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The Environmental Impact of Carbon Emissions and Carbon Dioxide Capture by a Reinforced Concrete Road Structure during Its Life Cycle

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***Abstract*— *This is a case study assessing the environmental impact of GHG emissions from the construction of a reinforced concrete structure. Studies of concrete carbonation focus on concerns about the reduction in pH that causes corrosion of reinforcement. The study aims to show that the CO_2 capture by exposed concrete structures is very small during their service life, but quite significant at the end of their life if the concrete is crushed and recycled, showing the importance of this action within the context of the circular economy. We estimated the emissions from the production of the main materials used. We calculated the CO_2 capture during the service life and the subsequent recycling in aggregates associated with carbon credits from scrap steel. A device was used to measure carbon levels for three years and produced a 100-year estimate. The results showed a minimal CO_2 capture during the service life compared to the respective emissions. However, there is a significant CO_2 capture when considering the circular economy involved in the recycling process. CO_2 captured by concrete and steel recycling accounts for 40% of emissions, contributing to the achievement of United Nations Sustainable Development Goals No. 8, 12 and 13.*

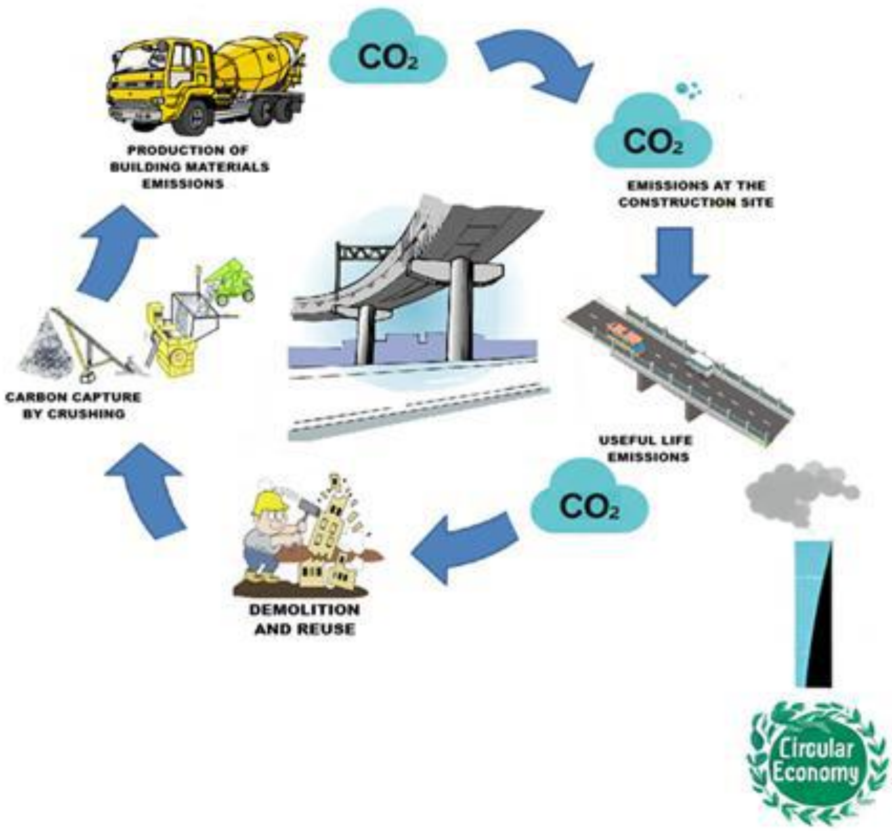

Fig.1. Work outline.

Source: the authors

I. INTRODUCTION

The Portland cement reinforced/prestressed concrete is the preferred technology for road structures such as bridges and underpasses. However, in the production of Portland cement, substantial amounts of greenhouse gases (GHG), especially CO_2 (carbon dioxide), are emitted; this poses a major challenge for contemporary society, civil engineering, and socio-environmental rights communities. To be precise, Portland cement accounts for 6% of the global GHG emissions, just behind fossil fuels (SAEED, 2016). Hence, the use of this cement is an important topic for contemporary society, civil engineers, and socio-environmental rights communities.

GHG emissions affect the global climate; therefore, agreements initiated by the United Nations Intergovernmental Panel on Climate Change (IPCC) control and restrict human-induced CO_2 emissions (IPCC, 2007). The United Nations Environment Program (UNEP, 2022) reported increasing GHG emissions due to construction of new buildings. Although building operations majorly account for the GHG emissions, the production process is a significant source as well.

