

Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability

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Abstract

Purpose Blended cements use waste products to replace Portland cement, the main contributor to CO₂ emissions in concrete manufacture. Using blended cements reduces the embodied greenhouse gas emissions; however, little attention has been paid to the reduction in CO₂ capture (carbonation) and durability. The aim of this study is to determine if the reduction in production emissions of blended cements compensates for the reduced durability and CO₂ capture.

Methods This study evaluates CO₂ emissions and CO₂ capture for a reinforced concrete column during its service life and after demolition and reuse as gravel filling material. Concrete depletion, due to carbonation and the unavoidable steel embedded corrosion, is studied, as this process consequently ends the concrete service life. Carbonation deepens progressively during service life and captures CO₂ even after demolition due to the greater exposed surface area. In this study, results are presented as a function of cement replaced by fly ash (FA) and blast furnace slag (BFS).

Results and discussion Concrete made with Portland cement, FA (35 % FA), and BFS blended cements (80 % BFS) captures 47, 41, and 20 % of CO₂ emissions, respectively. The service life of blended cements with high amounts of cement replacement, like CEM III/A (50 % BFS), CEM III/B (80 % BFS), and CEM II/B-V (35 % FA), was about 10 % shorter, given the higher carbonation rate coefficient. Compared to Portland cement and despite the reduced CO₂ capture and service life, CEM III/B emitted 20 % less CO₂ per year.

Conclusions To obtain reliable results in a life cycle assessment, it is crucial to consider carbonation during use and after demolition. Replacing Portland cement with FA, instead of BFS, leads to a lower material emission factor, since FA needs less processing after being collected, and transport distances are usually shorter. However, greater reductions were achieved using BFS, since a larger amount of cement can be replaced. Blended cements emit less CO₂ per year during the life cycle of a structure, although a high cement replacement reduces the service life notably. If the demolished concrete is crushed and recycled as gravel filling material, carbonation can cut CO₂ emissions by half. A case study is presented in this paper demonstrating how the results may be utilized.

Keywords Blended cement · Carbonation · CO₂ emission · Durability · Life cycle · Recycled concrete

1 Introduction

Over the recent decades, there has been a growing concern about the need to protect the environment and keep our planet safe. While the embodied greenhouse gas (GHG) emissions were limited by the Kyoto Protocol, in 2001, the Spanish construction industry produced 1.76 m³ of concrete per capita per year; Spain has the highest consumption rate in Europe, more than twice the average of other countries (ECO-SERVE 2004). The construction industry is second to the food industry in raw materials consumption (Berge 2000); in fact, building construction consumes 40 % of the world's raw materials. Furthermore, it generates 40–50 % of all global GHG emissions and agents of acid rain (CIWMB 2000). Concrete is the most heavily consumed material in the construction sector (ISO 2005; Weil et al. 2006). The manufacture of Portland cement contributes large amounts of CO₂ to the total emissions from concrete construction given the high energy

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demands during manufacture and limestone calcination, totaling to 5 % of the world's GHG emissions (Worrell et al. 2001).

Now, more than ever, engineers should choose environmentally friendly materials and cross-section dimensions to minimize the impact of their projects as well as the consumption of natural resources. Optimization is a suitable tool to minimize costs and, hence, reduce construction material consumption. Although optimization of construction costs is proportional to that of the CO₂ emissions, the diversity of materials used in concrete production requires more detailed analysis. Several recent studies have used multiobjective optimization algorithms to compare CO₂ efficiency and the cost design applied to reinforced concrete (RC) structures (Paya et al. 2008; Payá-Zaforteza et al. 2009; Yepes et al. 2012; Martínez-Martín et al. 2012; Camp and Huq 2013). These studies have only examined emissions at the different stages of production and placement; therefore, this research aims to analyze the cradle to grave life cycle of concrete, especially blended cement mixes. Thus, and in line with Jönsson et al. (1988), the life cycle of alternative construction materials can be assessed before the type of material is chosen for a particular construction project.

