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ORIGINAL ARTICLE

Optimized sizing of reinforced concrete structural elements considering the effect of carbonation

Dimensionamento otimizado de elementos estruturais em concreto armado considerando o efeito da carbonatação

Jeferson Junior Alievi[a]
Jair Frederico Santoro[b]
Moacir Kripka[a]

[a]Universidade de Passo Fundo – UPF, Programa de Pós-graduação em Engenharia Civil e Ambiental, Passo Fundo, RS, Brasil
[b]Instituto Federal Sul-Riograndense – IFSul, Faculdade de Engenharia, Passo Fundo, RS, Brasil

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Abstract: The environmental impact of reinforced concrete structures occurs during all phases of the building's life cycle, with emphasis on the stages of extraction and transport of raw materials and concrete production. An effective way to reduce the impact of these structures is to reduce the consumption of materials with the use of optimization techniques. The present study evaluates carbon dioxide emissions of concrete with two different compressive strengths for the region of Chapecó, SC. With these data, the optimization of structural elements was performed aiming to minimize their environmental impact. The carbonation of optimized elements was also evaluated. Among the results, it was observed that concretes with lower strength have better CO_2 absorption rates (for the elements analyzed 20MPa concrete absorbed about 90% and 112% more CO_2 than 35MPa concrete to columns and beams, respectively). In addition, it was observed that local factors can strongly influence the impacts, with the transport of materials reaching up to 6.4% of total emissions.

Keywords: reinforced concrete, optimization, carbonation, environmental impact, sustainability.

Resumo: O impacto ambiental das estruturas de concreto armado ocorre durante todas as fases do ciclo de vida da edificação, com destaque para as etapas de extração e transporte de matérias-primas e produção de concreto. Uma forma eficiente de reduzir o impacto dessas estruturas é reduzir o consumo de materiais com o uso de técnicas de otimização. O presente estudo avalia as emissões de dióxido de carbono de concreto com duas diferentes resistências à compressão para a região de Chapecó, SC. Com esses dados, foi efetuada a otimização de elementos estruturais visando a minimização de seu impacto ambiental. A carbonatação dos elementos otimizados também foi calculada. Dentre os resultados, observou-se que concretos com menor resistência apresentam melhores taxas de absorção de CO_2 (para os elementos analisados o concreto de 20 MPa absorveu aproximadamente 90% e 112% mais CO_2 que o concreto de 35 MPa para pilares e vigas, respectivamente). Além disso, observou-se que fatores locais podem influenciar significativamente os impactos, com o transporte atingindo até 6,4% das emissões totais.

Palavras-chave: concreto armado, otimização, carbonatação, impacto ambiental, sustentabilidade.

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1 INTRODUCTION

The production, consumption, and lifestyle of the world's population is potentially impacted by economic development, population growth, urbanization, and the technological revolution. As a result, the need for housing and infrastructure work is increasing.

Corresponding author: Moacir Kripka. E-mail: mkripka@gmail.com
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The construction sector is the biggest contributor to CO_2 emissions, accounting for about 30% of all greenhouse gas emissions on the planet. In addition, it accounts for about 40% of global resource use, including 12% of all freshwater. Concrete is one of the most important building materials in the world and the second most used on the planet, after water. Thus, considering the volume of concrete produced and the associated environmental impacts, the optimized design of reinforced concrete structures is an alternative for sustainable development. CO_2 emissions from fuel combustion, cement production, and other industrial processes accounts for about 70% of total global greenhouse gas emissions [1]. Despite the fact that the built environment contributes a large part of global greenhouse gas emissions, it has a great capacity for improvement through the modernization of processes [2].

To assess the environmental impact of civil construction, Life Cycle Assessment (LCA) can be used. Various environmental impacts can be assessed by LCA: global warming, destruction of the ozone layer, eutrophication, depletion of natural resources, energy consumption, land, and water use, among others. The LCA methodology is divided into four main steps: definition of goals (objective and scope), inventory analysis, evaluation, and analysis [3].