The construction industry carries the enormous responsibility of regenerating and decarbonizing the future; therefore, Portland cement has become increasingly problematic for the civil engineering community, with society demanding more decarbonization from buildings, according to the UNEP (2022). It is critical to assess the precise GHG emissions impact caused by Portland cement, considering its cradle-to-tomb life cycle.

Two inherent factors make Portland cement a large CO_2 emitter: (i) the chemical decomposition of limestone decarbonation, its dominant raw material, and (ii) the use of fossil fuels to create high temperatures.

The binder has limestone as its dominant raw material, whose main component is calcium carbonate ($CaCO_3$). The $CaCO_3$ decarbonation reaction decomposes the molecule into carbon dioxide (CO_2) and calcium oxide (CaO). Small amounts of magnesium carbonate ($MgCO_3$) are frequently present, with similar reactions. Therefore, chemical limestone decomposition is a significant CO_2 emitter.

The CO_2 emissions from decarbonation in Portland cement production add to the emissions from fossil fuels used to reach elevated temperatures. The temperature needed in ovens to produce cement clinker (the principal component of Portland cement) is around 1,450ºC. Despite the availability of several heat sources, petroleum coke is mostly the fuel of choice.

To obtain a precise environmental assessment, we must consider that Portland cement captures CO_2 from the atmosphere during its life cycle through recarbonation. The decarbonation reaction accounts for approximately 50% of CO_2 emissions during production (WBCSD, 2013); therefore, recarbonation can potentially reabsorb the emitted CO_2. This process consists of a chemical reversion to limestone, with the material turning into $CaCO_3$ again.

It is worth noting that recarbonation reactions are slow due to the formation of calcite crystals within the pores, significantly slowing down the evolution of CO_2 diffusion (CIZER et al., 2008).

Concrete carbonation studies typically focus on concerns about the reduction in pH that causes corrosion of reinforcement. Measuring the mass of carbon captured by concrete is somewhat delicate. No studies were found for concrete, only for mortars, that contained results for these masses of captured CO_2.

This study aimed to clarify through a real case study how much $CO_2$is absorbed by Portland cement concrete during its life cycle and after, considering recycling the concrete as an aggregate in a circular economy concept. The study presents an assessment based on actual environmental impact data for GHG emissions and CO_2 capture.

The study aims to show that CO_2 capture by exposed concrete structures is very small during the useful life of the work, but quite significant with the act of crushing and recycling the concrete, showing the importance of this action within the context of the circular economy.

It is worth noting that the site where the work is being carried out has a not very aggressive urban atmosphere and the CO_2 concentration at the site varies between 500 and 600 ppm, due to the heavy vehicle traffic. These values were obtained from some measurements taken at the site by the authors. The rate and progress of carbonation vary with the porosity of the concrete. Environments with different aggressiveness alter the amounts of CO_2 captured, but the results obtained show that these are almost irrelevant.

We established a relationship between civil engineering and socio-environmental laws as the latter tackles a new development paradigm to promote environmental and social sustainability, contributing to reduce the poverty (SDG 1), and inequality (SDG 10)(UNITED NATIONS, 2015), by promoting values such as equity and social justice. The relationship with civil engineering emerges as we join efforts to rethink GHG emissions while tending to the concerns of maintaining all forms of life (biodiversity) and human culture (social diversity).

This study contributes to the United Nations Sustainable Development Goals (SDGs) 8, 12, and 13 (UNITED NATIONS, 2015), asit aims to provide insights to support the formation of a low-carbon economy and sustainable economic growth cited in SDG 8(UNITED NATIONS, 2015), agreed upon in the Climate Change Conference (COP26, 2022) and a circular economy that contributes to responsible consumption and production placed in SDG 12 (UNITED NATIONS, 2015). Furthermore, this study discusses climate actions that contribute to a sustainable, low-carbon future with a new vision on reinforced concrete GHG emissions, participating in reduction of climate changing based on SDG 13 (UNITED NATIONS, 2015).

The IPCC has a new vision for engineering works asit is the global authority that defines the environmental agenda, coherently promotes the implementation of the environmental dimension in the UN, and acts as an authorized global environment defender. Additionally, the Chemicals and Pollution Action section from the UNEP report (2022b, p. 15) points out that the report helped Latin America and the Caribbean to develop the Regional Action Plan on Air Quality 2022-2025, which involves rethinking CO_2 emissions among several elements. The Climate Action section comprises GHG emissions considering scientific goals to decarbonize bank portfolios, lower electrical energy consumption, and reduce vehicular emissions.

Within this context, resilient infrastructure resolutions and environmental aspects of material management reinforce the role of circular economies, mainly because of the need for recycling civil construction materials from a long-term standpoint, considering the essentially collective socio-environmental rights, sometimes not economically valuable and not subject to individual appropriation but crucial for preserving and maintaining life with a healthy environment in mind.

