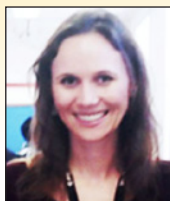
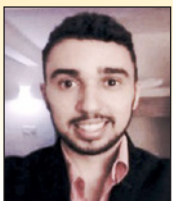


Balance emissions and CO₂ uptake in concrete structures: simulation based on the cement content and type

Balanço das emissões e da captura de CO₂ em estruturas de concreto: simulação em função do consumo e tipo de cimento



E. F. FELIX^a
emerson.felipe.felix@gmail.com

E. POSSAN^b
epossan@gmail.com

Abstract

While the cement plant is considered one of the most polluting industry, responsible for about 5% of global CO₂ emissions, the concrete has the potential to uptake this gas through the carbonation process, offset in part the emissions generated in its production. With the purpose to analyze this process, this study aims to evaluate emissions and CO₂ uptake with cement content 300-580 kg produced with different cement types (CP II F, CP II E, CP II Z, CP III, CP IV and CP V). Through mathematical modeling, the emissions balance was made, identifying the mix that shows good resistance to carbonation and greater absorption of CO₂ during the concrete life cycle. The results show that concrete with cement consumption between 380 and 420 kg/m³ showed better balance emissions.

Keywords: CO₂ sequestration, cement content, CO₂ emissions, compensatory measures, sustainability.

Resumo

Apesar da indústria cimenteira ser considerada uma das mais poluentes do setor, responsável por aproximadamente 5% das emissões mundiais de CO₂, o concreto tem a potencialidade de absorver esse gás, através do processo de carbonatação, compensando em partes as emissões geradas na sua produção. Com o objetivo de analisar este processo, o presente estudo avalia por meio de simulações as emissões e a captura de CO₂ de concretos com consumos de 300 a 580 kg de cimento por metro cúbico de concreto, produzidos com diferentes tipos de cimento Portland (CP II F, CP II E, CP II Z, CP III, CP IV e CP V). Por meio da modelagem matemática fez-se o balanço das emissões, identificando o traço que apresenta boa resistência à carbonatação e maior absorção de CO₂ durante o ciclo de vida do concreto. Os resultados apontam que concretos com consumo de cimento entre 380 e 420 kg/m³ e com maiores taxas de adições apresentam melhores balanços de emissões.

Palavras-chave: sequestro de CO₂, consumo de cimento, emissões de CO₂, medidas compensatórias, sustentabilidade.

^a Department of Structural Engineering, São Carlos School Engineering, University of São Paulo, São Carlos, SP, Brazil;
^b Postgraduate Program in Civil Engineering, Federal University of Latin American Integration, Foz do Iguaçu, PR, Brazil.

1. Introduction

The elevated gaseous emissions of the cement production have drawn the attention of the productive sector, since cementitious industry is, by itself, responsible for approximately 5 to 7% of CO₂ global emissions [1, 2, 3].

Due to rising consumption of concrete in the world and, consequently, of cement, there has been a lot of discussion regarding alternatives to reduce the emissions associated to concrete – the second most used material in the world [3]. According to Sindicato Nacional da Indústria do Cimento (Cement Industry National Union) [4], in Latin America, Brazil is among the countries with the highest rates of cement production and consumption, having produced 68 million of tons in 2012. In the same period, China showed a consumption that exceeded 2 billion of tons, being the largest producer and consumer of cement in the world, emitting almost the same quantity of CO₂, since according to sources [5], for the production of one ton of clinker, 700 to 1100 kg of CO₂ are generated globally.

In a domestic scenario, due to actions of the cementitious industry, the CO₂ emissions, caused by the cement production, represent a participation of 3%, according to data from the 2º Inventário Brasileiro de Emissões e Remoções Antrópicas de Gases de Efeito Estufa (Brazilian Inventory of Anthropogenic Emissions and Removal of Greenhouse Effect Gases), with data pertaining to the years from 1990 to 2005, with the country emitting around 536 kg of CO₂ per ton of cement produced [4].

However, an important feature of cement-based materials relates to their capacity of reabsorbing CO₂ from the atmosphere during the process of carbonation: reaction between CO₂, which enters through the concrete, and calcium hydroxide (Ca(OH)₂), present in the cementitious matrix, in the presence of water. According

to Pade and Guimarães [5], carbonation and its consequent CO₂ uptake occur throughout the entire service life of concrete structure and even after its demolition, when it is more intense.

In reinforced concrete structures, carbonation is considered a mechanism of deterioration, since it decreases of the concrete pH, leaving the steel reinforcement susceptible to corrosion. At environment temperature, concrete shows pH around 12.5 due to the presence of Ca(OH)₂. With the reduction of the calcium hydroxide levels in the interior of the pores of the hydrated cement paste and, afterwards, its transformation into calcium carbonate (CaCO₃), because of the carbonation reactions, the pH is reduced to values close to or lower than 9 [8, 9, 10, 11].

In non-reinforced concrete elements (i.e., dams, concrete walls, pavers, decorative elements, among others), though, carbonation can be beneficial, acting as a process of atmospheric CO₂ uptake, partially compensating the CO₂ generated in the cement production [7, 12, 13, 14], and thus can be considered in the balance of greenhouse effect gases emissions.

In light of this, this paper aims to achieve a balance between the emissions of CO₂ and the capture of this gas through carbonation for concretes with different types of binders and strength levels, expressed by the consumption of cement in the concrete mixture. In order to, using simulation and mathematical modelling, a period of 100 years will be analyzed, of which 70 years refers to the concrete service life and 30 years refer to the post demolition period.

2. Emissions associated to cement and CO₂ uptake due to concrete carbonation

The emissions of the cement production process are caused especially by the calcination of limestone rock, as demonstrated in

