LIFE-CYCLE EMISSIONS OF REINFORCED CONCRETE MADE WITH BLENDED CEMENTS

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This communication analyzes the CO_2 emissions during the production, construction, use and demolition of a reinforced concrete (RC) column made with blended cement. Likewise, the influence of carbonation and durability is examined. Portland cement production was the responsible for about 76% of the production and construction emissions in the RC column. Thus, the use of fly ash and blast furnace slag as a clinker replacement was studied for the CO_2 reduction. However, these types of cement had two characteristics that penalized their sustainability. CO_2 capture by carbonation was reduced between 20% and 80% due to the blended cement use, and service life was about 10% shorter. Results proved the influence of carbonation during the use and reuse as gravel in land filling. Even so, this study confirms that the use of blended cements reduces the annual emissions.

Keywords: *Life-cycle; Fly ash; Blast furnace slag; Carbonation; Durability*

EMISIONES DE CO_2 DURANTE EL CICLO DE VIDA DE UN HORMIGÓN ARMADO FABRICADO CON CEMENTOS CON ADICIONES

Esta comunicación analiza las emisiones de CO_2 producidas durante la fabricación, construcción, uso y demolición de un pilar de hormigón armado fabricado con cemento con adiciones. Asimismo, se comprueba la influencia de la carbonatación y durabilidad en los resultados. La producción del cemento Portland supuso alrededor del 76% de las emisiones de producción y construcción de un pilar de hormigón armado Por este motivo se estudió el uso de las cenizas volantes y escorias de alto horno como sustitución del clinker para reducir las emisiones de CO_2. Sin embargo, estos cementos tuvieron dos características que penalizaron su sostenibilidad. La absorción de CO_2 por carbonatación se redujo entre un 20 y 80% con el uso de estas adiciones, y la vida útil de la estructura se vio mermada en un 10%. Los resultados demostraron la gran influencia de la carbonatación durante la etapa de uso y reutilización como material de relleno. Aun así, se comprueba que el uso de cementos con adiciones reduce las emisiones anuales.

Palabras clave: *Ciclo de vida; Cenizas volantes; Escorias de alto horno; Carbonatación; Durabilidad*

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1. Introduction

Clinker production is a carbon-intensive process due to the emissions released by the calcination chemical process and the burning of fossil fuels to heat the kiln. The emissions of both processes are expected to be fairly similar (Börjesson & Gustavsson, 2000). The RC-08 Spanish Cement Code (Fomento 2008a) considers blended cements with blast furnace slag (BFS) and fly ash (FA) as common cements. BFS is a by-product of the steel industry and FA comes from the coal burning. Clinker replacement by supplementary cementitious materials is an effective technique to reduce cement production emissions (Collins, 2010). FA and BFS are widely extended for economic and environmental reasons. However, their use increases carbonation rates as long as the alkaline reserve is reduced.

Carbonation dissolves the protected layer essential for avoiding the embedded steel corrosion. This process reduces the reinforced concrete service life, but simultaneously, decreases the embedded CO_2 emissions. Kjellsen, Guimaraes & Nilsson (2005) studied the CO_2 uptake in Nordic concrete constructions. Findings indicated that 0.34, 0.22, 0.24 and 0.021 million metric tons of CO_2 can be absorbed in Denmark, Norway, Sweden and Iceland, respectively, during one year. Gajda (2001) studied the concrete used in the United States and concluded that 69 million tons of CO_2 were absorbed for 50 years. Therefore, the emission rates may be overestimated by as much as 13–48% when carbon capture (or carbonation) is ignored (Collins, 2010). Even so, it is often forgotten in a life-cycle greenhouse gas emissions assessment.

Structural designers should pay attention to CO_2 minimization through every stage of life cycle. The accurate selection of materials and their proportion leads to the reduction in emission production. The origin of materials determines the transport conditions. During use stage, the carbon capture takes place through the concrete exposed surface. The carbonation level will depend on the type of cement and its reuse during the secondary life. Durability lengthens concrete service life and reduces the maintenance requirements. The longer service life is, the higher amount of CO_2 is captured. Besides, smaller annual emissions are achieved. The recycling practices after the demolition are commonly the reused as aggregate for the new concrete production or as filling material for construction sites. The recycled concrete uses more amount of cement (about 5%) for getting the same compressive strength (Marinkovic et al., 2010). Consequently, cement emissions are increased unnecessarily. If the crushed concrete is exposed as filling material, the carbonation captures CO_2 and compensates for the emissions from other stages. About two thirds of the calcination emissions can be reabsorbed, if it is exposed for 30 years (Dodoo, Gustavsson & Sathre, 2009).