The current sustainability debate has seemingly overlooked the question of how concrete reabsorbs CO₂ from the atmosphere during its service life and in its secondary life following recycling. Leber and Blakey (1956) used chemical analysis to estimate the effects of CO₂ on mortars and concrete, assuming that all absorbed CO₂ reacts with the lime to form calcium carbonate. Aitcin (2000) later affirmed the importance of not just the cost of 1 m³ of concrete but rather the cost of 1 MPa or 1 year of the life cycle of a structure. Collins (2010) studied the inclusion of carbonation during the life cycle of built and recycled concrete, assuming a primary life of 100 years plus a 30-year secondary life. In contrast, this research sets out to first assess durability as determined by the lifetime of a structure and then compare the emissions per year of blended cements. As durability allows for the recovery of emissions from previous stages, scientists have searched for ways to extend concrete durability. However, the RC durability can be substantially reduced by degradation processes of environmental or functional origins (Angst et al. 2009; Guzmán et al. 2011). In fact, durability is also fundamental for good conceptual design, quality management in construction, and a good maintenance plan.

From the point of view of cement manufacturers, the carbonation process can be identified as recarbonation because the final product, calcium carbonate, is chemically the same as one of cement's primary raw ingredients. This process has been assessed using three different models: theoretical models (Papadakis et al. 1991), experimental models (Jiang et al. 2000), and models based on the diffusion theory and practical testing (Houst and Wittmann 2002). Concrete carbonation can completely dissolve the protective layer inducing corrosion, which may lead to a shortened service life. The rate of ingress

of the aggressive agents depends on the quality of the porosity, the permeability of the concrete cover, and wetting and drying conditions (Bertolini et al. 2004). Nevertheless, concrete carbonation captures CO₂ and compensates for the emissions from other stages of the life cycle. If carbon capture is ignored (Flower and Sanjayan 2007), emission rates may be overestimated by as much as 13–48 %, depending on the type of cement and the use of recycled concrete during its secondary life (Collins 2010). About two thirds of the calcination emissions can be reabsorbed, if the crushed concrete is exposed for 30 years (Dodoo et al. 2009). In fact, 70 % of the CO₂ released in cement production would be recaptured by the hardened concrete within 100 years (Börjesson and Gustavsson 2000). However, this effect is largely dependent on the recycling practices in each country (Pade and Guimaraes 2007).

The development of blended cements has resulted in CO₂ savings, since Portland cement is replaced with either blast furnace slag (BFS), a by-product of the steel industry, or fly ash (FA), a by-product of burning coal. It is known that the mix design can be adjusted in order to avoid changes in the properties of blended cement concrete. The variation in the mass of raw materials in the mix design can lead to differences in GHG emissions of less than 0.2 %, and there is only a negligible effect on embodied water (O'Brien et al. 2009), hence this study will assume the same mix design (Table 1).

The purpose of this study is, therefore, to quantify GHG emissions as a function of the cement used during the concrete life cycle and to determine if the reduction in production emissions of blended cements compensates for the reduced durability and CO₂ capture. The paper is organized following the different stages of concrete life, incorporating durability and CO₂ capture during the use stage and after demolition. A case study provides the life cycle assessment (LCA) of a RC column.

2 Materials and methods

Although several tools have been developed to measure sustainability, none are more complete than the LCA, as it evaluates the inputs–outputs as well as the potential environmental impacts of a product system throughout its life cycle. The LCA is divided into four phases: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase (ISO 2006). In the construction industry, only the inventory analysis and interpretation are common and are known as a life cycle inventory study. The LCA covers every product process, from obtaining the raw materials and processing them, to demolition and recycling; hence, in this study, the LCA is useful to compare the environmental impact of different concrete mixes.

Table 1 Concrete mix

	Cement	Water	Plasticizer	Coarse aggregate	Fine aggregate
kg/m ³	250	165	2.5	940	1,050

Several complications arise when a construction system is assessed. The cradle to grave life cycle of concrete is longer than other industrial systems, and numerous product processes are often entwined. Figure 1 illustrates the four stages within a construction system. The production stage involves obtaining raw materials and processing them, transport to the concrete plant, and the mixing. This stage also takes into account steel production of bars and transport to the building site. The second stage is construction, that is, when the structure is actually built. The next stage, and the most long-lasting one, is the use stage. Finally, once the structure’s life has ended, it is pulled down, and the demolished concrete is crushed and recycled as gravel filling material.