II. METHOD AND RESULTS

Focusing on the construction project of a road underpass in Curitiba, Brazil, this study estimated how much CO_2would be emitted in the production of materials and how much CO_2would be captured during the cement's life cycle and the recycling of concrete aggregate and steel afterward. Was considered the production emissions by the concrete, steel, and wooden forms (decomposition too).

The underpass construction ended in 2022, connecting the Fúlvio José Alice and Amazonas de Souza Azevedo streets. The structure is part of a set of urban improvement works in the Northern Green Line of Curitiba.

2.1 The case study object

The Fúlvio José Alice Street underpass is a buried road measuring approximately 212 meters under the Green Line in Bairro Alto district, Curitiba, Brazil. The reinforced concrete structure can withstand class 450 accidental loads (NBR 7188:2013) (ABNT, 2013). It has a pile foundation excavated with clamshells and stabilized with bentonite slurry. The pile wall simultaneously acts as the foundation and a retaining wall, creating a 5.50m tall and 11.00m wide gallery for a three-lane road. The walls support reinforced concrete headers and approach slabs. Precast prestressed longitudinal beams, cast-in-place reinforced concrete transverse beams, and precast and cast-in-place slabs cover the gallery span. The beam spacing isper pile spacing, creating a 2.50m slab span, close to the upper limit, ensuring that only one axle or one axle group could be at a given time on the structure.

Figures 2 - 7 show the underpass before and after the conclusion. These images illustrate how locally important this structure is, aiming to improve the traffic in the Paraná state capital.

Fig.2. Aerial view

Source: the authors

Fig.3. Overpass filling.

Source: the authors

Fig.4. Aerial view: construction at an advanced stage.

Source: the authors

Fig.5. A ramp at the stage of near-completion.

Source: the authors

Fig.6. Gallery interior.

Source: the authors

Fig.7. Finished gallery interior.

Source: the authors

2.2 Construction materials

The structure used 30MPa concrete obtained from a plant located 8km away from the site. The materials were cement CPII F 32 (Portland cement with limestone filler), gravel with a nominal maximum size of 12.5mm (B0) and 19mm (B1), crushed rock sand, natural sand, and plasticizer.

Were collected aggregate and binder samples directly from the plant and stored them in closed containers to avoid carbonation. Were also collected concrete specimens to assess CO_2 capture.

Table 1 shows the material consumption, and Figure 8 is an image of a concrete sample from the site.

Table 1 – Mass of material consumption for one cubic meter of concrete.

Material	Consumption (t/m^3)	% mass
Cement CP II F 32	0.318	13.6%
B0 (12.5 mm)	0.185	7.9%
B1 (19 mm)	0.740	31.7%
Crushed rock sand	0.409	17.5%
Medium natural sand	0.267	11.4%
Fine natural sand	0.221	9.5%
Water	0.196	8.4%
Plasticizer	0.00191	0.1%
TOTAL	2.33791	13,6%

Source: the authors

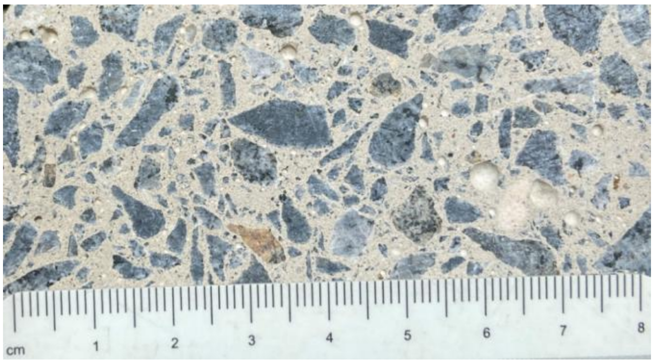

Fig.8. A concrete sample from the site.

Source: the authors

The work also considered GHG emissions by reinforced and prestressed concrete steel, sawed wood and plywood forms. The forms had their production and biogenic decomposition specifically assessed.

2.3 Structural parts

We surveyed the amounts of materials, that is, concrete, steel, forms, and the contact points between concrete and air. That allowed us to estimate the amount of CO_2 emitted into the atmosphere by the materials and the potential of capture through recarbonation along the lifespan and afterward.

The structural steel rebars for reinforced and prestressed concrete added up to 447.56 metric tons. Plywood forms accounted for 70.10m^3 and sawed wood for 31.49m^3. Table 2 shows the volumes and mass of the main materials used, in addition to structural concrete areas in contact with air.