This study proposes a RC column made with six types of cement for the life-cycle CO_2 emissions evaluation. Service life is assessed according to the cement used and the carbon capture is examined during this period. After that, the concrete is recycled and exposed to the atmosphere for completing the carbonation. The aim of this paper is to confirm the CO_2 reduction due to the fly ash or blast furnace slag use. Finally, the annual emissions are determined to compare solutions.

2. Life-cycle CO_2 emissions

Life cycle assessment (LCA) is a complete tool to measure the potential environmental impacts according to the input-output data from cradle to grave (ISO, 2010). Thus, this analysis can only be carried out with a complete environmental profile. For the present study, only CO_2 information is available for each material and process. Therefore, this paper evaluates the carbon footprint from obtaining the raw materials to the final recycling.

Table 1. CO_2 unit emissions and transport distances

	CO_2 emissions	Transport distances	Transport emissions
Portland cement production	819 kg CO_2/t	32 km	0.03 kg CO_2/km*t
BFS production	52 kg CO_2/t	1640 km	0.03 kg CO_2/km*t
FA production	4 kg CO_2/t	180 km	0.03 kg CO_2/km*t
Aggregate production	4 kg CO_2/t	12 km	0.03 kg CO_2/km*t
Plasticizer production	220 kg CO_2/t	724 km	0.03 kg CO_2/km*t
Concrete manufacture	0.18 kg CO_2/m^3	26 km	0.07 kg CO_2/km*t
Steel bars production	920 kg CO_2/t	680 km	0.03 kg CO_2/km*t
Pump	0.74 kg CO_2/m^3		
Vibrator	0.04 kg CO_2/m^3		
Demolition	3.81 kg CO_2/m^3		
Crushing	0.59 kg CO_2/m^3		

Four main stages are taken into account. Production stage covers every material production, their transport to the concrete plant, the concrete manufacture and its transport by mixer to the building site. Table 1 summarizes the unit emissions. It is considered that FA and BFS only emit CO_2 during the post-process and transport, as they are waste products from other materials production. Reinforcing steel bars were taken from Yiwei, Qun & Jian (2011), since this study considers the recycling of steel. The plasticizer emission was obtained from the European Federation of Concrete Admixtures Associations (2006) and other material emissions come from the Concrete Center (2009). Regarding transport, distances are assessed from the closest manufacturing site to a standard building in central Valencia and the return trip. Vehicles and machines specifications were given by national contractors and subcontractors. The energy emissions were selected for Spanish industrial energy (Institute for Diversification and Energy Saving, 2010).

Construction stage takes into account the pumping and vibration activities. Use stage takes place during the years of service life according to durability conditions. This study considers that there is no need for maintenance during this stage. Afterwards, the column is demolished and the concrete is crushed to be reused as gravel filling material. During the use stage and the reused stage, concrete carbonation captures CO_2 from the atmosphere. This is assessed as a negative emission. The following section describes the consequences of this phenomenon in detail.

3. The influence of concrete carbonation on durability and CO_2 capture

Carbonation is the main process to reinforced concrete depletion in a normal environment. This phenomenon reduces concrete alkalinity and therefore, it leads to steel corrosion. The Spanish Code EHE-08 (Fomento, 2008b) proposes the equation (1) to assess service life, based on Tuutti (1982) model .The time from which the consequences of corrosion can no longer be tolerated is evaluated as the sum of two phases. During the first one, namely the initiation of corrosion, the carbonation penetrates the concrete cover losing the passivity. The second phase is the propagation of corrosion.

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

Note that *t* are the years of service life, *d* is the concrete cover (mm), *k* is the carbonation rate coefficient (mm/year$^{0.5}$), Ø is the bar diameter (mm), and v_c is the corrosion speed (µm/year).

The carbonation rate coefficient depends on the porosity and permeability of concrete cover, as well as the microclimatic conditions at the concrete surface (Bertolin et al., 2004). The ingress of CO_2 is hindered by reducing the water/binder relation. Humidity is one of the most influential factors in concrete carbonation (Galan at al., 2010) because of the blockage of pores by the water. Consequently, the carbonation rate is higher in concrete protected against the rain. The amount of CO_2 required to reach a pH near neutral, at which steel is not protected, varies according to the alkaline reserve. This is determined by the amount and type of concrete used (Ho & Lewis, 1987; Kobayashi & Uno, 1989). The code EHE-08 proposes the carbonation rate coefficient based on the protection against the rain, the percentage of occluded air, the concrete strength and the cement type.