In recent years, the themes of sustainability and environmental impact in civil construction have been studied with greater intensity, with the common objective of the studies being the reduction of pollutant emissions into the atmosphere. Due to its importance, reinforced concrete structures have been the subject of several research projects aimed especially at reducing CO_2 emissions and energy consumption [1], [3–11]. However, a small number of studies consider that concrete has the property of absorbing CO_2 from the environment through carbonation, making a kind of compensation through the capture of the gas. In these studies, the results obtained are quite different in the estimation of the amount of carbon dioxide reabsorbed by the concrete. For example, according to research conducted by Jacobsen and Jahren [12] in Norway, it was estimated that 11% of CO_2 emissions in the production of concrete are reabsorbed by the concrete, due to carbonation, during its life cycle. The research by Gajda and Miller [13] report a reabsorption percentage of 7.6%. In Denmark, a study developed by Pade and Guimarães [14] estimated, from a 100-year perspective, an absorption of 57% of CO_2 emissions generated in the production of concrete, considering the demolition of the structure (if the demolition of the structure is not considered, this value is reduced to 24%). In a similar study conducted in the United States, Haselbach and Thomas [15] estimated CO_2 capture of 28.2% during the useful life of the structure. According to Possan et al. [7], these differences recorded in the literature are due to the influence of several factors on the carbonation of concrete (such as strength, exposure environment, content and type of cement, etc.), in addition to differences in the methodology used for its determination.

The present work aimed to evaluate the environmental impact of reinforced concrete taking as a measurement factor the CO_2 emissions. This evaluation was conducted based on the emissions of $1m^3$ of concrete with different characteristic strengths, adjusting the data from the SimaPro Software for the region under study. The values obtained were used for the optimized design of beams and columns, also including the consideration of the carbonation effect of concrete. To achieve these objectives, this article is structured as follows. The introductory section describes the motivation and objectives of the study. Section 2 presents some concepts that support the study related to life cycle assessment, while the third section addresses concepts related to carbonation in concrete structures. The fourth section describes the methodology used to obtain the impacts of the materials and the formulations adopted to optimize the elements. Section 5 presents the results, and in section 6 the conclusions of the study are summarized.

2 LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) is a tool used to identify the environmental impacts of a product, service, or process throughout its life cycle. The ABNT NBR ISO 14040 standards [16] present a methodological framework for the analysis and assessment of environmental effects throughout the life cycle of a product. Several types of environmental impacts can be estimated by LCA: global warming, ozone layer depletion, eutrophication, acidification, toxicity to humans and ecosystems, depletion of natural resources, energy consumption, land use, and water, among others. ACVs performance depends on the information to be used and the quality of this information, as well as knowledge of the technology adopted.

LCA models the life cycle of an object through its product system performing one or more defined functions. The essential property of a product system is characterized by its function and does not necessarily need to be defined in terms of end products. The subdivision of a product system into the elementary processes that compose it facilitates the identification of inputs and outputs of the product system [16].

With the beginning of the concept of the LCA term, divergent approaches, terminologies, and results emerged, as there was no specific scientific platform. Therefore, the initial analyzes were conducted considering different techniques without a common reference. The results obtained were different, even when the objectives of the study were the same [17].

LCA includes the definition of the object and scope, inventory analysis, impact assessment, and interpretation of results. The definition of objectives and scope is the moment when, among others, the study boundary, the functional unit and the impact categories to be considered are determined. Life Cycle Inventory (LCI) analysis involves data collection and calculation procedures to quantify the relevant inputs and outputs of a product system. The result of this step is the quantification of all the resources used and the emissions associated with the production of a certain quantity (functional unit) of the product under study. The impact assessment phase of the LCA aims to link inventory data with specific impact categories and category indicators. The calculation of the results of the indicators takes place by converting the results into common units and aggregating them into the same impact category. Its result is a numerical value of the indicator. The two main impact modeling approaches are midpoint and endpoint. While the midpoint approach uses indicators located along the environmental mechanism, the endpoint approach refers to a specific damage, related to a broader area of production that can be human health, the natural environment, or natural resources.

Increased attention has been paid to the environmental impacts attributed to the built environment in recent years, and this occurs both in the form of academic research and the initiative of the civil construction industry. In academic environments, 1068 papers on green buildings were published between 2010 and 2019 [18].

Navarro et al. [19] highlight the importance of environmental impacts being considered in the life cycle of buildings, and that this assessment needs to be conducted in the initial stages of the project.

In recent years, several studies have been developed with an emphasis on the Life Cycle Assessment of buildings, covering everything from the extraction of raw materials to the final disposal of the demolition of the building. The studies aim the search for alternative materials and a lower generation of pollutants for the construction of environmentally sustainable buildings. As an example of the search for viable economic, technical, and environmental solutions for the manufacture of concrete, there is the study developed by Rajan et al. [20], which investigates the addition of rubber waste from naturally treated tires for partial replacement of fine aggregate; the study by Verma et al. [21], which seeks efficient solutions in the use of silica fume and stone dust in partial replacement of cement and fine aggregate; the work of Joanna et al. [22], which uses fly ash to replace cement in the manufacture of concrete; and the study by Majhi and Nayak [23] that uses blast furnace slag of high aggregated volume and recycled with lime activator, in partial or total replacement of the natural aggregate.