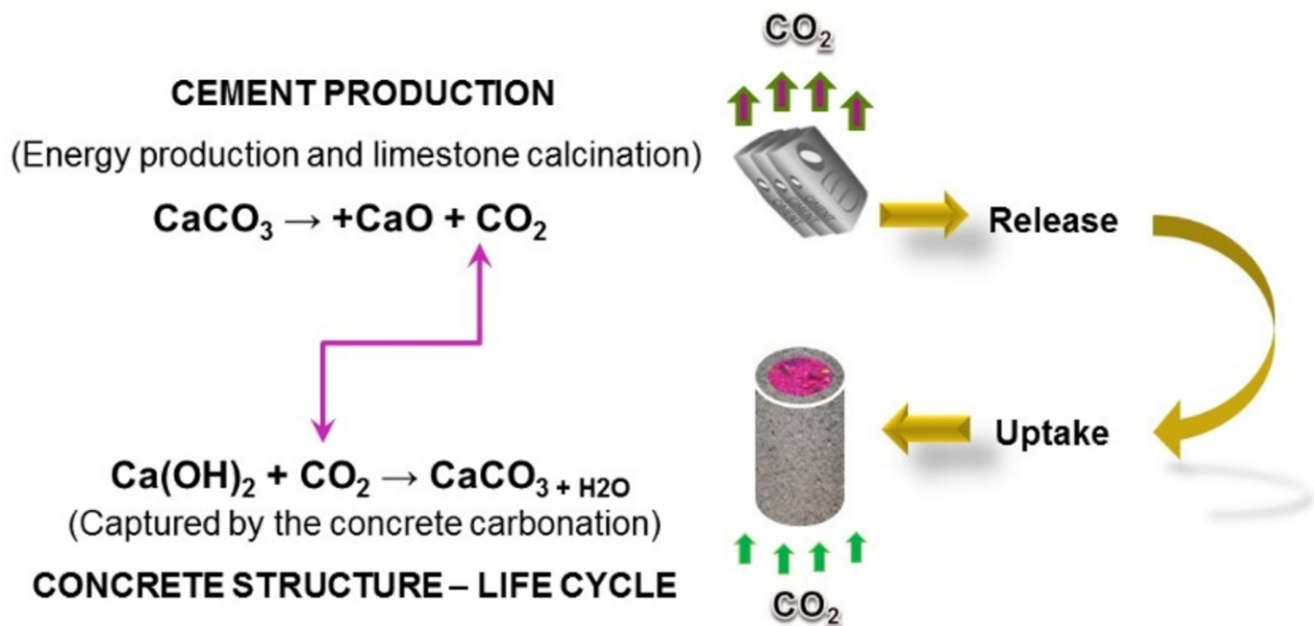


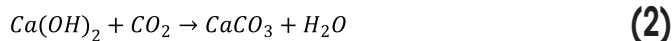
Figure 1
Concrete carbonation versus CO₂ uptake [23]

the simplified reaction showed in Equation 1, and by the fossil fuel burning for the production of clinker.



In cement life cycle, 95% of total CO₂ emitted comes from the production stage [15], with almost the entire emission in cement industry concentrating on the clinker production [5], since during the cement production process, half of the emitted CO₂ is caused by the calcination of limestone rock, and the other half derives from the burning of fuels for energy generation in the clinkering process [6]. However, it has been argued that concrete has the potential to capture CO₂ from the atmosphere through a process known as carbonation [16, 7, 13]. One of the results of this reaction (Equation 2) is the reduction of the concrete pH, which destroys the passivity

of the steel, leaving the reinforcement susceptible to corrosion, which is not desirable from a durability perspective. Another result is the CO₂ uptake from the atmosphere, generating calcium carbonate (CaCO₃), which apprehends the carbon dioxide inside the concrete structure, removing it from the atmosphere, in a process inverted to the cement production (Equation 1).



Generally, the process of CO₂ uptake due to the carbonation of the concrete can be outlined as in Figure 1.

The study verifies that the previous works shows discrepancies in relation to the potential of CO₂ uptake due to concrete carbonation. Pade [17] highlights a global potentiality of CO₂ uptake due to the carbonation of concrete structures of 33-57%, while Gajda [18]

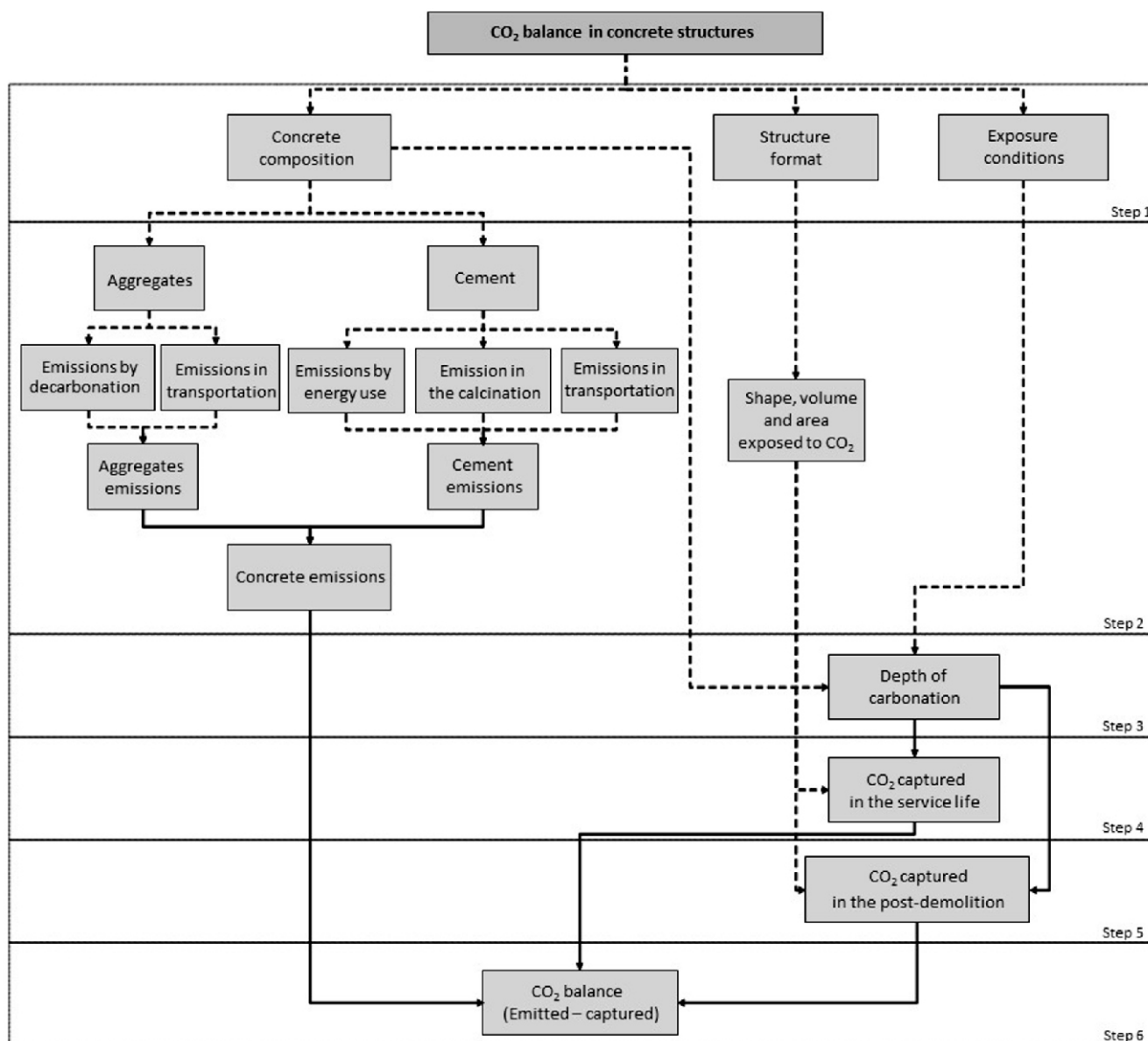


Figure 2
Methodology for calculating the balance of CO₂ emissions

reports that only 7.6% of the emitted CO₂ can be absorbed. In South Korea, Lee, Park and Lee [19] mention the uptake of only 2.9% of CO₂ in a structure during 20 years of its service life. In a study developed in Norway, Jacobsen e Jahren [20] estimated that 11% of the CO₂ emitted during cement production is reabsorbed by the concrete due to carbonation during its service life. In the USA, Haselbach and Thomas [21] mention 28.2% of CO₂ uptake during service life. Pade and Guimarães [7], in a study developed in Denmark, estimate, for a 100 years perspective, considering the demolition of the structure, which, due to carbonation, the concrete can absorb up to 57% of the CO₂ emitted during cement production. If the demolition of the structure is not considered, this value is reduced to 24%. The method adopted by Pade and Guimarães [7] assumes that the concrete has a

degree of hydration of 100%, while the diffusion and concentration of CO₂ were assumed constants over time. The authors also considered that the aggregates generated by the demolition of the structure will be 100% carbonated during a 30 years period, with the structure and its demolition waste under the same environmental conditions. Felix and Possan [22] highlight that the carbonation of post-demolition concrete is strongly dependent of the exposure conditions and of the dimensions of the demolished materials, therefore there are some practicality problems in the calculation methods adopted by some authors. One of the major problems discovered is finding a way to expose the demolition waste of a structure, in a way that it stays in contact with the CO₂ for the carbonation to occur. Hence, the CO₂ uptake due to concrete