Carbonation is a chemical reaction that consumes CO_2. Equation (2) evaluates the kg of CO_2 captured (CO_2) according to the carbonation rate coefficient (*k*), the service life (*t*), the quantity of Portland cement per cubic meter of concrete (*c*), the amount of CaO content in Portland cement (*CaO* is assumed to be 0.65), the proportion of calcium oxide that can be carbonated (*r* is assumed to be 0.75), the exposed surface area of concrete (*A*), and the chemical molar fraction CO_2/CaO (*M* is 0.79) (García-Segura, Yepes & Alcalá, 2014). This equation is based on Fick's first law of diffusion.

$$CO_2 = k * \sqrt{t} * c * CaO * r * A * M \quad (2)$$

The CO_2 capture during the use stage depends on the service life, which, in turn, is directly correlated to the cement used. Afterwards, the concrete is reused as gravel filling material with a greater exposed surface area. After use stage, a new cycle of CO_2 uptake will start at higher speed. Engelsen et al. (2005) crushed concrete mixtures with water/cement relation of 0.6 or higher for the grain size of 1-8 mm, and 60-80 % of the CO_2 released during calcination was reabsorbed within 20-35 days of exposure. In this study, the time needed to complete carbonation is evaluated according to the post-use conditions.

4. Case study

This study analyzes the life-cycle emissions of a reinforced concrete column made with six types of cement. Portland cement, three types of BFS blended cement (CEM II/B-S, CEM III/A and CEM III/B) and two types of FA blended cement (CEM II/A-V and CEM II/B-V) are examined. The column is 3 m high with a 30×30 cm^2 cross-section and four 20-mm diameter steel bars. The concrete cover is 30 mm and concrete strength is 25 MPa. Table 2 summarizes the concrete mix.

Table 2. Concrete mix

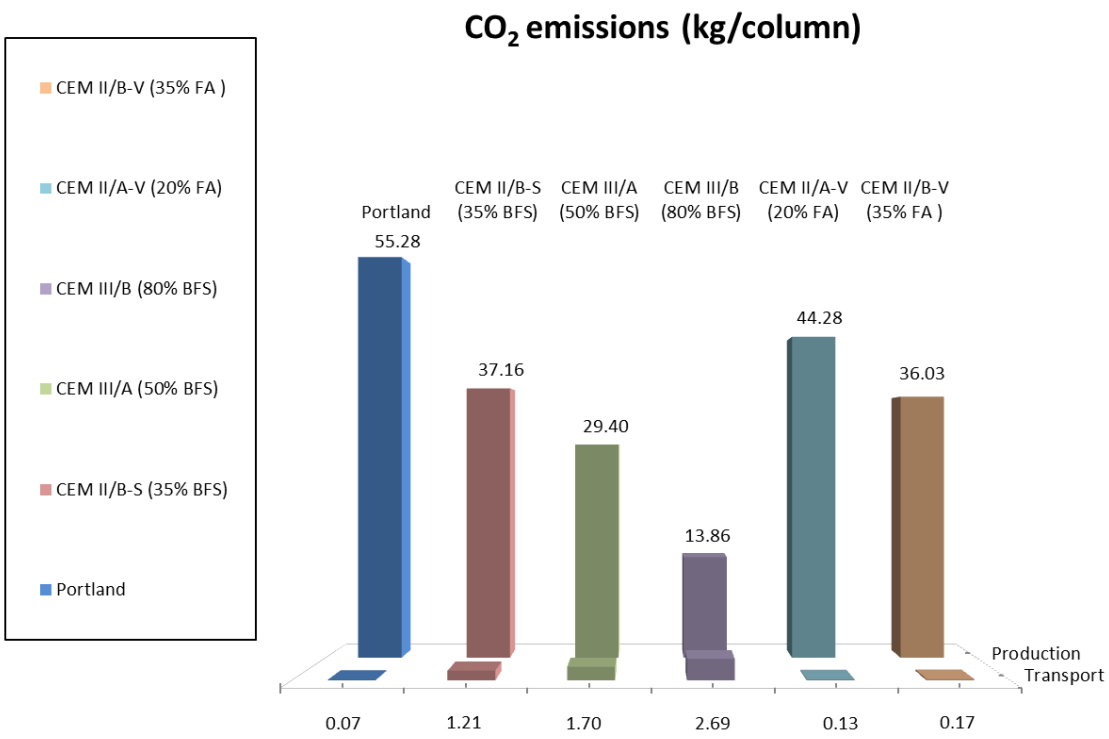
	Cement	Water	Plasticizer	Coarse aggregate	Fine aggregate
kg/m^3	250	165	2.5	940	1050