2.1 Production stage

The concrete production stage is the main contributor to CO₂ emissions, specifically those derived from quarrying, crushing, and cement manufacture. The high CO₂ emissions are due to the energy demands during manufacture and limestone calcination. Hence, cement is commonly replaced with cementitious materials like FA and BFS. It is considered that these materials do not emit CO₂, except for post-process and transport emissions, since they are waste products from other materials production. Besides, FA is collected at power stations for air quality reasons, even if it is not to be used in

concrete production (O’Brien et al. 2009). Additionally, FA needs little processing after being collected, so it emits less CO₂ than BFS.

As presented in Table 2, the environmental data analyzed in this study include the production emissions of all materials and their transport distances, transport emissions by lorry, concrete plant emissions and their transport distances, and concrete transport emissions by the mixer. Production emissions were taken from European associations, whose reports are corroborated and used by many companies. The source of energy has a strong influence on primary energy use and net CO₂ balance. Data on industrial energy use can vary depending on how the said data were obtained. Since industrial technologies differ in each country, in this study, data were selected for Spanish industrial energy (Institute for Diversification and Energy 2010). As this study assumed a manufacturing process after considering recycling, data emissions for reinforcing steel bars were taken from Yiwei et al. (2011). It is worth noting that recycling rates in steel construction average about 85 %, and CO₂ emissions of steel made from ore total around 1.8 kg CO₂ per kilogram of steel, while scrap using the basic oxygen furnace emit about 0.4 kg CO₂ per kilogram of steel (World Steel Association 2010). Transport distances vary depending on the locations; nevertheless, a standard building in central Valencia was assumed, and distances were doubled to account for the return trip. All concrete components were transported from the nearest factory to the concrete plant; the reinforcing steel bars were transported directly to the building site. Once the concrete was made, a mixer transported it from the concrete plant to the building site. Transport emissions were based on the transport vehicle specifications given by national contractors and subcontractors, and energy emission data were taken