Table 2 - Volumes of concrete, wood, and concrete areas in contact with air.

Structural parts	**Concrete(m^3)**	**Forms (m^2)**	**Forms (m^3)**	**Areas in contact with air(m^2)**
Transverse beams	184.62	171.13	5.13	1,540.14

Stringer beams	388.60	427.30	12.82	3,845.66
Pre-slabs	144.43	119.50	3.58	2,389.95
Headers	105.83	548.31	16.45	732.54
Slabs	310.85	1,255.74	37.67	627.87
Approach slabs	202.92	864.41	25.93	864.41
Barrette piles	3,770.22	-	-	2,936.00
Total	5,107.47	3,386.37	101.59	12,936.56

Source: the authors

2.4 Estimates of GHG emissions

This study limited itself to GHG emissions by materials, disregarding services (e.g., grading, paving, and painting).The emission factors (EF) selected for this study were selected because the authors believed that they best represent the emissions from the materials actually applied in the work, whether due to characteristics similar to local materials or taken from internationally representative studies.

This emissions estimate is not a life cycle analysis (LCA), it is limited to the numbers shown, and therefore does not cover all relative emissions from mechanical energy consumption, transport emissions and demolition during the construction phase.No specific preliminary assumptions were made regarding the carbonation rate of concrete, the replacement rate of recycled aggregates or the recycling trajectory of steel scrap because the study was limited to an estimation.

Was used EF of concrete, steel, and wood to estimate GHG emissions by materials. The EFs choice occurred according to the reliability of origin and similarity with the structure materials. The concrete EF came from an EPD (Environmental Product Declaration) by a Brazilian manufacturer for a similar concrete that uses the same cement with similar consumption. The steel EF came from the manufacturer's EPD. The sawed wood and plywood EF came from publications by an international researcher (mentioned in Table 3). The EFs and sources of information are presented in Table 3. The EF values are in CO_2e (CO_2 equivalent), which accounts for CO_2 emissions accumulated to other GHG emissions per the IPCC.

Table 3 - Materials and emission factors.

Material	EF	Source
30MPa concrete	0.267 tCO_2e/m^3	(EPD Votorantim Cimentos, 2016)
Steel for reinforced and prestressed concrete	1.6 $KgCO_2e$ /Kg	(WSA, 2011)
Sawed wood	0.0429 $KgCO_2$ e/Kg	(RUUSKA,2013)
14mm plywood	0.605 $KgCO_2$ e/Kg	(RUUSKA,2013)

Source: the authors

Emissions from steel production vary greatly depending on the type of steel mill that produces it. Mills that use iron ore have EF above 2 tCO_2/t of steel; this variation is caused by the different energy efficiencies of the equipment and the pH characteristics of the iron ore used. In industrial plants that only recycle steel scrap, emissions vary around 0.6 tCO_2/t of steel. The carbon credit of 0.256 tCO_2/t of steel cited in the EPD used obviously varies with the conditions of each industrial plant, but the authors understand that this is still a representative value under current conditions. It is worth noting that the main focus of the study is to show the importance of recycling concrete for capturing CO_2.

The carbon emissions from wood and plywood were considered based on their production (per production EF) and biogenic decomposition as the forms are for temporary use in the construction process, as Nabuus et al. (2007) recommended in a study published in the IPCC Forestry.

The estimates for CO_2 emissions from the biogenic decomposition of wood considered the pine carbon content (CC), usually manufactured into plywood for concrete forms in the region (Pine). The CO_2 emissions of sawed wood used the eucalyptus CC, commonly used in the region. The CC, density of drywood, and sources of information are presented in Table 4.

Table 4 - Information about the wood.

Material	EF	Source
Carbon content in plywood	41%	Pine - OLIVEIRA, et. al. (2011)
Basic density of plywood	0.40t/ m^3	IPT (1989)
Carbon content in sawed wood	42%	Eucalyptus - OLIVEIRA, et. al. (2011)

Basic density of sawed wood	0.49 t/m^3	Eucalyptus - OLIVEIRA, et. al. (2011)

Source: the authors

2.5 Carbon content measurements

We obtained the samples' carbon percentage content (CC) from their powder. The concrete samples were taken, with the best possible precision, from the surface of the test specimen. We then encapsulated each individual 37 g sample in tin foil.