4.1. Emissions from cement production and transport

This section analyzes the cement production and transport to concrete plant (see figure 1). Clinker replacement by FA and BFS reduces from 20% to 70% the cement production emissions. Transport emissions were far smaller than production emissions. Therefore, even transport distances are greater for BFS, the total emissions are smaller. The greatest effect

was observed in CEM III/B with 80% BFS. Comparing two blended cements with the same replacement quantities, like CEM II/B-S and CEM II/B-V, it is worth noting that FA replacement presented less carbon footprint, since this material has fewer unit emissions and shorter transport distances.

Figure 1. CO_2 balances of cement production and transport



4.2. CO_2 capture during use and reuse stage

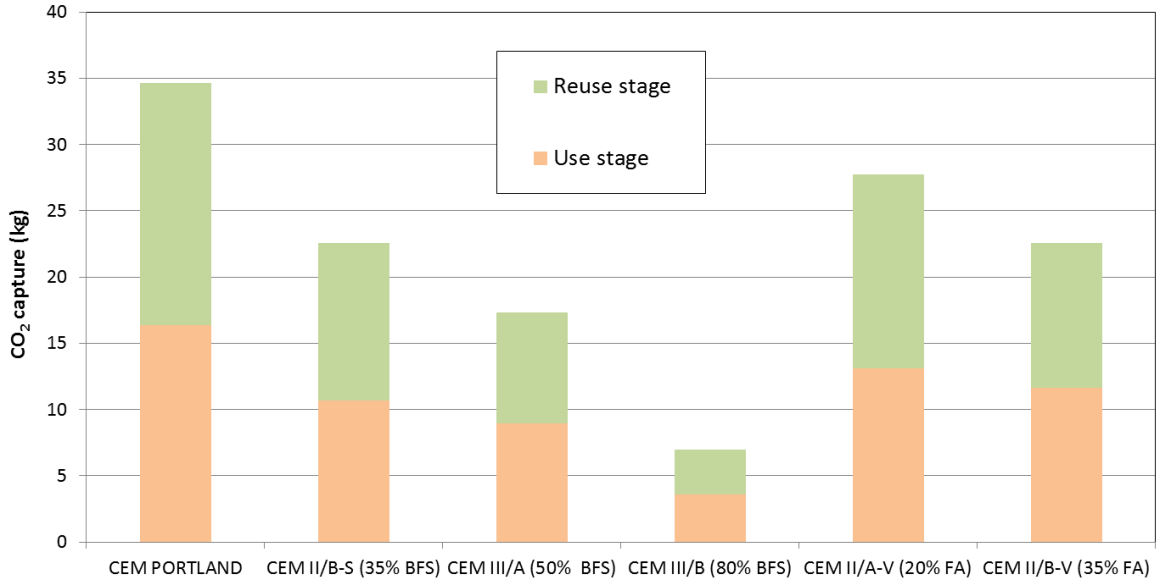
Use stage is constrained by the structure service life. We assumed that the column was protected against the rain and the percentage of occluded air was less than 4.5 %. The corrosion speed for the IIb ambient was 2 μm/year (Fomento, 2008b). The carbonation rate coefficient depends on the percentage of additions. The EHE-08 code (Fomento, 2008b) proposes for the CEM Portland, CEM II/B-S and CEM II/A-V a carbonation rate of 4.718 mm /year$^{0.5}$, and therefore, the service life is 100.42 years. With respect to CEM III/A, CEM III/B and CEM II/B-V, the carbonation rate is 5.421 mm /year$^{0.5}$ and the service life is 90.62 years. As a result, the last ones took a 10 % reduction in service life.

Carbon capture during use stage is determined by the duration of service life and the amount and type of cement. Figure 2 illustrates the reduction in carbon capture obtained by blended cements. CEM III/B captured 78% less CO_2 than Portland cement during the use stage, due to the 10 % reduction in service life and the 80 % BFS replacement. CEM II/B-V with 35% FA and the same service life presented a 29% reduction in carbon capture.