Fig. 1 Life cycle of the construction system

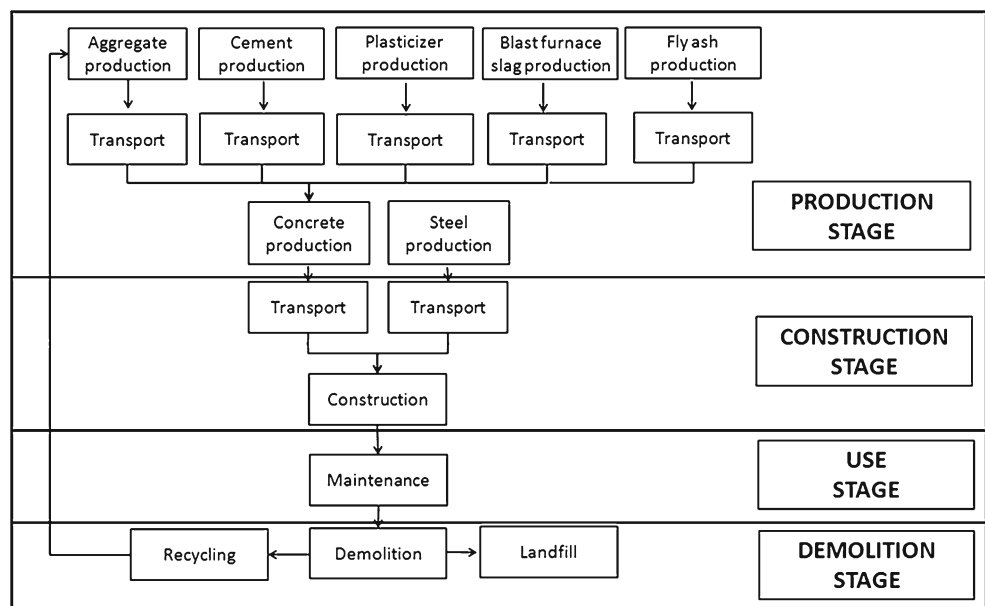


Table 2 CO₂ emission factors and distances

Stage	CO ₂ emissions	Units	Distance (km)	Reference	Observation
Production	819	kg CO ₂ /t	32	The Concrete Centre (2009)	
Portland cement	52	kg CO ₂ /t	1,640	The Concrete Centre (2009)	
Blast furnace slag	4	kg CO ₂ /t	180	The Concrete Centre (2009)	
Fly ash	4	kg CO ₂ /t	12	The Concrete Centre (2009)	
Aggregates	920	kg CO ₂ /t	680	Yiwei et al. (2011)	Manufacturing after considering recycling
Steel bars	220	kg CO ₂ /t	724	European Federation of Concrete Admixtures Associations (2006)	
Plasticizer	0.03	kg CO ₂ /km t		Institute for Diversification and Energy Saving (2010)	Fuel emission:2.6 kg CO ₂ /l Load weigh: 30 t Fuel consumption:35 l/100 km
Lorry	0.18	kg CO ₂ /m ³	26	Institute for Diversification and Energy Saving (2010); Database (2012)	Electric energy emission:0.254 kg CO ₂ /kWh Energy Consumption:0.71 kWh/m ³
Concrete plant	0.07	kg CO ₂ /km t		Institute for Diversification and Energy Saving (2010)	Fuel emission:2.6 kg CO ₂ /l Load weigh:12 t Fuel consumption:30 l/100Km
Mobile agitator	0.74	kg CO ₂ /m ³		Institute for Diversification and Energy Saving (2010)	Fuel energy emission:0.263 kg CO ₂ /kWh Power: 161 kW Performance:57 m ³ /h
Construction	0.04	kg CO ₂ /m ³		Institute for Diversification and Energy Saving (2010)	Fuel energy emission:0.263 kg CO ₂ /kWh Power: 15 kW Performance:100 m ³ /h
Pump	3.81	kg CO ₂ /m ³		Institute for Diversification and Energy Saving (2010)	Fuel energy emission:0.263 kg CO ₂ /kWh Energy consumption:14.5 kWh/m ³
Vibrator	0.59	kg CO ₂ /m ³		Institute for Diversification and Energy Saving (2010)	Fuel energy emission:0.263 kg CO ₂ /kWh Power: 13.52 kW Performance:6 m ³ /h
Demolition					
Demolition					
Crushing					

Table 3 CO₂ balances of blast furnace slag blended cement production and transport

		CO ₂ emissions (kg/column)		
		Production	Transport	Total
CEM Portland	Portland cement	55.28	0.07	55.35
	CEM II/B-S (35 % blast furnace slag)	Portland cement	0.04	
	Blast furnace slag	1.23	1.17	
	Total	37.16	1.21	38.37
	CEM III/A (50 % blast furnace slag)	Portland cement	0.03	
	Blast furnace slag	1.76	1.67	
	Total	29.40	1.70	31.10
	CEM III/B (80 % blast furnace slag)	Portland cement	0.01	
	Blast furnace slag	2.81	2.67	
	Total	13.86	2.69	16.55

from the Institute for Diversification and Energy Saving (2010).

2.2 Construction stage

During the construction stage, no differences were noted between the two blended cement mixes. In addition, the emissions during construction were almost negligible compared to those during production. So, it was not an outstanding stage, and therefore, only pumping and vibration for the construction activities were studied. Table 2 shows the total construction emissions. Like transport emissions, construction emissions were obtained from a survey of national contractors and subcontractors, and energy emission data were taken from the Institute for Diversification and Energy Saving (2010).

2.3 Use stage

Structure life is influenced by atmospheric agents, which limit RC durability. According to the EHE code (M. Fomento 2008), there are two main types of concrete depletion: carbonation and chloride penetration (Saassouh and Lounis 2012). This study focuses on carbonation not only because it leads to the depletion of concrete alkalinity and thus steel embedded corrosion, but also because CO₂ is

captured, and the emissions from other stages can be subtracted.