Regarding the materials involved in the construction and maintenance of buildings and infrastructures, cement is one of the most important building materials. It is responsible for 5% to 7% of global CO_2 emissions and 12% to 15% of the total energy consumed in the industry worldwide. In addition, cement production is projected to increase annually by 0.8% to 1.2% [24]. In the cement life cycle, 95% of the total CO_2 emitted comes from the production stage, and almost all the emission in the cement industry is concentrated in the production of clinker. During the cement production process, half of the CO_2 emitted refers to the calcination of limestone rock, while the remaining part is due to the burning of fuels for energy generation, in the clinkerization process [25]. The cement industry generates for each ton of cement produced, between 0.7 and 1.0 tons of CO_2 [26]. Currently, the Brazilian cement industry has one of the lowest specific CO_2 emission rates in the world, thanks to mitigating actions that have been implemented by the sector in recent decades. For example, from 1990 to 2014, total emissions decreased from 0.7 tons of CO_2 to 0.564 tons of CO_2/t of cement [27].

The iron and steel sector are relevant to the global economy in terms of employment and economic growth. Worldwide more than six million jobs are directly or indirectly linked to the steel sector. On the other hand, this sector is responsible for about 17% of energy consumption in the industrial sector [28]. The carbon dioxide emission from the steel industry is 997 kg per ton of steel, accounting for 4 to 5% of global emissions [29].

Aggregates (fine and coarse) used in civil construction are the most consumed minerals in the world. Globally, it is estimated that annually eleven billion tons of concrete are consumed, and sand and gravel account for 60–80% of the volume of concrete [30,31]. The extraction, processing, and transport operations involving aggregates produce considerable amounts of unfavorable effects on the environment. Among the main environmental impacts caused by the mineral extraction of aggregates, landscape alterations, vegetation suppression, alteration in watercourses, instability of banks and slopes, and water turbidity stand out.

3 CARBONATION OF CONCRETE STRUCTURES

The carbonation of concrete occurs due to the ingress of CO_2 atmospheric in concrete. Several factors influence the carbonation process, highlighting the relative humidity of the air, the type of cement, the concrete mix, curing, and temperature [32]. According to Possan et al. [7] concrete has the property of absorbing CO_2 from the environment through carbonation. Almost all cement-based materials undergo a certain amount of carbonation reaction during their lifetime, and this is due to the presence of carbon dioxide in the earth's atmosphere. This process begins at construction, through the structure's life cycle, and continues through the demolition process.

Given the importance of the carbonation process of reinforced concrete structures, the number of works in the literature that describe in detail the methodology for calculating CO_2 absorptions can be considered small. A mathematical model for calculating the carbonation depth y over time is presented by Felix and Possan [25], according to Equation 1:

$$y = k_c \cdot \left(\frac{20}{f_c}\right)^{k_{fc}} \cdot \left(\frac{t}{20}\right)^{\frac{1}{2}} \cdot \exp\left[\left(\frac{k_{ad}.a_d^{\frac{3}{2}}}{40+f_c}\right) + \left(\frac{k_{co_2}.co_2^{\frac{1}{2}}}{60+f_c}\right) - \left(\frac{k_{ur}.(UR-0{,}58)^2}{100+f_c}\right)\right] \cdot k_{ce} \quad (1)$$

Where:
y – Average depth of concrete carbonation (mm);
f_c −Characteristic strength of compression of concrete (MPa);
k_c −Variable factor referring to the type of cement used;
k_{fc} −Variable factor referring to the compressive strength of the concrete, depending on the type of cement used;
t −Concrete age (years);
a_d − Content of pozzolanic addition in the concrete (% in relation to the mass of cement);
k_{ad} − Variable factor referring to the pozzolanic additions of the concrete – silica fume, metakaolin, and rice husk ash, depending on the type of cement;
UR −Average relative humidity (%/100);
k_{ur} − Variable factor referring to relative humidity, depending on the type of cement used; co_2 − CO_2 content of the atmosphere (%);
k_{co_2} −Variable factor referring to the CO_2 content the environment, depending on the type of cement used;
k_{ce} −Variable factor referring to exposure to rain, depending on the exposure conditions of the structure.

The amount of CO_2 (in kg) captured during the service life (carbonation) of reinforced concrete structures (unpainted and exposed concrete) is determined from Equation 2:

$$CO_2 = y \cdot c \cdot CaO \cdot r \cdot A \cdot \mathrm{M} \quad (2)$$

Where:
c −It is the amount of cement used to produce one m^3 of concrete (kg/m^3);
CaO −It is the amount of calcium oxide contained in the cement (%);
r −Proportion of CaO =fully carbonated (%);
A − Surface area of the concrete exposed to the action of CO_2 (m^2);
M −Molar fraction of CO_2/CaO.