Table 1
Concrete compositions used in the simulations (with blended cements: CP II Z, E and F)

Type of cement	Addition		F _{ci} (MPa)	Dosage (kg/m ³)			
	Type*	Content*		Cement	Stone	Sand	Water
CP II-E	Slag	6 - 34	20.92	300.00	864.17	1056.21	120.00
			25.55	340.00	860.41	1051.61	136.00
			29.78	380.00	849.14	1037.84	152.00
			31.75	400.00	845.39	1033.25	160.00
			33.63	420.00	841.63	1028.66	168.00
			37.13	460.00	834.12	1019.47	184.00
			40.30	500.00	826.60	1010.29	200.00
			43.20	540.00	819.09	1001.11	216.00
			45.84	580.00	811.57	991.92	232.00
CP II-F	Limestone filler	15 - 50	20.22	300.00	818.24	1000.07	120.00
			24.87	340.00	808.99	988.76	136.00
			29.90	380.00	799.74	977.46	152.00
			32.59	400.00	842.95	1090.77	160.00
			34.48	420.00	790.49	966.15	168.00
			38.66	460.00	781.24	954.85	184.00
			42.46	500.00	771.99	943.54	200.00
			45.93	540.00	762.74	932.24	216.00
			49.10	580.00	753.49	920.94	232.00
CP II-Z	Fly ash	15 - 50	21.98	300.00	926.26	1132.09	120.00
			26.56	340.00	912.73	1115.56	136.00
			30.69	380.00	899.21	1099.04	152.00
			32.24	400.00	795.11	971.81	160.00
			34.39	420.00	885.69	1082.51	168.00
			37.72	460.00	872.16	1065.98	184.00
			40.73	500.00	858.64	1049.45	200.00
			43.45	540.00	845.12	1032.92	216.00
			45.92	580.00	831.60	1016.39	232.00

* ABNT NBR 11578:1991 Revised Version: 1997

carbonation on the post-demolition period requires further studies in order to verify whether it can be conducted in a real scale.

These discrepancies found in previous works come of the many factors that influence the concrete carbonation phenomenon (strength, exposure environment, amount of cement used for concrete production, age of the structure, among others). They are, also, dependent of the adopted calculation methods and assumptions made by the researcher, what hinders the comparison of results generated by different researches [22].

3. Methodology for estimating the CO₂ balance

Since the study of CO₂ uptake associated with concrete structures is

recent, few published articles describe the methods adopted for these estimates in detail. In light of this, Felix, Possan and Thomaz [23] developed a methodology as described by the flow chart in Figure 2. Composed by six steps, the method begins with the description of the structure scenario (Step 1), then to estimating the emissions associated with cement and aggregates (Step 2) and the concrete carbonation depth over time (Step 3). In Steps 4 and 5, the potential of CO₂ uptake due to carbonation is estimated during the service life and post-demolition period of the structure, respectively, culminating in Step 6, the balance of emissions (difference between emitted and captured CO₂). In the sequence, the methods and materials adopted in this work are presented in detail, in accordance with the flow chart in Figure 2.

Table 2

Concrete compositions used in the simulations (with blended cements: CP III, II and V)

Type of cement	Addition		F _{ci} (MPa)	Dosage (kg/m ³)			
	Type*	Content*		Cement	Stone	Sand	Water
CP III*	Slag	6 - 34	19.64	300.00	875.35	1069.88	120.00
			22.53	340.00	860.82	1052.11	136.00
			28.19	380.00	846.28	1034.34	152.00
			30.92	400.00	839.01	1025.46	160.00
			33.56	420.00	831.74	1016.58	168.00
			38.61	460.00	817.21	998.81	184.00
			43.33	500.00	802.67	981.04	200.00
			47.73	540.00	788.13	963.28	216.00
			51.83	580.00	773.60	945.51	232.00
CP IV**	Fly ash	15 - 50	25.09	300.00	757.21	925.48	120.00
			30.62	340.00	746.04	911.82	136.00
			35.68	380.00	734.86	898.16	152.00
			38.03	400.00	729.27	891.33	160.00
			40.28	420.00	723.68	884.50	168.00
			44.46	460.00	712.50	870.84	184.00
			48.26	500.00	701.32	857.17	200.00
			51.73	540.00	690.15	843.51	216.00
			54.89	580.00	678.97	829.85	232.00
CP V ARI***	Limestone filler	0 - 5	24.01	300.00	785.03	959.48	120.00
			30.26	340.00	774.23	946.28	136.00
			36.32	380.00	763.44	933.09	152.00
			39.25	400.00	758.04	926.49	160.00
			42.10	420.00	752.64	919.89	168.00
			47.57	460.00	741.84	906.70	184.00
			52.70	500.00	731.05	893.50	200.00
			57.51	540.00	720.25	880.30	216.00
			62.02	580.00	709.45	867.11	232.00

* ABNT NBR 5735:1991; ** ABNT NBR 5736:1991; *** ABNT NBR 5733:1991.

3.1 Step 1 – Determination of concrete characteristics and exposure conditions of the structure

Considering that many factors influence the concrete carbonation, especially concrete proportioning (cement consumption, compressive strength, water/cement ration, type of the cement used, among others), geometrical characteristics of the structure or structural elements (shape, volume and superficial area in contact with the atmosphere) and characteristics of the exposure environment of the structure (CO₂ content in the environment, relative humidity of the air, rain exposure – internal or external area, sheltered or not sheltered from the rain) [23], in this step, it is important to describe clearly the variables employed in the simulation.

In relation to the concrete, in this study, various compositions were simulated through the ABCP/ACI method. The compositions were obtained by fixating the water/cement ratio as 0.4. For the constituent materials of the concrete, a large aggregate of basaltic origin with maximum diameter of 19 mm, specific weight of 2700 kg/m³ and unit mass of 1515 kg/m³. The small aggregate used was natural quartzitic sand with fineness modulus of 2.9, specific weight of 2660 kg/m³ and unit mass of 1490 kg/m³.

For the binder, six types of Portland cement were considered in the simulation: three blended cements (CP II E, with slag, CP II F, with filler, and CP II Z, with pozzolan) [25], one Portland-Slag Cement (CP III) [26], one Portland-Pozzolan Cement (CP IV) [27] and one High Early-Strength Cement (CP V ARI) [28].

The concrete composition obtained through the ABCP/ACI method

(Tables 1 and 2) have different cement consumptions, varying between 300 and 580 kg/m³.

It is assumed that the structure will be built in urban environment, not sheltered from rain, with average annual humidity of 70%¹ and a CO₂ local content of 0.04%². No rendering layer will be considered (apparent concrete, no painting). All the evaluated variables are presented in Table 3.

3.2 Step 2 – Estimating the CO₂ emissions

CO₂ emissions resulting from cement production were estimated considering emissions due to cement manufacturing, aggregates production and transportation until it is available on the construction site, be it from an industry or produced in the site.