Carbonation is the main cause of RC decay. The degree of carbonation depends on three decisive factors:

- The w/b is decisive as far as porosity is concerned. Porosity can speed up carbonation. Cement replacement increases carbonation rates, as the pozzolanic reaction reduces the alkaline reserve (Zornoza et al. 2009).
- Decisive as well is the concentration of CO₂ in the surrounding air and the specific climatic conditions. The carbonation rate is higher in concrete protected against rain, as the pores are partially blocked by the rain (Galán 2011). If we compare the differences between protected and unprotected concrete, it is clear that humidity is one of the most influential factors in concrete carbonation (Galán et al. 2010).
- The depth of the embedded steel is also decisive in terms of RC decay. The greater the depth of the embedded steel, the longer it takes for CO₂ to carbonate the steel protection.

This study evaluates durability according to the EHE code (M. Fomento 2008), which is based on the Tuutti (1982) model. The service life of RC structures is divided in two distinct phases. The first phase is initiation of corrosion; carbonation penetrates in the concrete cover and leads to the loss of reinforcement passivity. The second phase involves the propagation of corrosion that begins when the steel is depassivated and ends

Table 4 CO₂ balances of fly ash blended cement production and transport

		CO ₂ emissions (kg/column)		
		Production	Transport	Total
CEM Portland	Portland cement	55.28	0.07	55.35
	CEM II/A-V (20 % fly ash)	Portland cement	0.05	
	Fly ash	0.05	0.07	
	Total	44.28	0.13	44.41
	CEM II/B-V (35 % fly ash)	Portland cement	0.04	
	Fly ash	0.09	0.13	
	Total	36.03	0.17	36.20

when a limiting state is reached, beyond which consequences of corrosion can no longer be tolerated. The service life is therefore calculated as the sum of the two phases:

$$t = \left(\frac{d}{k}\right)^2 + \frac{80 \cdot d}{\varnothing \cdot v_c} \quad (1)$$

Where t are the years of service life, d is concrete cover (in millimeter), k is the carbonation rate coefficient, \varnothing is the bar diameter (in millimeter), and v_c is the corrosion speed (in micrometers per year). The carbonation rate coefficient varies with rain-protected and unprotected concretes, the percentage of occluded air, and the cement type. The rate of corrosion is dependent on the type of exposure of the structural element. Table 5 indicates the values of k and v_c as obtained from the EHE code (M. Fomento 2008).

Service life defines the moment when concrete deterioration reaches an unacceptable limit. The use stage is considered finalized when the service life ends. Thus, there is no need for maintenance during this stage. However, we can lengthen the technical lifetime of a RC structure, but this will involve high costs for maintenance and repair. It is crucial to consider service life to calculate annual emissions, and therefore, a more reliable benchmark.

Once the life of the structure is known, CO₂ capture can be assessed during the service life. Pade and Guimaraes (2007), Dadoo et al. (2009), and Collins (2010) used Eq. (2) to estimate CO₂ capture based on the predictive models of Fick's first law of diffusion and the study by Lagerblad (2005). CO₂ capture can be calculated here as the product of the carbonation rate coefficient k , which was calculated previously in the durability assessment, the structure service life t , the quantity of Portland cement per cubic meter of concrete c , the amount of CaO content in Portland cement CaO (assumed to be 0.65), the proportion of calcium oxide that can be carbonated r (assumed to be 0.75, Lagerblad 2005), the exposed surface area of concrete A , and the chemical molar fraction M (CO₂/CaO is 0.79.) It can be said that the reduction in CO₂ capture is proportional to the reduction in Portland cement in blended cements:

$$\text{CO}_2 = k \cdot \sqrt{t} \cdot c \cdot \text{CaO} \cdot r \cdot A \cdot M \quad (2)$$

Table 5 Estimates of service life

	k (mm/year ^{0.5})	v_c (μm/year)	Service life (year)
CEM Portland CEM II/B-S CEM II/A-V	4.718	2	100.42
CEM III/A CEM III/B CEM II/B-V	5.421	2	90.62

2.4 Demolition stage

There is a greater degree of carbonation at the end of concrete's structural life, when it is typically crushed for reuse as an aggregate. This results from the significant increase in surface area of the aggregate, which helps to speed up CO₂ absorption, even when used in ground works. Nowadays, crushed concrete is increasingly reused as an aggregate in the production of new concrete, although the mechanical and durability properties are worse in a concrete with recycled aggregates. To obtain the same compressive strength and the same workability as unrecycled concrete, it is possible to increase the amount of cement (about 5 %) (Marinkovic et al. 2010); however, this will increase CO₂ emissions once more. Nevertheless, limiting the additional amount of cement used for recycled concrete to about 10 % keeps the impact in a comparable range (Knoeri et al. 2013).