The equipment used to measure the captured carbon was a LECO 144 Analyzer (LECO Corporation, St. Joseph, USA) and an Elementar Vario EL III Analyzer (Elementar, Langenselbold, Germany). This equipment burns and reduces the samples, breaking carbon compounds to release the carbon. Subsequently, gases go through a detection cell that measures the carbon concentration. The equipment's software converts the values into percentages through a predefined equation that considers the weight of samples, calibration, and moisture content. To obtain reasonable accuracy of the study, the chemical analyzer used is frequently calibrated. The equipment uses samples encapsulated in tin foil and their preparation is done in an environment free from the presence of CO_2, minimizing contamination of the samples before analysis.

The percentage of carbon (CC) represents the percentage of the chemical element in the sample. Therefore, we correlated this percentage to the CO_2 mass by multiplying the result by 3.667. This value is the mass ratio between the mass of the carbon atom and the mass of the CO_2 molecule.

We assessed the percentage of carbon in four stages to evaluate the CO_2 captured by the concrete. The first was at age zero, that is, the concrete's manufacturing date, measuring the percentage of carbon in the materials (Table 6).

Subsequently, the % carbon in the concrete samples at different ages studied was measured. The second assessment used specimens on the 17th day. The third was on the 155th day, and the fourth was on the 887th. Table 6 shows the percentages of carbon in the materials used for manufacturing concrete. Table 7 shows the percentages of carbon in the specimens' surface at the other ages and statistical information on these results.

We used the information from Tables 1 and 6 to calculate the percentage of carbon in the concrete on the manufacturing date (Table 6) — 0.38%, representing the starting point of carbonation tracking.

Measurements of carbon in crushed concrete (sand level or a 4.8mm diameter) represented the CO_2 capture at the end of the life cycle. In the table 7 are presented the percentages of carbon in concrete uncrushed specimens, in the Table 8 are the results for crushed concrete CO_2 absorption through analyses of crushed material kept in the environment for 94 days to carbonate and freshly ground material from the specimens. We crushed the remaining material on the 971st day, stored for 94 days until new carbon measurements, and crushed, for the second time, on the 1,065thday with immediate carbon measurement.

The ages of 17, 155 and 887 days, mentioned in table 6, were defined based on the limitations of availability of use of the chemical analysis equipment, similarly 94 days after crushing.

In summary, day 0 (zero), the day the concrete was made. Days 17, 155 and 887, days after the concrete was made, were when the samples were collected for measurement, in the chemical analyzer. On days 155, 941 and 1346, counted after the concrete was made, measurements of the carbonated thicknesses were made. On day 971 the concrete was crushed, when samples were taken for analysis of the percentage of captured carbon. On day 1065 (94 days after crushing) samples were taken again, from the crushed material, for analysis of the percentage of captured carbon. In the table 5 are presented the research schedule with ages in days and respective actions.

Table 5 - Research schedule with ages in days and respective actions.

Day	Action
0	Concrete production
17	Collection of concrete samples for analysis of %C
155	Collection of concrete samples for analysis of %C
887	Collection of concrete samples for analysis of %C
941	Measurement of carbonate thickness in uncrushed concrete specimens
971	Concrete crushing
971	Measurement of %C in crushed concrete
1065	Second concrete crushing

1065	Measurement of %C in concrete crushed 94 days ago (day 971)
1065	Measurement of %C in freshly crushed concrete (day 1065)
1346	Measurement of carbonate thickness in uncrushed concrete specimens

Source: the authors

Table 6 - Percentages of carbon in the materials used for manufacturing concrete.

Origin	**%C**	**Mean (%)**	**σ**	**CV**
Cement	2.317478 2.404644 2.331143	2.35	0.046881	1.99
Fine sand	0.058574 0.048811 0.060895	0.06	0.006413	11.43
Gravel	0.083171 0.090635 0.082643	0.09	0.00447	5.23
Medium sand	0.091076 0.083557 0.079319	0.08	0.005954	7.03
Coarse sand	0.119997 0.113959 0.110081	0.11	0.004997	4.36

Source: the authors

Table 7 - Percentages of carbon in concrete uncrushed specimens.

Age (days)	**%C**	**Mean (%)**	**σ**	**CV**
17	2.713547 2.310105 2.759012	2.594221	0.247099	9.53
155	2.200827 2.222157 2.169894	2.197626	0.026278	1.20
887	2.547232 2.383757 2.471418 2.358414 2.317615	2.415687	0.092638	3.83

Source: the authors

Table 8 - Percentages of carbon in crushed concrete. Ages refer to the time of and after crushing.