Therefore, based on methodologies by IPCC [29] and CSI [30] to estimate CO₂ emissions due to cement production (E_{cim}), Equation 3 was used, in which are considered emissions due to energy use (E_{ene}), to decomposition of the material (calcination) (E_{desc}) and to transportation during cement production (E_{trans}). All emissions are given in kgCO₂/t.

$$E_{cim} = E_{ene} + E_{desc} + E_{trans} \quad (\text{kgCO}_2/\text{t}) \quad (3)$$

To calculate E_{ene} , E_{desc} e E_{trans} , the methodology presented by Lima [5] was used with the energy data collected by the Balanço Energético Nacional (National Energetic Balance) [31] presented in Table 4.

It should also be considered that the different Portland cements traded in Brazil (CPI, CP II, CP III, CP IV e CP V) have different

Table 3
Input data to determine carbonation depth

Variáveis de análise	Concrete					
	CP II E ¹	CP II Z ¹	CP II F ¹	CP III ²	CP IV ³	CP V ARI ⁴
Compressive strength (MPa)	Variable	Variable	Variable	Variable	Variable	Variable
Addition content (%)	6 – 34	6 – 14	0 – 10	35 – 70	15 – 50	0 – 5
Addition type	Slag	Fly ash	Fly ash	Slag	Fly ash	Limestone filler
Exposure condition ⁵	EP	EP	EP	EP	EP	EP
Relative humidity (%)	70	70	70	70	70	70
CO ₂ concentration (%)	0.04	0.04	0.04	0.04	0.04	0.04
Time (years)	1 - 100	1 - 100	1 - 100	1 - 100	1 - 100	1 - 100

¹ ABNT NBR 11578:1991 Revised version: 1997; ² ABNT NBR 5735:1991; ³ ABNT NBR 5736:1991; ⁴ ABNT NBR 5733:1991; ⁵ EP = Outdoor, sheltered from rain.

Table 4
Average CO₂ emissions (in kg) for the production of one ton of cement [29]

Emissions/year	2008	2009	2010	2011	2012
Energy use	246.00	224.00	210.00	214.38	210.27
Calcination	368.00	363.00	358.00	364.78	361.10
Transportation	33.00	31.00	31.00	30.66	30.26

¹ Average humidity estimated for the city of Foz do Iguaçu (Brazil).

² Average value based on report from IPCC [27].

Table 5

Coefficients of the model according to: (a) concrete characteristics and environment conditions; (b) exposure conditions [33]

(a)					
Type of cement	Properties of concrete			Environmental conditions	
	Cement	f_c	Addition	CO_2	UR
	k_c	k_{fc}	k_{ad}	k_{co2}	K_{ur}
CP I	19.80	1.70	0.24	18.00	1300
CP II E	22.48	1.50	0.32	15.50	1300
CP II F	21.68	1.50	0.24	18.00	1100
CP II Z	23.66	1.50	0.32	15.50	1300
CP III	30.50	1.70	0.32	15.50	1300
CP IV	33.27	1.70	0.32	15.50	1000
CP V ARI	19.80	1.70	0.24	18.00	1300

(b)	
Exposure conditions of structures	
Sheltered from rain	kce
Indoor sheltered from rain	1.30
Outdoor, sheltered from rain	1.00
Outdoor, exposed to rain	0.65

contents of mineral admixtures, and it is necessary to subtract them from the emissions calculations, since they are inserted at the end of the cement production process, not being part of the complete production process [23]. This way, only the clinker contained in each type of cement is considered, according to the limits set by the corresponding technical standards [24-28].

In the estimation of emissions caused by the production of the aggregates, indicators found on the literature were used, such as 5.81 kgCO₂/t for natural sand and 15.46 kgCO₂/t for gravel [32]. For the estimation of emissions for concrete transportation, Lima [5] suggests using 8.4 kgCO₂/t.

Therefore, according to Equation 4, with the sum of all CO₂ emissions (in kgCO₂/g) regarding cement production (E_{cim}), aggregate production (E_{agr}) and concrete transportation ($E_{trans-con}$), it is possible to estimate the emissions of the concrete production, provided that the concrete proportioning is known.

$$E_{con} = E_{cim} + E_{agr} + E_{trans-con} \quad (kgCO_2/t) \quad (4)$$

3.3 Step 3 – Estimating carbonation depth

To estimate the carbonation depth it is necessary to consider the exposure conditions of the structure (defined in step 1), as well as employing a model of carbonation depth behavior over time, for which the mathematic model of Possan [33] was used, as shown in Equation 5.

$$y = k_c \cdot \left(\frac{20}{f_c}\right)^{k_{fc}} \cdot \left(\frac{t}{20}\right)^{\frac{1}{2}} \cdot \exp \left[\left(\frac{k_{ad} \cdot a_d^3}{40 + f_c} \right) + \left(\frac{k_{CO_2} \cdot CO_2^{\frac{1}{2}}}{60 + f_c} \right) - \left(\frac{k_{ur} \cdot (UR - 0,58)^2}{100 + f_c} \right) \right] \cdot k_{ce} \quad (5)$$

In which:

y = average carbonation depth of the concrete, in mm;

f_c = average characteristic compressive strength of concrete, in MPa;

k_c = variable factor relative to the type of cement used (Table 5.a);

k_{fc} = variable factor related to the compressive strength of the concrete, according to the type of cement used (Table 5.a);

t = concrete age, in years;

a_d = pozzolanic admixture content in the concrete, in % of concrete mass;

k_{ad} = variable factor relative to pozzolanic admixtures in the concrete – silica fume, metacaulin and rice husk ash, according to the type of cement used (Table 5.a);

UR = average relative humidity, in %/100;

k_{ur} = variable factor related to relative humidity, according to the type of cement used (Table 5.a);

CO_2 = atmospheric CO₂ content, in %;

k_{co2} = variable factor related to the CO₂ content in the environment, according to the type of cement used (Table 5.a);

k_{ce} = variable factor related to rain exposure, according to the exposure conditions of the structure (Table 5.b).

Possan model [33] is used because it shows good results when estimating the carbonated depth (it represents 85% of tested cases) and demands input data easily obtained (concrete compressive strength, type of cement, CO₂ content in the exposure environment) [34].

3.4 Step 4 – Estimating CO₂ uptake throughout the concrete structure service life

To estimate the CO₂ uptake during the service life (SL) of the structures (70-year period), carbonation calculations were conducted considering the concrete in the structural element presented in Figure 3.a in different configurations (corresponding to Tables 1 and 2). Through stoichiometric calculations, the CO₂ uptake due to carbonation was estimated by Equation 6.

$$CO_2 = y \cdot c \cdot CaO.r.A.M \quad (kgCO_2) \quad (6)$$

In which: “ y ” is the carbonation depth (in meters), “ c ” is the amount of cement used to produce one cubic meter of concrete (without