In this study, the crushed concrete was employed as gravel-filling material, which will expose new surfaces to air for a significant period of time with a fresh paste, and a new cycle of CO₂ uptake will start. Even though a filling material submerged in water or buried in soil carbonates more slowly, with time, all concrete structures will indeed carbonate (Lagerblad 2005). Recycling or recovering concrete materials conserves natural landfill materials and eliminates the associated environmental costs of exploitation and transportation. These additional savings in emissions were not taken into account in this study. Table 2 summarizes the CO₂ emissions arising from the fuel consumed during demolition and crushing. The data are based on a survey of national contractors and subcontractors, and energy emission data were published by the Institute for Diversification and Energy Saving (2010).

3 Results

As the objective of this study was to analyze carbonation as a function of concrete mix, results are presented here from the LCA of a RC building column made with FA and BFS blended cements. The column is 3 m high, and the cross-section is 30×30 cm². Steel reinforcement consisted of four 20-mm diameter steel bars. The concrete cover is 30 mm. The concrete mix, specified in Table 1, provides a compressive strength value of 25 MPa. In this study, the functional unit is the RC column during the lifetime of the structure.

To obtain the production emissions, the amount of concrete mix design and steel were multiplied by the emissions associated with their materials production and transport by lorry. The concrete manufacture and transport by mobile agitator were also considered. Construction and demolition emissions are the product of the emission factors, shown in Table 2, multiplied by the concrete volume.

Table 6 Concrete carbonation during use stage and after demolition

CO ₂ captures (kg/column)						
	CEM Portland	CEM II/B-S (35 % blast furnace slag)	CEM III/A (50 % blast furnace slag)	CEM III/B (80 % blast furnace slag)	CEM II/A-V (20 % fly ash)	CEM II/B-V (35 % fly ash)
Use stage	16.39	10.65	8.94	3.58	13.11	11.63
After demolition	18.28	11.89	8.39	3.36	14.63	10.91
Total	34.67	22.54	17.33	6.93	27.74	22.53

3.1 Emissions from blended cement production

Table 3 shows data for the CO₂ balances from cement production and transport to the concrete plant for Portland cement and three types of BFS blended cement (CEN 2011). Table 4 illustrates the results for Portland cement and two types of FA blended cement (CEN 2011).

The overall CO₂ balance is the sum of the emissions from production and transport of cement. Greater reductions were achieved using BFS, since the amount of Portland cement that can be replaced by FA is less than BFS. The greatest effect was observed in CEM III/B, about a 70 % reduction compared to CEM Portland. Concerning the FA blended cement, CEM II/B-V achieved a 36 % reduction compared to Portland. If we examine two blended cements with the same replacement quantities, like CEM II/B-S and CEM II/B-V, the results reveal that the FA replacement is more environmentally friendly, since this material has fewer product emissions and shorter transport distances.

3.2 Service life

Durability, according to the EHE code (M. Fomento 2008), depends on the cement used. The column was considered to be protected against rain, and the percentage of occluded air was less than 4.5 %. Table 5 presents the results for the durability of blended cements. Results for CEM Portland, CEM II/B-S, and CEM II/A-V were the same. The quantity

of cement replacement is so low that the code uses the same carbonation rate coefficient as for Portland. Similar results were obtained for CEM III/A, CEM III/B, and CEM II/B-V, which all had a higher carbonation rate coefficient and therefore a 10 % shorter service life.