Age (days)	%C	Mean (%)	σ	CV
0	3.041739 3.026613 3.000782 2.989244 2.957892	3.00	0.0327	1.09
94	3.218485 3.082356 2.902053 2.896192 2.846031	2.99	0.1565	5.24

Source: the authors

2.6 Carbonated thickness measurements

In the concrete specimens at age 155, 941, and 1,346 days, we applied 1% phenolphthalein, a chemical dye that marked the carbonated regions. Phenolphthalein, a product available to the authors, is a pH indicator, suitable for use in concrete, which reacts forming a purple color when the pH is higher than 10. pH values below 10 indicate a significant possibility of oxidation of steel reinforcement. The table 9 shows the results from the carbonated thickness measurements at five points. The calculations considered the mean thickness. Figure 9 is an image of the carbonated region measurements. Figure 10 is a graph obtained from a fitted equation, with points up to three years measured and extrapolating the curve representing the future prediction of carbonation progression up to 100 years of age. Figure 11 is a chart with the percentages of carbon and the adjusted behavior curve.

Table 9 - Carbonated thickness in mm measurements.

Age 155 days			941 days			1,346 days		
1	2.7	mm	1	2.8	mm	1	3.8	mm
2	2.4	mm	2	3.2	mm	2	3.7	mm
3	2.5	mm	3	3.2	mm	3	3.4	mm
4	2.6	mm	4	3.0	mm	4	3.3	mm
5	2.5	mm	5	2.9	mm	5	2.9	mm
Mean	**2.54**	**mm**	**Mean**	**3.02**	**mm**	**Mean**	**3.42**	**mm**
σ	0.114018	mm	σ	0.178885	mm	σ	1.5811	Mm
CV	4.49	%	CV	5.92	%	CV	10.42	%

Source: the authors

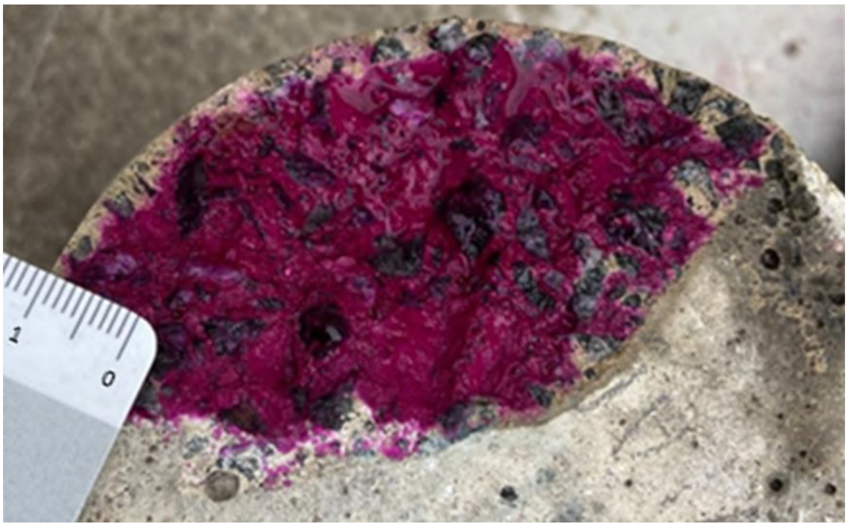

Fig.9. The carbonated thickness in cm measured on the 941st day.

Source: the authors

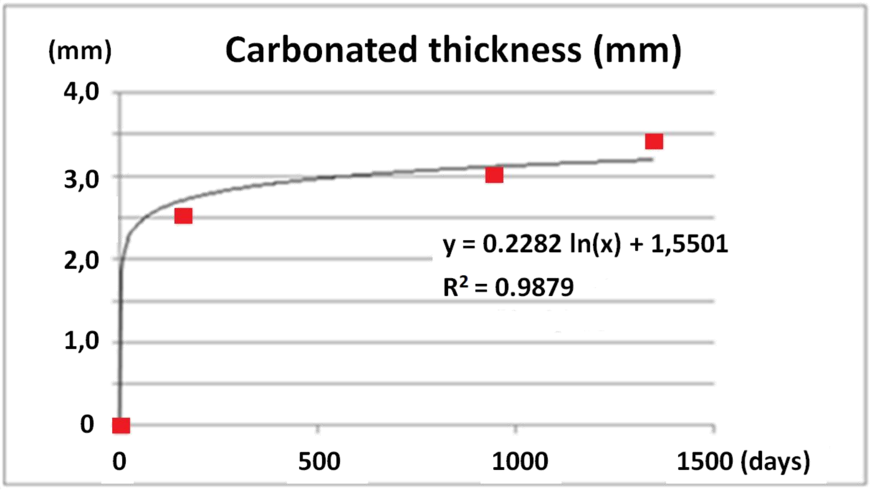

Fig.10. The advance of carbonation in mm /days.