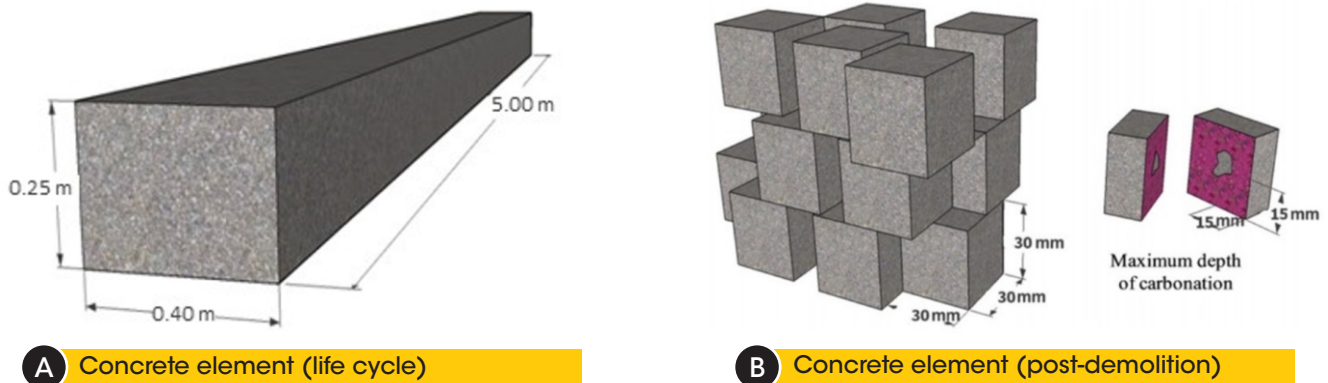


Figure 3
Concrete elements during: (a) service life; (b) post-demolition

considering the mineral admixtures) (in kg/m³), “CaO” is the amount of calcium oxide contained in the cement (in %), “r” is the CaO proportion completely carbonated (in %), “A” is the concrete superficial area exposed to CO₂ action (in m²) and “M” is the CO₂/CaO mole fraction.

3.5 Step 5 – Estimating CO₂ uptake in the post-demolition period

To estimate the CO₂ uptake after the demolition of the structure, concrete elements were assumed to be crushed and to have its dimensions reduced to the scale of aggregates in the simulation. To do

so, since carbonation occurs from the surface to the inner layers of the structure, the “cover” of the concrete carbonated during service life was removed, the “non-carbonated concrete” was transformed in cubes with small dimensions (i.e. 30x30x30 mm bricks), as represented in Figure 3.b. The exposure of these elements to CO₂ activity for a certain time period was considered (30 years or the time interval needed for full carbonation of the concrete elements to occur). The cubic shape was adopted to simulate the crushed elements since this geometry provides an easier way to describe carbonated and non-carbonated volumes in the post-demolition period. For the length adopted for the sides of the cubes, it is reported that analyzed samples of demolition waste have average characteristic dimension of 30 mm.

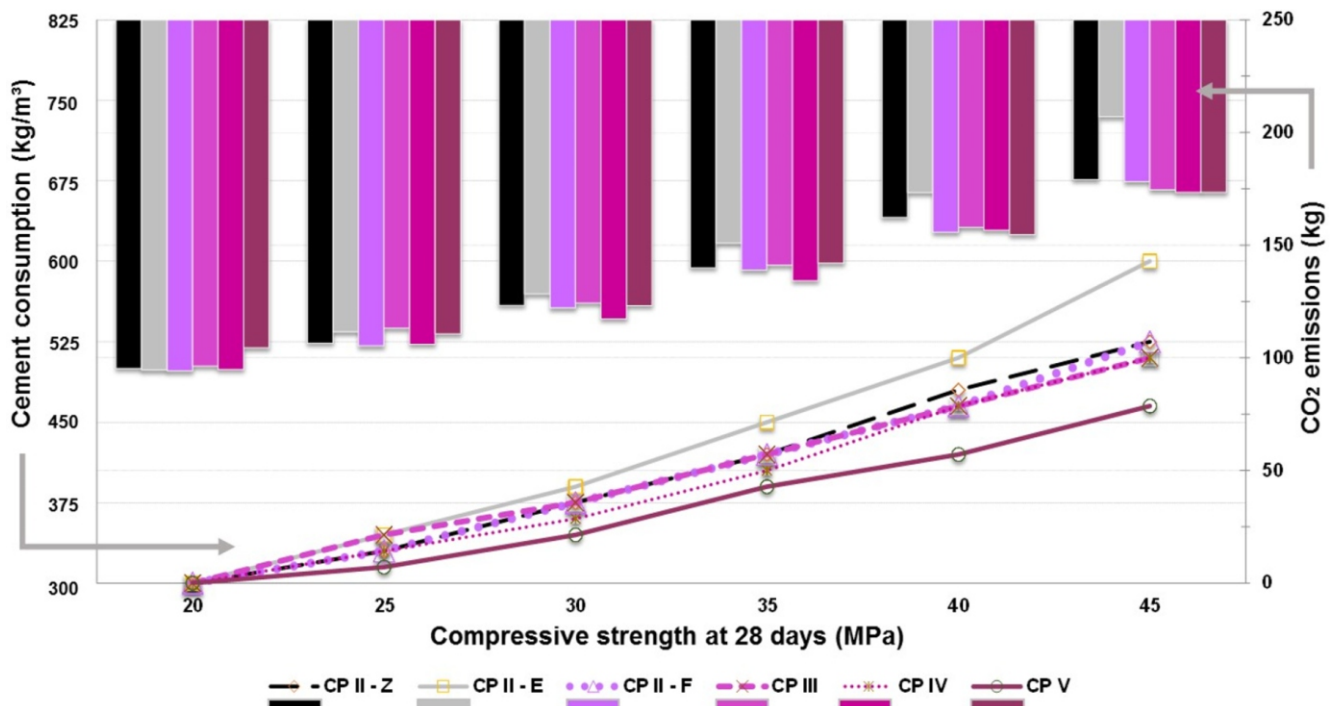


Figure 4
Cement consumption and CO₂ emissions as functions of compressive strength and type of binder

Therefore, to estimate CO₂ uptake by the concrete post-demolition, the following substeps:

- Estimative of carbonation depth at the end of the service life of the structure (70 years) according to Step 3;
- Estimative of the volume of carbonated concrete (Equation 7) and non-carbonated concrete (Equation 8) during service life;
- Definition of approximated dimensions of the concrete elements (cubes) after demolition;
- Computation of the new total superficial area of concrete elements after demolition;
- Determination of carbonation depth in the post-demolition period (applying Equation 5);
- Computation of the new carbonated superficial area (Equation 9) to determine the amount of CO₂ uptake (kg/m³) after demolition (Equation 6).

$$V_{carb} = y \cdot A_{st} \quad (m^3) \quad (7)$$

$$V_{nc} = V_{ee} - V_{carb} \quad (m^3) \quad (8)$$

$$A_{dem} = A_{par} \cdot \frac{V_{nc}}{V_{part}} \quad (m^2) \quad (9)$$

In which:

V_{carb} = Volume of carbonated concrete during service life (in m³);

y = Concrete carbonation depth over time (in m);

A_{st} = Total superficial area of the concrete element that is in contact with the atmosphere during SL (in m²);

V_{nc} = Volume of concrete that has not been carbonated (in m³);

V_{ee} = Total volume of concrete element in SL (in m³);

Table 6

Concrete carbonation depth over time, as a function of the type and consumption of cement