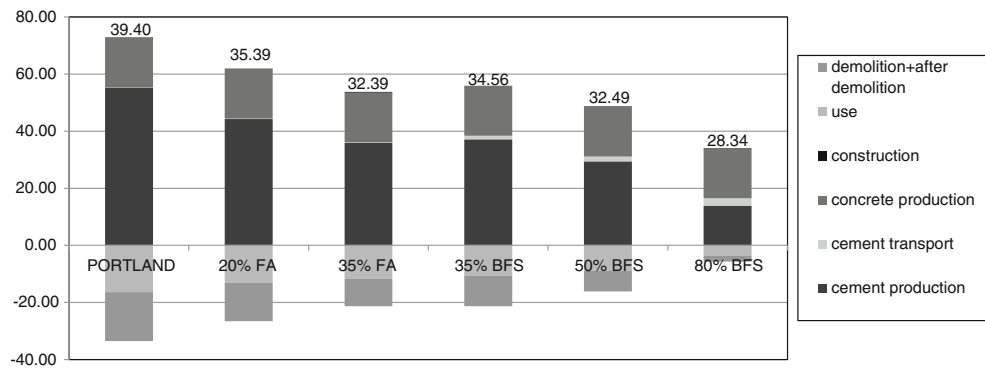
3.3 Carbonation during use stage and after demolition

During the use stage, CO₂ capture depends on the type and quantity of cement and the service life; hence, there is less carbonation in blended cement than in Portland cement. Carbonation of CEM III/B during the use stage was 22 % than that of Portland cement, reflecting a 10 % reduction in service life with an 80 % BFS replacement for Portland cement. CEM II/B-V with 35 % FA and 65 % Portland cement showed the same reduction in service life along with a CO₂ capture equal to 71 % of Portland cement capture. The calcium oxide that did not carbonate during the use stage can be carbonated after demolition (Table 6). Unsurprisingly, blended cements with higher carbonation rate coefficients captured more CO₂ during the use stage than after demolition.

We assumed that during the post-use stage, all concrete will be carbonated. Lagerblad (2005) reported the carbonation rate coefficients according to the environmental factors, since concrete submerged in water or buried in soil carbonates but not as fast. Based on these carbonation rate relations, the crushed concrete aggregate (20-mm diameter) takes 44.44, 6.25, 177.78 or 100.00 years to carbonate, depending on whether it

Table 7 Life cycle CO₂ balances

CO ₂ emissions (kg/column)						
	CEM Portland	CEM II/B-S (35 % blast furnace slag)	CEM III/A (50 % blast furnace slag)	CEM III/B (80 % blast furnace slag)	CEM II/A-V (20 % fly ash)	CEM II/B-V (35 % fly ash)
Production	72.67	55.69	48.42	33.87	61.72	53.52
Construction	0.21	0.21	0.21	0.21	0.21	0.21
Use	-16.39	-10.65	-8.94	-3.58	-13.11	-11.63
Demolition	1.19	1.19	1.19	1.19	1.19	1.19
After demolition	-18.28	-11.89	-8.39	-3.36	-14.63	-10.91
Total (kg)	39.4	34.56	32.49	28.34	35.39	32.39

Fig. 2 CO₂ emissions through every stage of concrete life

is exposed to rain ($k=1.5 \text{ mm/year}^{0.5}$), protected ($k=4 \text{ mm/year}^{0.5}$), wet ($k=0.75 \text{ mm/year}^{0.5}$), or buried ($k=1 \text{ mm/year}^{0.5}$), respectively. The results show the importance of the exposure environment.

3.4 Emissions summary

Table 7 presents the results of life cycle emissions. These results are not surprising, if we remember that the cement production stage contributes most CO₂ emissions. Figure 2 shows CO₂ emissions rising through every stage of concrete life, using FA and BFS blended cements. There is a huge difference between Portland cement and blended cement, when CO₂ emissions are taken into account up to the construction stage. CO₂ emissions for Portland cement and blended cement after the use stage and primarily after demolition were not significant, since there was less carbonation in blended cement than in Portland cement.