The carbonation deepens progressively up to the demolition. Then, the reuse as gravel filling material results in a carbonation progress. The time required to reach the complete carbonation was assessed according to the carbonation rates proposed by Lagerblad (2005). The concrete was crushed into 20 mm diameter gravel. Depending whether it was protected to rain (k=4mm/year0.5), exposed (k=1.5 mm/year0.5), wet (k=0.75 mm/year0.5), or buried (k=1 mm/year0.5), the gravel took 6.25, 44.44, 177.78 or 100.00 years to carbonate. Results

indicated that the CO_2 uptake can be reduced from 20% to 80% using additions. The differences between both stages are smaller than 12% (see figure 2).

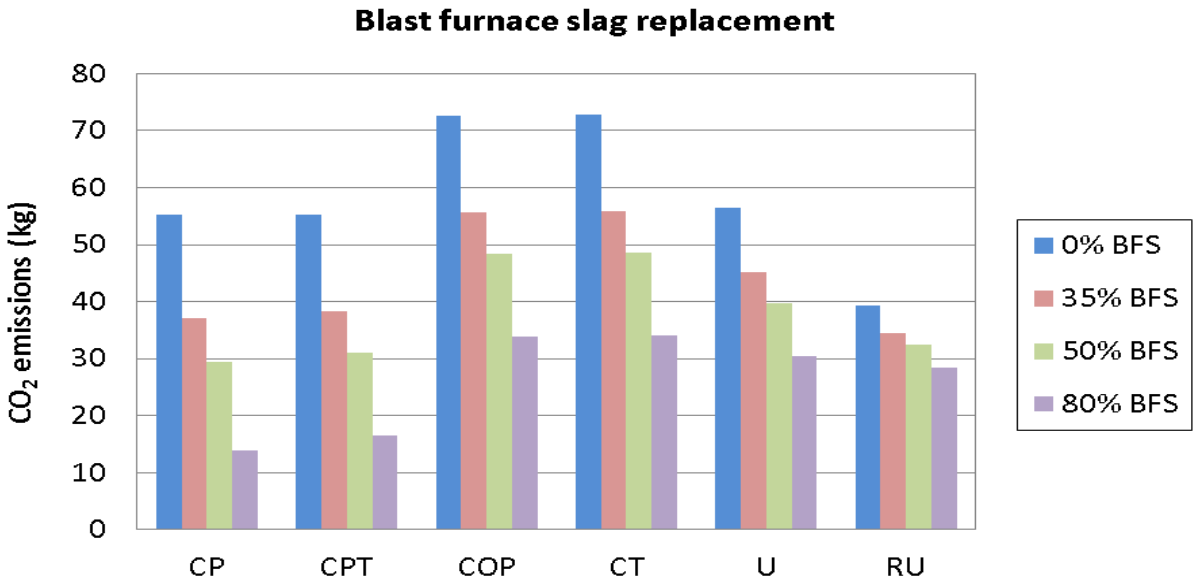
Figure 2. Carbon capture during use and reuse stages



4.3. Carbon dioxide balance and annual emissions

Figures 3 and 4 show the evolution of GHG emissions of a column made with BFS and FA blended cement.