Type of cement	C ¹ (kg/m ³)	Depth carbonation (mm)													
		Structure (As ² = 6,5 m ²)								Waste particles (post-demolition) (As ² = 64±1 m ²)					
		5	10	20	30	40	50	60	70	75	80	85	90	95	100
CP II Z	300	10	14.3	20.1	24.6	28.4	31.8	34.9	37.5	10	14.5	*	*	*	*
	400	5.6	7.8	11.2	13.6	15.7	17.6	19.2	20.8	5.6	7.76	9.51	10.9	12.2	13.4
	500	3.9	5.6	7.9	9.7	11.2	12.6	13.7	14.9	3.9	5.42	6.64	7.67	8.57	9.39
	580	3.3	4.7	6.6	8.2	9.3	10.5	11.4	12.5	3.3	4.46	5.47	6.31	7.06	7.74
CP II E	300	10.3	14.6	20.6	25.2	29.1	32.6	35.7	38.6	10.3	14.5	*	*	*	*
	400	5.5	7.8	11.0	13.5	15.5	17.4	19.0	20.6	5.5	7.76	9.51	10.9	12.2	13.4
	500	3.8	5.4	7.7	9.4	10.8	12.1	13.3	14.4	3.8	5.42	6.64	7.67	8.57	9.39
	580	3.2	4.5	6.3	7.7	8.9	10.0	10.9	11.8	3.2	4.46	5.47	6.31	7.06	7.74
CP II F	300	11.0	15.5	21.9	26.8	31.0	34.6	37.9	41.0	11.0	*	*	*	*	*
	400	5.4	7.6	10.8	13.2	15.3	17.1	18.7	20.2	5.4	7.62	9.34	10.7	12.0	13.2
	500	3.6	5.0	7.1	8.7	10.0	11.2	12.3	13.3	3.6	5.02	6.14	7.10	7.93	8.69
	580	2.8	4.0	5.7	7.0	8.1	9.0	9.9	10.7	2.8	4.02	4.93	5.69	6.36	6.97
CP III	300	15.4	21.8	30.9	37.8	43.7	48.8	53.5	57.8	15.4	*	*	*	*	*
	400	7.1	10.1	14.2	17.4	20.1	22.5	24.6	26.6	7.1	10.0	12.3	14.2	*	*
	500	4.0	5.7	8.0	9.8	11.3	12.6	13.9	15.0	4.0	5.65	6.92	7.99	8.94	9.79
	580	2.9	4.2	5.9	7.2	8.3	9.3	10.2	11.0	2.9	4.16	5.10	5.89	6.58	7.21
CP IV	300	11.5	16.2	22.9	28.1	32.5	36.3	39.7	42.9	11.5	*	*	*	*	*
	400	5.6	7.9	11.2	13.8	15.9	17.8	19.5	21.0	5.6	7.94	9.73	11.2	12.5	13.7
	500	3.7	5.3	7.5	9.2	10.6	11.8	12.9	14.0	3.7	5.28	6.47	7.47	8.35	9.15
	580	3.0	4.2	6.0	7.3	8.5	9.5	10.4	11.2	3.0	4.23	5.19	5.99	6.70	7.34
CP V ARI	300	7.3	10.3	14.5	17.8	20.5	23.0	25.2	27.2	7.3	10.2	12.5	14.5	*	*
	400	3.1	4.4	6.3	7.7	8.8	9.9	10.8	11.7	3.1	4.42	5.41	6.25	6.99	7.66
	500	1.9	2.7	3.8	4.6	5.3	6.0	6.5	7.1	1.9	2.67	3.27	3.77	4.22	4.62
	580	1.4	2.0	2.9	3.5	4.0	4.5	5.0	5.4	1.4	2.02	2.47	2.85	3.19	3.50

¹Cement consumption; ²As = Superficial area (in m²); *Element 100% carbonated.

A_{dem} = Superficial area of concrete elements (cubes) that is in contact with the atmosphere in the post-demolition period (in m²);
 A_{par} = Superficial area of concrete elements (cubes) (in m²);
 V_{part} = Volume of crushed concrete elements (cubes) (in m³).

Equation 10 was used, in which B_{CO_2} is the CO₂ balance, E_{con} is the amount of CO₂ emitted in concrete production (determined in Step 2) and C_{cap} is the amount of CO₂ uptake by the concrete (determined in steps 4 and 5).

3.6 Step 6 – CO₂ balance

$$B_{CO_2} = E_{con} - C_{cap} \quad (kgCO_2) \tag{10}$$

To balance the CO₂ during the life cycle (LC) of concrete structures,

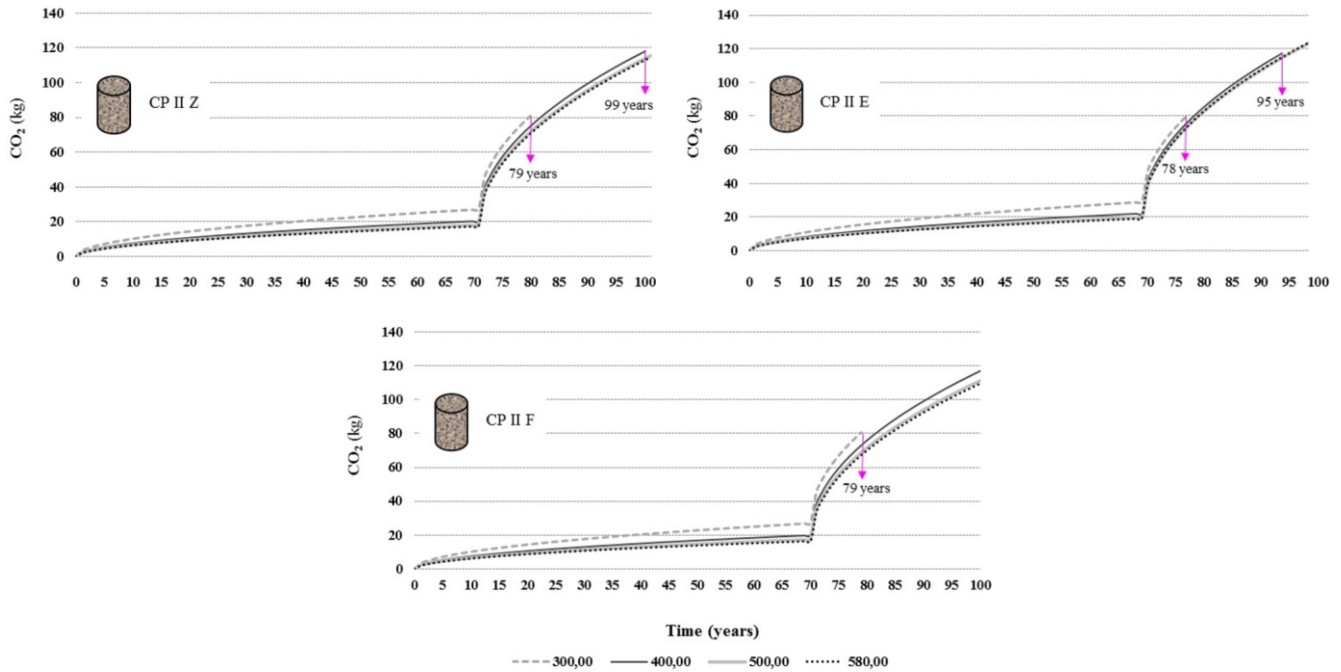


Figure 5
 Evolution of CO₂ uptake over time for concretes with blended cements (CP II Z, E and F) and with different consumptions