Concerning the concrete mix design with Portland cement, CO₂ capture during the use stage represents 22 % of the total CO₂ emissions. If the demolished concrete is crushed and recycled as gravel-filling material, concrete made with Portland cement, FA (35 % FA), and BFS blended cements (80 % BFS) captures 47, 41, and 20 % of the CO₂ emissions, respectively. It is essential to guarantee that the gravel is exposed to atmospheric conditions after being recycled to assure complete carbonation. These results confirmed Collins' conclusions (2010). Besides, half of all the CO₂ emissions in the cement production stage come from the calcination of limestone (Dodoo et al. 2009). The results from our study also show that 66 % of the calcination emissions are

reabsorbed by Portland carbonation during the post-use stage. It is worth noting that if we assess the carbon implications of an entire building, the carbonation uptake will not be so significant (Dodoo et al. 2009).

As durability depends on the cement, it was necessary to assess the ratio of CO₂ emissions per year (see Table 8). The data obtained indicate that the reduction in CO₂ per year was not as remarkable as that of the total emissions. CEM III/B reduced CO₂ emissions by 70 % due to its production, and in terms of CO₂ emissions per year, the reduction dropped to 20 %. As for CEM II/B-V, emissions fell from 36 to 7 %. Besides, the loss of durability of the blended cements with high rates of replacement resulted in higher values for CO₂ emissions per year compared to the lower replacement rates.

4 Conclusions

This study aimed to evaluate the CO₂ emissions of a RC building column made with BFS and FA blended cements. The emissions are analyzed during the life cycle of the column, whose lifetime finishes when the service life is exhausted and, after that, the column is demolished and used as gravel-filling material. Concrete carbonation is assessed during the service life and after demolition. The total emission, after subtracting the CO₂ captured, is divided throughout the service life to obtain the emissions per year. Under the assumptions adopted in this specific case study, the following conclusions may be drawn:

- Replacing Portland cement with FA rather than BFS lowers the material emission factor, since FA needs less

Table 8 CO₂ emissions per year

	CEM Portland	CEM II/B-S (35 % blast furnace slag)	CEM III/A (50 % blast furnace slag)	CEM III/B (80 % blast furnace slag)	CEM II/A-V (20 % fly ash)	CEM II/B-V (35 % fly ash)
Life (year)	100.42	100.42	90.62	90.62	100.42	90.62
Total (kg CO ₂ /column/year)	0.392	0.344	0.359	0.313	0.352	0.365

processing after being collected and more coal-fired power stations mean shorter FA transport distances. However, greater reductions are achieved using BFS, since the amount of cement that can be replaced is higher.

- Blended cements with high rates of cement replacement, like CEM III/A (50 % BFS), CEM III/B (80 % BFS), and CEM II/B-V (35 % FA), decreases service life about 10 % due to the higher carbonation rate coefficients. The loss of durability of these blended cements leads to more CO₂ emissions per year compared to lower replacement rates.
- The reduction in CO₂ capture is proportional to the replacement of Portland cement in blended cements. For instance, during the use stage, CEM III/B (80 % BFS) captures only 22 % of the CO₂ captured by Portland cement, and considering demolition and reuse as gravel in land filling, it captures 20 % of the CO₂ captured by Portland cement. In this case, CEM III/B carbonation is higher during the use stage than after demolition.
- To obtain reliable results in a LCA, it is crucial to consider carbonation during the use stage and after demolition. Concerning the concrete mix design with Portland cement, the CO₂ capture during the use stage represents 22 % of the total CO₂ emissions. If the demolished concrete is crushed and recycled as gravel-filling material, the reduction in CO₂ emissions reaches 47 %. Concrete made with FA (35 % FA) and BFS blended cements (80 % BFS) capture 41 and 20 % of CO₂ emissions, respectively. Thus, it is essential to guarantee the gravel atmospheric exposure after recycling to assure complete carbonation. If the gravel is buried, the carbonation rate may drop, but over time, it too will carbonate.
- Blended cement production for CEM III/B (80 % BFS) emits 70 % less GHG than Portland cement, although considering concrete life cycle with CEM III/B, there are only 20 % fewer emissions per year than with Portland cement. Regarding CEM II/B-V, the emissions drop from 36 to 7 %. Therefore, the slight reduction in production emissions of blended cements compensates the reduced durability and CO₂ capture.

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