4 METHODOLOGY

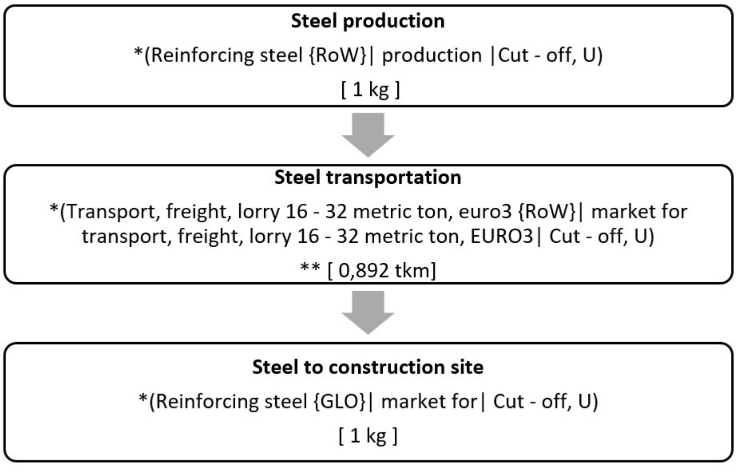
4.1. Carbon dioxide emissions from component materials of reinforced concrete

In the present study, the environmental impact assessment of the component materials of reinforced concrete was conducted for the region of Chapecó, SC, based on the CO_2 emissions generated for the production and transport of concrete, steel, and wooden formworks. The concrete analyzed in this study was 20 MPa and 35 MPa, the dosages being supplied by a concrete batcher in the region and summarized in Table 1. The concrete batcher also provided a list of its suppliers of materials to produce concrete. The coarse aggregate and fine aggregate (industrial sand) used are produced in the same city, about 4 km from the concrete plant. The fine aggregate (natural sand) is produced in the city of São Cristóvão do Sul, SC, 294 km away. Cement is produced in the city of Rio Branco do Sul, PR, 505 km away, steel is produced in Sapucaia do Sul, RS, 446 km Away, and wood used for formworks production is extracted in the city of União do Oeste, SC (distance of 60 km).

The calculation of CO_2 emissions was done using the SimaPro Software, version 9.2.0.1 Faculty UPF 003, considering the Ecoinvent 3.7.1 database of 2021, impact category ReciPe 2016 Midpoint method (H) version 1-05 Hierarchical (standard method with characterizing factors for the global scale). The SimaPro Software database was adjusted to the reality of the region under study. Emissions from steel, formworks, and concrete were determined in Simapro according to the flowcharts in Figures 1 to 4. These Figures indicate which data were obtained directly from the software base, and which were adjusted from the distances and dosages used in the present study. The calculation of CO_2 emissions was made for a cubic meter of concrete, a kilo of steel, and a cubic meter of wood for formworks.

Table 1. Concrete dosage

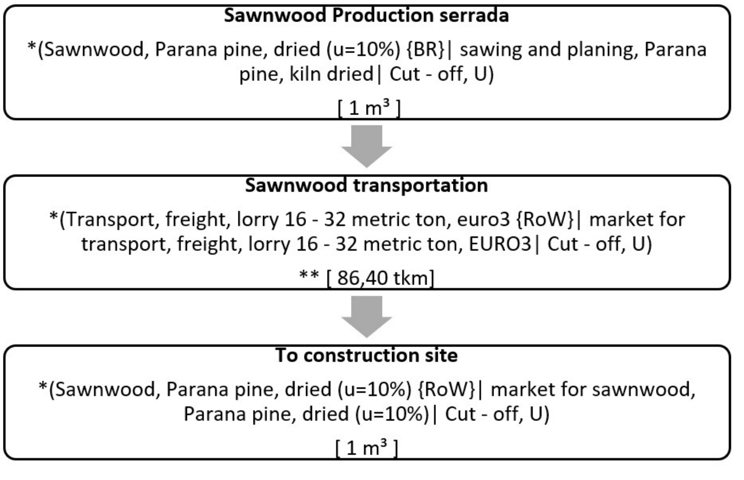
Raw material	Amount (kg/m^3)	
	Concrete 20 MPa	Concrete 35 MPa
Coarse aggregate	625	730
Fine aggregate	315	290
Industrial sand	300	350
Natural sand	670	550
Cement (CPII-F-32)	270	340