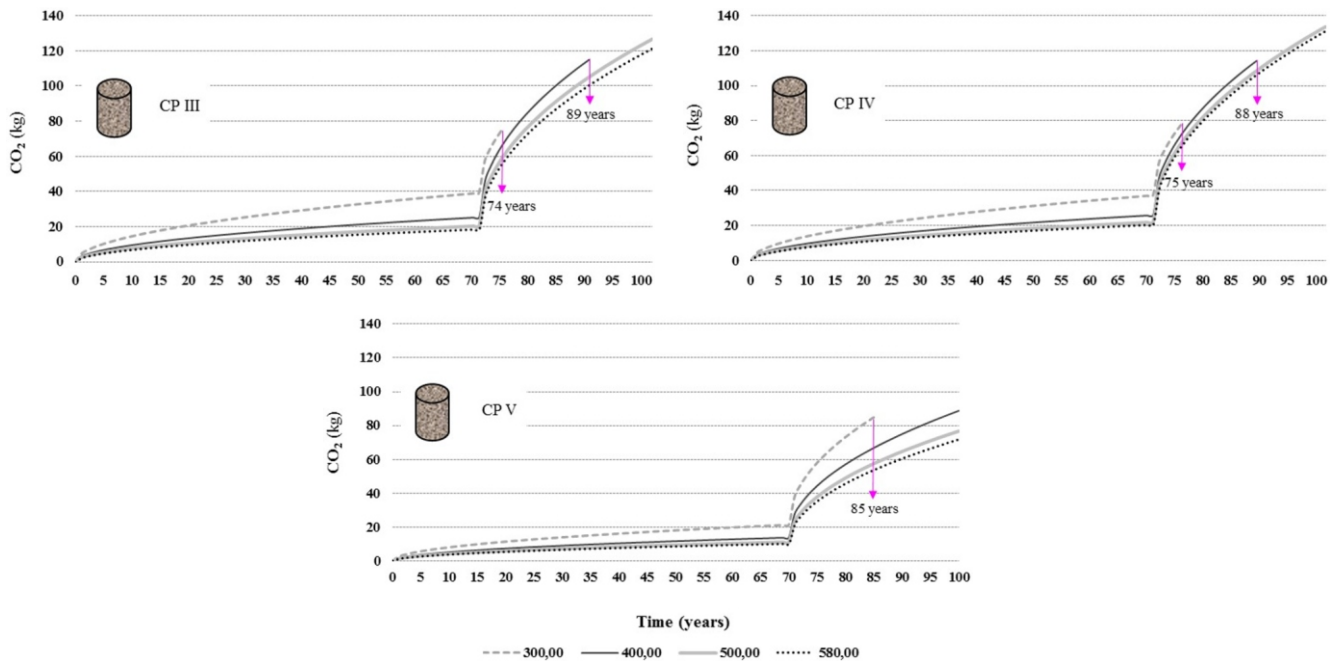


Figure 6
 Evolution of CO₂ uptake over time for concretes with blended cements (CP III, IV and V) and with different consumptions

4. Results and discussions

In Figure 4, two analysis performed with the various concretes listed in Tables 1 and 2 are presented. The first one (axis of ordinates on the left) refers to the cement consumption (kg/m^3) needed to produce concretes with characteristic compressive strength of 20, 25, 30, 35, 40 and 45 MPa. The second one reports the CO_2 emissions (in kg) associated with concrete production (axis of ordinates on the right) as a function of the compressive strength. It was observed that concrete elements with higher compressive strength demand more cement per volume in their production, as was reported by Mehta and Monteiro [3], also, they release a larger volume of CO_2 to the atmosphere, proving that emissions grow gradually with the increase in binder consumption by the concrete. Table 6 presents the carbonation depth of the structures over time for consumptions of 300, 400, 500 and $580 \text{ kg}/\text{m}^3$ (calculated by Equation 4). In some cases (all the concretes with $300 \text{ kg}/\text{m}^3$ consumption, regardless of the type of cement), it was observed that, in the post-demolition period, the concrete was completely carbonated before the end of the 30-year period. This fact is explained by the shape and dimensions of the demolition waste particles, which were assumed as cubes with 30 mm sides. Considering that the CO_2 can enter through all faces of cube, the maximum carbonation depth of each particle is 15 mm (see detail of Figure 3.b), what is easily obtained in concretes with low compressive strength or high water/cement ratio.

The increase in cement consumption has direct impact in compressive strength (see Tables 1 and 2) if the same water/cement ratio is adopted. The elevation in concrete compressive strength causes a decrease in the carbonation depth of the material [33, 35], reducing the amount of carbon absorbed by the atmosphere (see Figures 5 and 6). According to Kumar and

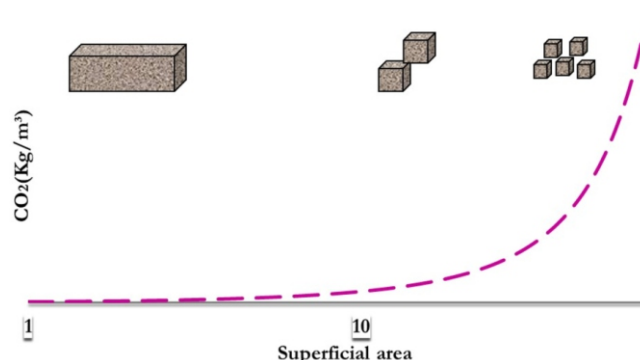


Figure 7
 CO_2 uptake as a function of the concrete element superficial area [22]

Bhattacharjee [36], due to the influence of the water/cement ratio, concretes with greater strengths show less porosity, hindering the CO_2 intake. Therefore, the potential of CO_2 uptake due to concrete carbonation is decreased, as observed in this research.

In Figures 5 and 6, the values of CO_2 (kg) taken from the atmosphere by the concrete structures over their service life (0 to 70 years) and in the post-demolition period (71 to 100 years) are presented as a function of the type and consumption of cement. A further analysis of these Figures, in parallel with Table 6, verifies that, for cement consumptions between 300 and $400 \text{ kg}/\text{m}^3$, the carbonation front is larger, resulting in a higher CO_2 uptake.

It is possible to verify that for concretes with consumptions higher than $300 \text{ kg}/\text{m}^3$ and compressive strength over 20 MPa, the CO_2 uptake potential due to concrete carbonation in the structure demolition (considering only the first five years of the post-demolition