Figure 3. Life-cycle emissions of the column made with BFS blended cement

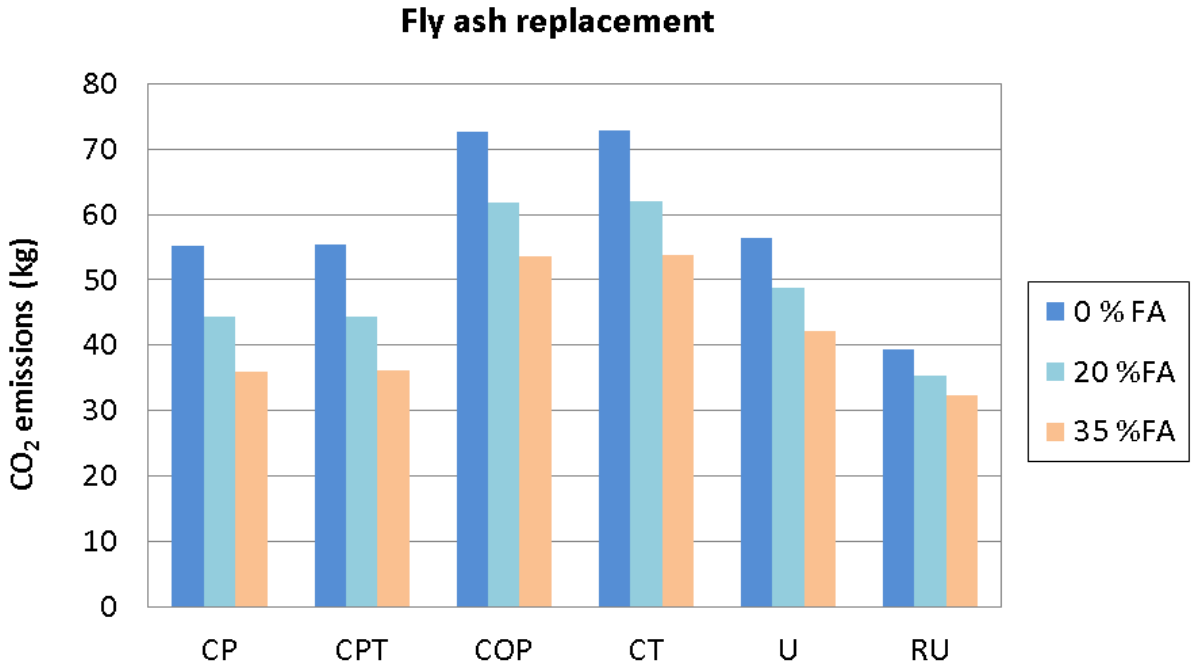


CP-cement production, CPT-cement production and transport, COP- concrete production, CT- construction, U-use, RU- reuse

Note the positive rate until the construction stage and the drop due to carbonation during use and reuse stage. Construction and demolition produced 0.21 and 1.19 kg CO_2 emissions, respectively. Portland production emissions represented 76% of the production and construction emissions.

Comparing the results according to the cement used, it is worth noting the differences from production to construction stage. However, this variation was attenuated during use and reuse stage. Regarding Portland cement, carbon capture during use stage represented 22% of the total emissions. And, furthermore, the capture reached 47% when the reuse stage is taken into account. Unsurprisingly, blended cement achieved less negative emissions through carbonation. The reduction in CO_2 emissions was about 41% and 20% in concrete made with CEM II/B-V (35% FA) and CEM III/B (80% BFS). Findings proved Collins (2010) conclusions; since this author stated that ignoring carbonation the emissions are overestimated. Besides, considering that half of cement production emissions are related to the limestone calcination (Dodoo, Gustavsson & Sathre, 2009), this study also obtained that 66% of the calcination emissions were captured during the reuse stage.

Figure 4. Life-cycle emissions of the column made with FA blended cement



CP-cement production, CPT-cement production and transport, COP- concrete production, CT- construction, U-use, RU- reuse

Annual emission is a realistic benchmark to evaluate the benefits of blended cement, since this metric considers durability. Table 3 specifies the service life and the annual emissions. Results show that durability penalizes the use of additions. The use of BFS in CEM III/B production reduced the production emissions by 70%. However, considering the life cycle emissions and durability, CEM III/B only reduced the annual emissions by 20%. Even so, findings indicate that the use of BFS and FA blended cements results in annual emission savings.

Table 3. Annual emissions

	CEM PORTLAND	CEM II/B-S (35% BFS)	CEM III/A (50% BFS)	CEM III/B (80% BFS)	CEM II/A-V (20% FA)	CEM II/B-V (35% FA)
Service life (year)	100.42	100.42	90.62	90.62	100.42	90.62
Annual emissions (kg CO_2/column/year)	0.392	0.344	0.359	0.313	0.352	0.365

5. Conclusions

This study examines the life-cycle emissions of a reinforced concrete column made with blended cement. Clinker production is the main contributor to GHG emissions. Portland production represents 76% of the reinforced concrete production and construction. Thus, clinker replacement is decisive for reducing the carbon footprint. CEMIII/B (80%BFS) decreases cement emissions by 70%.

Carbonation is evaluated during use stage and reuse as gravel filling material. This process involves negative emissions. Under the assumptions adopted in this specific case study, Portland cement captures 22% of the CO_2 emissions during use stage. If we add further the capture during the reuse, the emissions are shortened by 47%. Therefore, it is necessary to point out the environmental gain of carbon capture. The concrete recycling and its atmospheric exposure are essential for reducing the cement footprint. Wet and buried gravel carbonates at a lower rate, so it takes longer to complete the carbonation.

However, the use of additions influences on carbonation and durability. CO_2 uptake can be reduced from 20% to 80% using additions. Carbon capture for CEM III/B (80 % BFS) and CEM II/B-V (35% FA) is 20% and 41% of the Portland capture and their service life is about 10% shorter. Annual life-cycle emission is an appropriate benchmark to compare alternatives. CEM III/B emits 20 % less annual emissions than Portland cement.

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