* As obtained from SimaPro

**Adjusted data

Figure 1. Flowchart with adjusted data for steel



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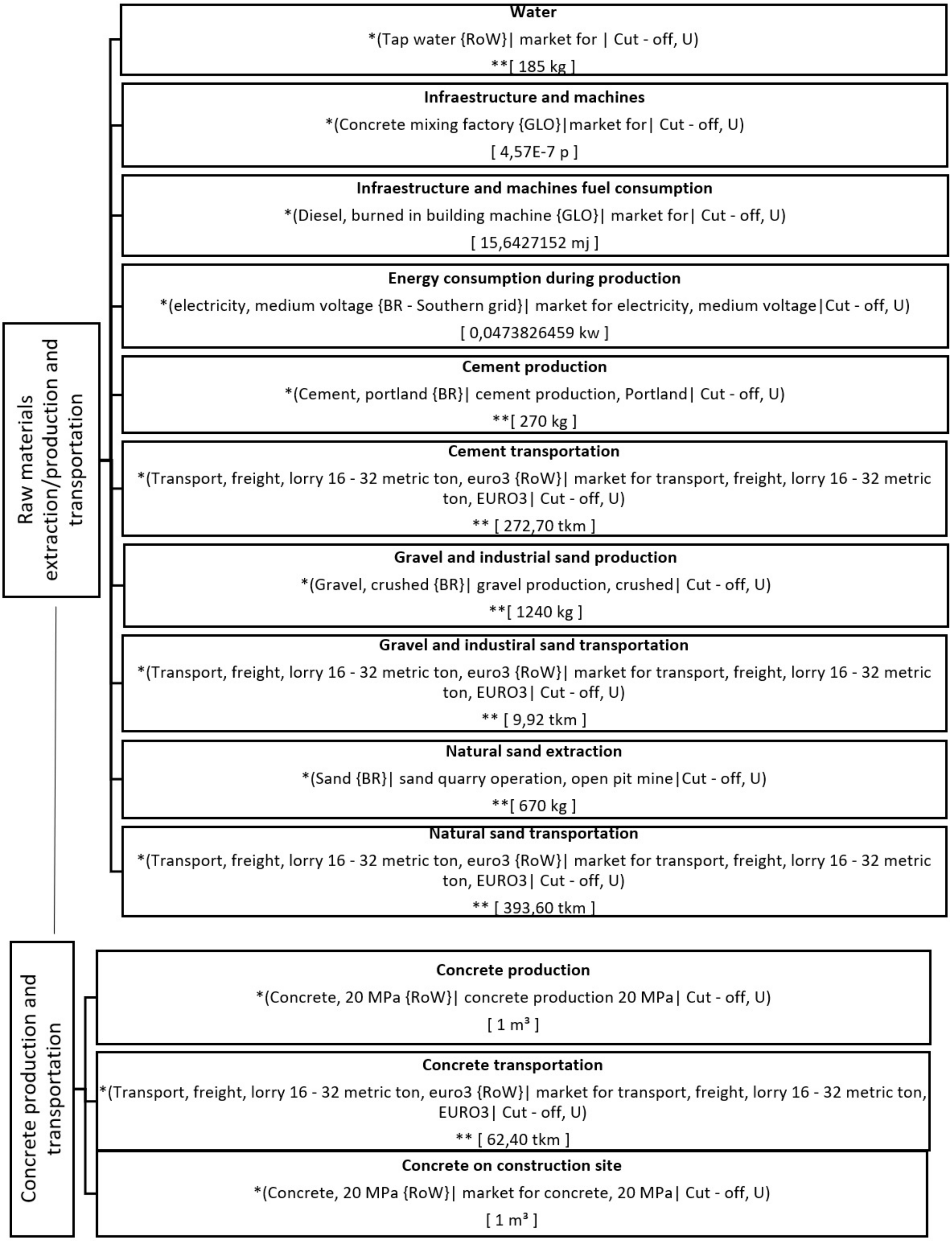
** Adjusted data

Figure 2. Flowchart with adjusted data for wooden shapes.