Source: the authors

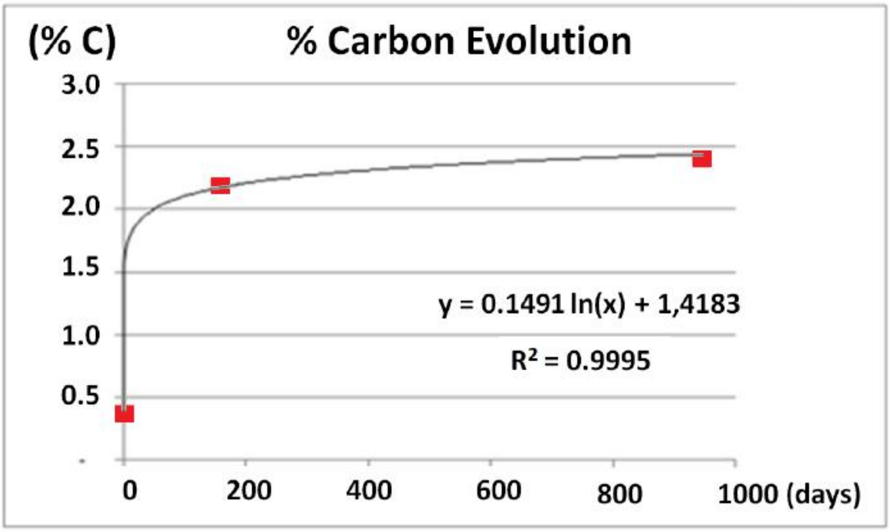

Fig.11. The measured percentage of carbon in days.

Source: the authors

With the 100-year life cycle recommended by the FIB Model Code for Concrete Structures (2010) and applying the adjusted equation (Figure 10), the predicted carbonated thickness is approximately 3.95mm. It is well below the reinforced concrete cover thickness (15 - 25mm). It is worth noting that it is a painted structure (Figure 7), which is significant for its lifespan extension. It should be noted that the 100-year projection was made based on measurements, on available samples, of the advance of the carbonate front within the study period; obviously, maintenance work or other unforeseen degradations may change this period.

2.7 Emission estimates

Were used the volumes of concrete, wooden forms, and steel (table 2) to estimate the CO_2e emissions at the structure-building stage. Table 10 shows the results of CO_2e emissions by the materials and their respective relative percentages.

Table 10 - The CO_2e emissions by materials.

Material	**Amount**	**Emissions (tCO_2e)**	**%**
Concrete	5,107.4 m^3	1,363.69	63%
Steel	447.56 t	716.10	33%
Sawed wood production	31.49 m^3	0.66	0%
Sawed wood decomposition		23.76	1%
Plywood production	70.10 m^3	16.96	1%
Plywood decomposition		42.15	2%
	Total	2,163.33	**tCO_2e**

Source: the authors

2.8 The CO_2 captured by concrete

We calculated the CO_2 captured by the concrete surface at ages 155, 941, and 1,346 days. The values are from the structural concrete area exposed to the air, this area was calculated from the structure projects, following this way, the carbonated area is 12,936.56m^2.The carbonated thickness values are presented in the table 8, and the percentages of carbon in the concrete specimens' surface measured with the chemical analyzer are presented in the table 6. From this information and with the adjustment of an appropriate curve, the 1,346 days and the estimated 100 years values were presented in the figure 11.

The capture calculations disregarded the carbon from the concrete in the manufacturing process by using the percentage of carbon before manufacturing (preexisting carbon). This operation used the values from Tables 1 and 6, with the 0.38% result subtracted from posterior ages. Table 11 shows the advance of carbonation and the percentage of carbon. Table 10 shows the volumes and masses of carbonated concrete at different ages. Table 12 shows the mass of carbon (C) and carbon dioxide (CO_2) in the carbonated concrete. Table 13 shows the progression of volumes and mass of carbonated concrete.

Table 11 - The progression of concrete carbonation.

Carbonated thickness (mm)			
2.54	mm	155	days
3.02	mm	941	days
3.42	mm	1,346	days (estimated)
3.95	mm	100	years (estimated)
Measured carbon (%)			
0.38	%	0	days (preexisting)
2.20	%	155	days
2.42	%	941	days

2.49	%	1,346	days (estimated)
2.98	%	100	years (estimated)

Source: the authors

Table 12 - The progression of volumes and mass of carbonated concrete.

Volume of carbonated concrete (m^3)			
32.86	m^3	155	days
39.07	m^3	941	days
44.24	m^3	1,346	days
51.07	m^3	100	years (estimated)
Mass of carbonated concrete (t)			
76.82	t	155	days
91.34	t	941	days
103.44	t	1,346	days
119.39	t	100	years (estimated)

Source: the authors

Table 13 - The progression of volumes and mass of carbonated concrete.