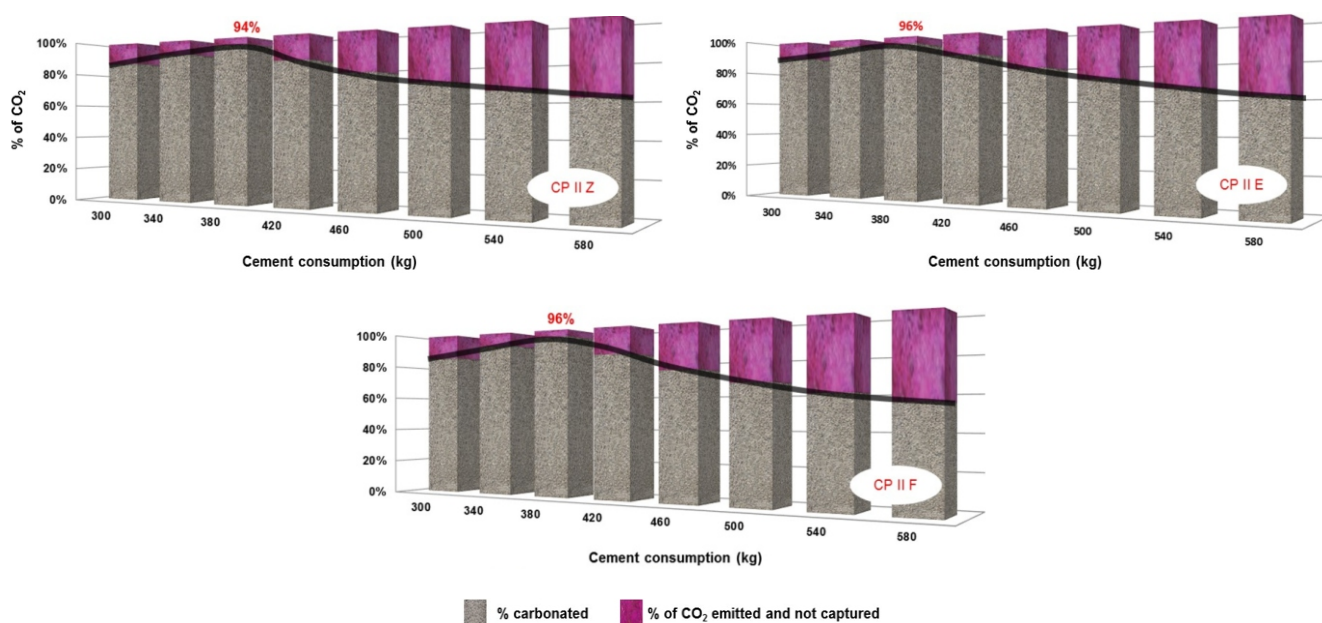


Figure 8
 CO_2 emissions balance in concretes with cements CP II Z, E and F

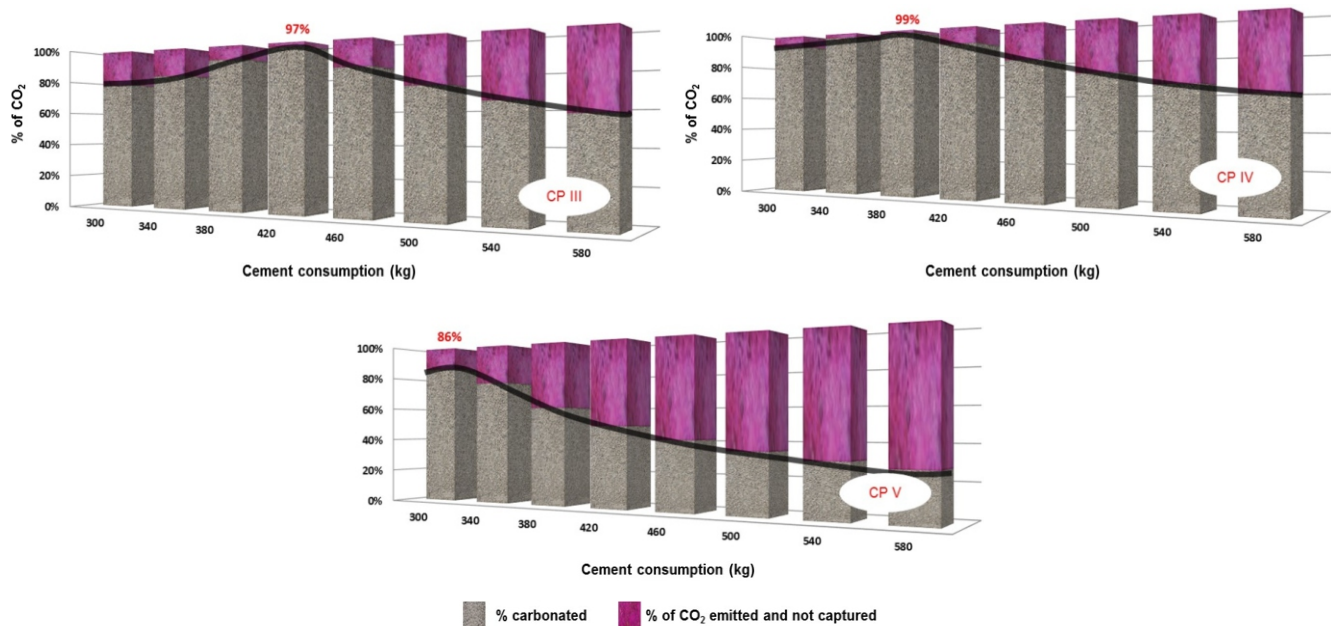


Figure 9
CO₂ emissions balance in concretes with cements CP III, IV and V

period) is on average 60% superior to the service life period. This indicates the importance of considering the structure demolition in the CO₂ emissions balance. This result is related to the larger superficial area of concrete exposed to carbon gas action (present in the atmosphere) in the structure post-demolition period (see Figure 7), generating, thus, a higher taking of CO₂ due to carbonation, as exposed in the literature [19, 22, 37].

Regarding the emissions balance (emitted CO₂ volume vs. captured CO₂ volume, according to Equation 9), it was possible to determine, for the different types of agglomerates, the consumption which result in the higher CO₂ balance (Figures 8 and 9).

For concretes with CP II Z (Figure 8), the 380 kg/m³ consumption was the one that generated the best emissions balance, reabsorbing around 94% if all the CO₂ emitted in its production. For concretes with CP II E, CP II F, CP III, CP IV and CP V, the consumptions that generated the best balances for each type of cement were, respectively, 380, 380, 420, 420 and 300 kg/m³. It can be seen that on average the concretes produced with type II, III and IV cements show ideal consumption (regarding CO₂ balance) between 380 and 420 kg/m³, suggesting that in this range there is an optimum point (optimization point) in the curve cement consumption versus CO₂ uptake.

Finally, for concretes with cement CP V (Figure 9), the 300 kg/m³ consumption was the one that presented the best results concerning the emissions balance, ensuring that 86% of the CO₂ released in its production was reabsorbed from the atmosphere in the 100 years of analysis. It can be noted that the maximum value of CO₂ capture by the concrete with CP V was considerably lower than the other four types of cement (between 94 and 99%), and that the consumption that achieves the best balance is 300 kg/m³, a lower value than the other types. These results were obtained due to different factors, such as: (i) smaller content of mineral admixtures in the cement (and, consequently, higher content of

clinker) (ii) higher mechanical strength and higher CO₂ penetration (due to the lower porosity of the concrete matrix and alkaline reserve availability); (iii) lower consumption of necessary cement for the production of concretes with greater strength.

5. Conclusions

The CO₂ uptake due to concrete carbonation can be relevant to the construction industry because, through knowledge of this process, it becomes possible to designate concretes by their performances in respect to durability, less cement consumption and CO₂ uptake potential. In the future, these parameters could be considered as compensatory measures in the design of concrete structures.

Regarding emissions balance, concretes with cement consumption between 380 and 420 kg/m³ presented the best performances, capturing more than 90% of the CO₂ emitted during their production. Concretes produced with CP II, CP III and CP IV cements show, in average, the same intervals for the optimum point between cement consumption, carbonation depth and CO₂ uptake. The emissions balance for the different cement consumptions is, in average, 74% (average amount of carbon dioxide that is taken from the atmosphere by the concrete, compensating the emissions in its production).

Concretes produced with CP IV cement present generally the best emissions balance. Regardless of the cement consumption analyzed, the average balance is of 81%. The concretes can be produced with larger cement consumptions and still have a good sustainability index (with respect to CO₂ emissions).

Concretes with CP V show the worst CO₂ balances, in comparison with the others, reabsorbing in average 50% of the emitted CO₂. This work also indicated an optimal point between cement consumption, carbonation depth and CO₂ uptake situated between

380 and 420 kg of cement per m³ of concrete. This point generates an average carbonation depth during service life compatible with the durability performance (carbonation depth smaller than the concrete cover on the reinforcements).

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