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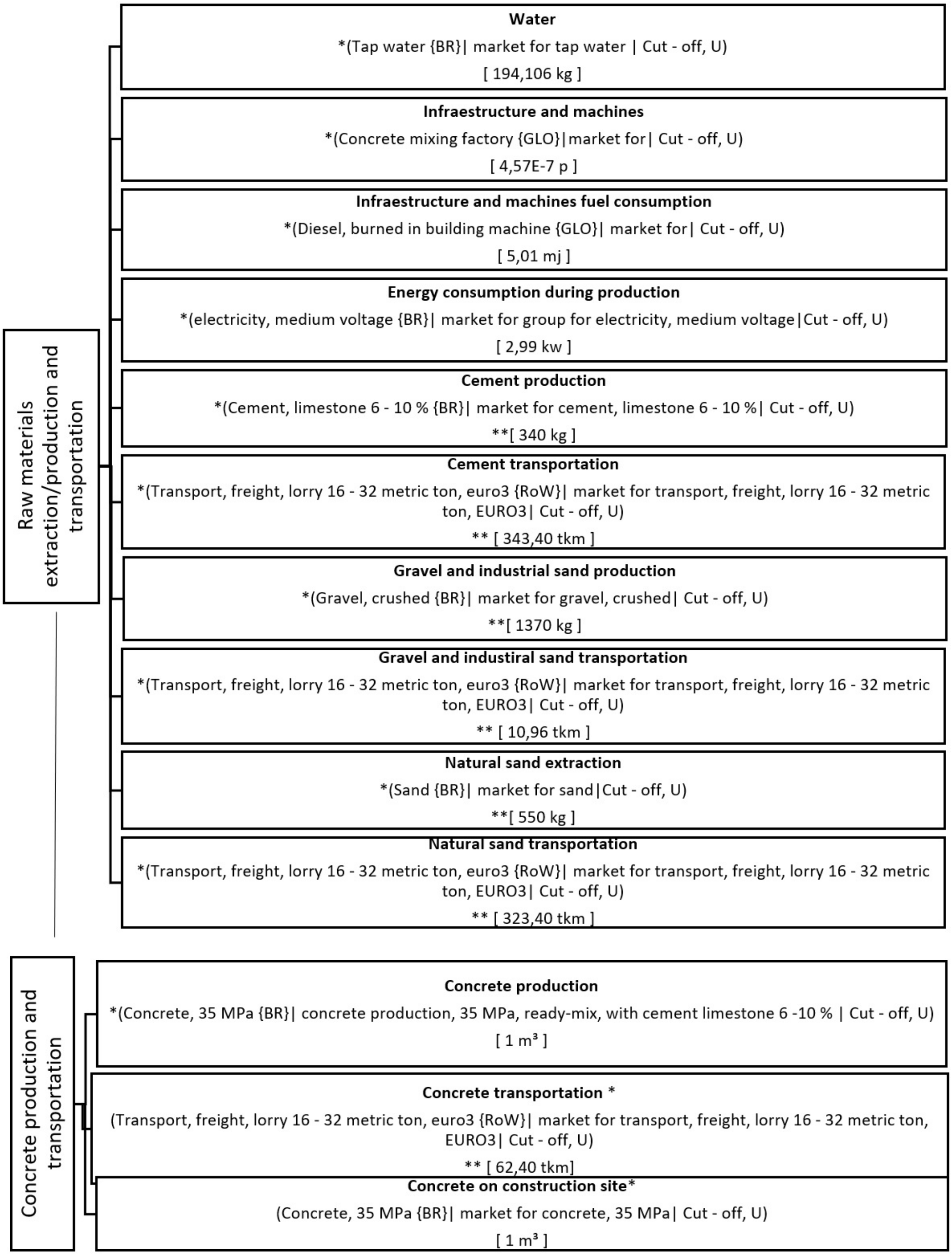
** Adjusted data

Figure 3. Flowchart with adjusted data for 20 MPa concrete.



* As obtained from SimaPro

** Adjusted data

Figure 4. Flowchart with adjusted data for 35 MPa concrete.

4.2 Columns optimization

The optimized design of reinforced concrete column sections subjected to uniaxial bending-compression was conducted using a software developed by Bordignon and Kripka [33] and updated in 2019, where the Simulated Annealing method was used for the optimization associated with a routine for checking the strength of columns.

Considering a rectangular cross-section, the objective of optimal design is to obtain a configuration that is capable of producing resistant bending and axial forces (M_{rd} and N_{rd}), equal to or greater than the acting forces (M_{sd} and N_{sd}), with minimal environmental impact. The design variables were considered as discrete, with the values related to the dimensioning of the concrete cross-section (x_1 and x_2) varying every centimeter, and the areas, quantities, and disposition of the reinforcements (x_3 to x_7, respectively) limited to commercial values, as shown in Figure 5.

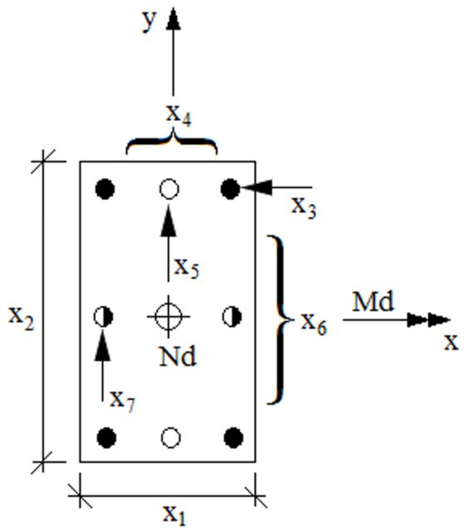


Figure 5. Column optimization design variables Source: Bordignon and Kripka [33]