Mass of preexisting carbon and CO_2 (t)			
0.30	tC	0	days
1.08	tCO_2	0	days
Mass of measured carbon (t)			
1.69	tC	155	days
2.21	tC	941	days
2.58	tC	1,346	days (estimated)
3.56	tC	100	years (estimated)
Mass from the measured CO_2 (tCO_2)			
6.19	tCO_2	155	days
8.09	tCO_2	941	days
9.45	tCO_2	1,346	days (estimated)
13.06	tCO_2	100	years (estimated)
Mass of captured CO_2 (tCO_2)			
5.11	tCO_2	155	days
7.01	tCO_2	941	days
8.37	tCO_2	1,346	days (estimated)
11.98	tCO_2	100	years (estimated)

Source: the authors

We finalized the study of CO_2 capture by considering the end of the life cycle based on carbon measurements for crushed concrete. There were two carbon measurements, one from crushed concrete on the 971st day and stored for 94 days (the result was 3.00% of carbon content), and another on the 1,065th day with immediate measurement (2.99%), obviously within the measurement error. Figure 12 the size of the particles of the crushed concrete.

It was possible to evaluate how much additional carbon was present with a 90-day storage of aggregates, with the material exposed to air. These measurements sought to simulate the CO_2 capture by concrete when demolishing the structure. The equal results show that the CO_2 capture occurs right after crushing, and a 90-day storage, the results show an insignificant capture gain.

Considering the 3.00% carbon in the crushed concrete samples, the captured carbon corresponds to 197.28t or 723.24tCO_2 for the 3,222.36m^3 or 7,533.57t of crushable concrete.

Fig.12. The size of the particles of the crushed concrete.

Source: the authors

2.9 Final considerations

The amount of CO_2 captured in the structure life cycle will be insignificant. Table 13 shows the percentage of captured carbon compared to the emissions. In the table 14 are presented the percentages of captured carbon compared to the emissions.

Table 14 - Percentage of captured carbon compared to the emissions.

% CO_2capture compared to emissions from concrete production		
0.37 %	of emissions	155 days
0.51 %		941 days
0.61 %		1,346 days
0.88 %		100 years (estimated)
% CO_2capture compared to the emissions from the structure building (concrete + steel + wood)		
0.24 %	of the structure building emissions (concrete + steel + wood)	155 days
0.32 %		941 days
0.39 %		1,346 days
0.55 %		100 years (estimated)

Source: the authors

Considering, however, that the correct action for every work, from a circular economy standpoint, as recommended by the UNEP report (2022a), is recycling the structure, the reinforced concrete can provide aggregates and steel.

The crushable concrete accounts for 3,222m^3 or 7,533t since part of the foundations is inaccessible for recycling. The 3.00% carbon in the crushed concrete corresponds to capturing 226tC or 828tCO_2. This value represents 61% of the emissions from the materials used in concrete manufacturing.

Within this context, the 0.256tCO_2/t carbon credit mentioned in the EPD by Arcelor Mittal Brazil Steelworks (EPD-ARC-20180141-CBD1-EN, 2018) for reinforced steel bars produced in 2017 adds up to 91.7t of carbon credits for this structure.

The total carbon credits from the CO_2 captured by crushed concrete and steel recycling are 920tCO_2, representing 42.5% of emissions from all structural materials.

This estimated value of 42.5% compensation is approximate, it will obviously vary from project to project, and the relevant point of this study is to show the importance of recycling by crushing concrete to promote a much greater capture of CO_2.

III. CONCLUSION

Typically, studies of concrete carbonation focus on concerns about reinforcement corrosion. This study focuses primarily on the measurements of carbon masses captured by the natural process of concrete carbonation.

First, we conclude that carbon dioxide capture occurs over several years but is insignificant during the structure's lifespan compared with the emissions. However, in a correct circular economy context where concrete is recycled into aggregates, the captured CO_2 can reach significant amounts. This case study demonstrated that concrete and steel recycling can capture carbon corresponding is proximally to 40% of GHG emissions caused by materials, with concrete recycling accounting for 90% of this amount.

Therefore, we conclude that the environmental impact resulting from GHG emissions by the construction of this type of structure can be significantly reduced if the concrete was crushed in the final of the lifespan of the structure.

This action is important too considering the circular economy concept mentioned in the UNEP report (2022a) that recycles the structure residues into aggregates and steel.

Finally, we can state that the engineering study connects to socio-environmental laws and the UN SDGs no. 8, 12, and 13 that pursue the welfare of current and future generations.

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