Apr 2016

Silva FB, Reis DC, Mack-Vergara YL et al (2020) Primary data priorities for the life cycle inventory of construction products: focus on foreground processes. Int J Life Cycle Assess 25:980–997. https://doi.org/10.1007/s11367-020-01762-4

Tait MW, Cheung WM (2016) A comparative cradle-to-gate life cycle assessment of three concrete mix designs. Int J Life Cycle Assess 21:847–860. https://doi.org/10.1007/s11367-016-1045-5

The Concrete Centre (2020) Specifying Sustainable Concrete. 24

UN Economic and Social Council (2019) Special Edition: progress towards achieving the Sustainable Development Goals

United Nations (2015) Goal 12: ensure sustainable consumption and production patterns. https://www.un.org/sustainabledevelopment/sustainable-consumption-production/. Accessed 2 Aug 2020

Vizcaino L, Sanchez S, Damas S et al (2015) Industrial trial to produce a low clinker, low carbon cement. Mater Constr 65:e045. https://doi.org/10.3989/mc.2015.00614

Watari T, Cao Z, Hata S, Nansai K (2022) Efficient use of cement and concrete to reduce reliance on supply-side technologies for net-zero emissions. Nat Commun 13:1–9. https://doi.org/10.1038/s41467-022-31806-2

Wild S, Khatib JM, Jones A (1996) Relative strength, pozzolanic activity and cement hydration in superplasticised metakaolin concrete. Cem Concr Res 26:1537–1544. https://doi.org/10.1016/0008-8846(96)00148-2

Zhang C, Chen WQ, Ruth M (2018) Measuring material efficiency: a review of the historical evolution of indicators, methodologies and findings. Resour Conserv Recycl 132:79–92. https://doi.org/10.1016/j.resconrec.2018.01.028