The original objective function was adapted to minimize the environmental impact produced by the component materials of the section, per linear meter of column. From the variables described in Figure 6, the objective function can be written as in Equation 3:

$$f(x)=(x_1.x_2).C_c+(4.x_3+2.x_4.x_5+2.x_6.x_7).C_s+2.(x_1+x_2).C_f \quad (3)$$

The first part of the function represents the CO_2 emissions from the concrete, where Cc is the CO_2 emission per unit volume. The second part represents the emissions from the longitudinal reinforcement, being Cs the respective impact per unit of mass. The last part represents the CO_2 emission relative to wood forms, where Cf is the CO_2 emission per unit area.

The constraints imposed on the optimization problem refer to the strength criteria and aspects related to minimum and maximum dimensions of the concrete section, the reinforcement ratio, and spacing between bars. More details on the formulation and implementation aspects can be found in Bordignon and Kripka [33].

Based on the formulation described, four sections of columns were optimized with acting forces taken from [33] and listed in Table 2.

Table 2. Values of forces acting on the columns

	N (kN)	M (kN.cm)
P1	500	6,250
P2	2,250	28,125
P3	5,000	62,500
P4	7,250	90,625

4.3 Beams optimization

To perform the optimized design of the reinforced concrete beams, the software developed by Tres Junior and Kripka [34] was used, which adopts a modified version of Harmony Search as the optimization method [35]. As with the optimization of the columns, the objective was to minimize the total impact produced by the concrete, steel, and formworks, measured in $kgCO_2$. Aiming to reduce the cost of reinforced concrete beams, the following design variables were defined, also represented in Figure 6: *b* is the beam width; *h* is the beam height; Nb_{int} is the number of internal rebars; *Øe* is the diameter of the outer rebars, and *Øi* is the diameter of the inner rebars. All design variables of the problem are discrete and can assume pre-established values. The constraints of the problem involve the verification of the ultimate and service limit states, according to the guidelines of the Brazilian standard ABNT NBR 6118 [36], related to bending moments, rebar spacing, crack opening, and displacements [34].

In this study, double-supported beams with span L from 3 to 10m were designed for live loads and dead loads of 9.5 kN/m and 2 kN/m, respectively (plus self-weight).

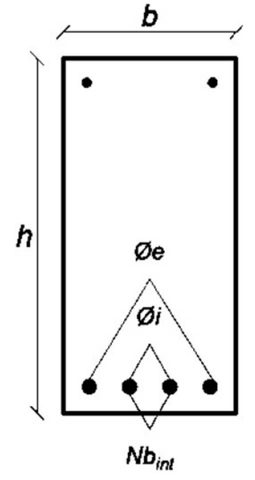


Figure 6. Optimization problem design variables

4.4. Effect of carbonation

To evaluate the effect of carbonation in reducing the total CO_2 emission of the structures, the optimized columns and beams of the previous examples were considered. To calculate the carbonation depth, the structures were considered to be built in an urban environment protected from rain, with an average annual humidity of 70% and a CO_2 content of 0.04%, in exposed and unpainted concrete. Initially, the useful life of 50 years was adopted, and again, concrete with a compressive strength of 20 MPa and 35 MPa with CP II-F-32 cement was used (Portland cement with filler). Based on the methodology previously described, CO_2 emissions from component materials of reinforced concrete were obtained. Carbonation depth over time and the amount of CO_2 captured during the service life of the structures were obtained from Equations 1 and 2 previously presented. It was considered that the surface area of the concrete section is fully exposed to the action of CO_2. This last consideration is not verified to inner beams and columns of buildings, for example, and in this case, can be seen as an "upper limit" of carbonation.

5 OPTIMIZED SIZING OF REINFORCED CONCRETE ELEMENTS

The corresponding values are presented in Table 3, considering the phase from cradle to gate of the raw materials.

Table 3. CO_2 emissions from component materials of reinforced concrete structures.

	Extraction/Production	Transport	Total Emissions
Steel ($kgCO_2/kg$)	1.85	0.12	1.97
Formworks ($kgCO_2/m^2$)	20.44	0.48	20.92
Concrete 20 MPa ($kgCO_2/m^3$)	330.17	8.79	338.96
Concrete 35 MPa ($kgCO_2/m^3$)	401.49	4.61	406.10

From the table, the emissions from the extraction and production phases of the materials correspond to most of the impacts produced. However, the impact of transport cannot be neglected either, as it can reach up to 6.4% of total emissions, as in the case of steel. It can also be seen that, in unitary terms, the impact of concrete is significantly greater than that of other materials. Comparing the results obtained for concrete emissions from the city of Passo Fundo, RS [10], less than 200 km distant, the impacts of the present study are higher (6.4% for 35MPa concrete and 10.2% for 20MPa). The 35MPa concrete, as it uses a greater amount of cement, also has a greater impact compared to the 20MPa concrete (about 20% greater). On the other hand, it is interesting to notice that in terms of efficiency, concrete 35MPa produces an impact of 11.60 $kgCO_2/m^3/MPa$, 31.5% lesser than 20MPa concrete (16.94 $kgCO_2/m^3/MPa$). It is clear that a fair comparison between these materials must be made considering their application to a structural element.

The result of the optimized dimensioning of the sections of the columns proposed for the concretes with characteristic strengths of 20 MPa and 35 MPa, for the unit impacts listed in Table 3, are presented in Figure 7, where the value of emissions is given in $kgCO_2/m$ of the column.

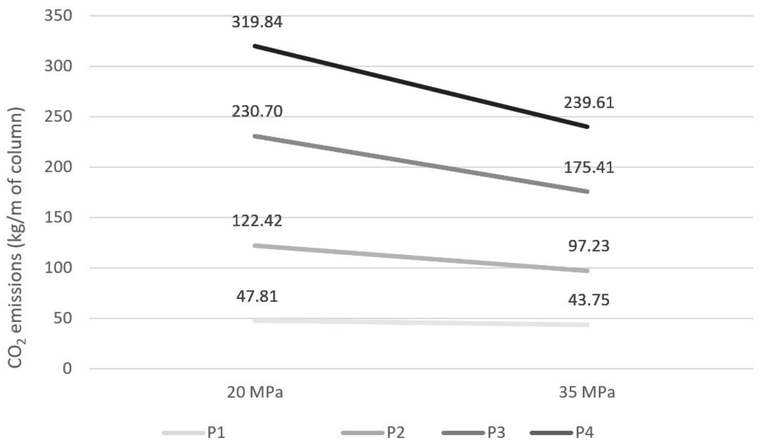
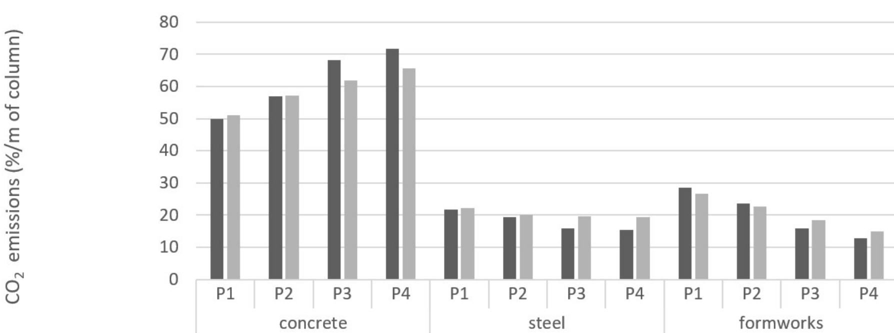


Figure 7. CO_2 emissions of the optimized design of reinforced concrete columns.

From Figure 7 it can be noticed that CO_2 emissions progressively decrease with increasing concrete strength for all considered stresses. When considering the efficiency in terms of $kgCO_2/m^3/MPa$, the advantage regarding the usage of higher strengths is even greater.

Figure 8 presents the percentage contributions of CO_2 emissions from materials to the optimized columns. The percentage contributions are given in %/m of column, for the four optimized columns, considering the strengths and materials used (concrete, steel, and formworks). It was observed that for smaller acting moments (P1) a significant reduction of concrete section due to the increase in concrete strength (about 25%) does not imply in a percentual reduction of the total contribution of concrete regarding global emissions. To the other acting forces considered, the reduction of the concrete section was more significant, leading to an effective reduction in its relative contribution to total impact.



	concrete				steel				formworks			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
Concrete - 20 MPa	49.84	56.98	68.23	71.65	21.64	19.36	15.84	15.5	28.52	23.66	15.93	12.85
Concrete - 35 MPa	51.15	57.13	61.93	65.69	22.15	20.09	19.72	19.28	26.7	22.78	18.35	15.03

■ Concrete - 20 MPa ■ Concrete - 35 MPa

Figure 8. Percentage contributions of CO_2 emissions of materials for the optimized abutments.

Regarding the results presented in Figure 8, the analysis shows that the percentage contributions of concrete tend to increase as the stress increase, whereas for steel and wooden formworks the percentage contributions tend to decrease as the stress increases.

Figure 9 shows the result of the optimized dimensioning of the beams in relation to the impact measured in terms of $kgCO_2/m$ for the two analyzed strengths.

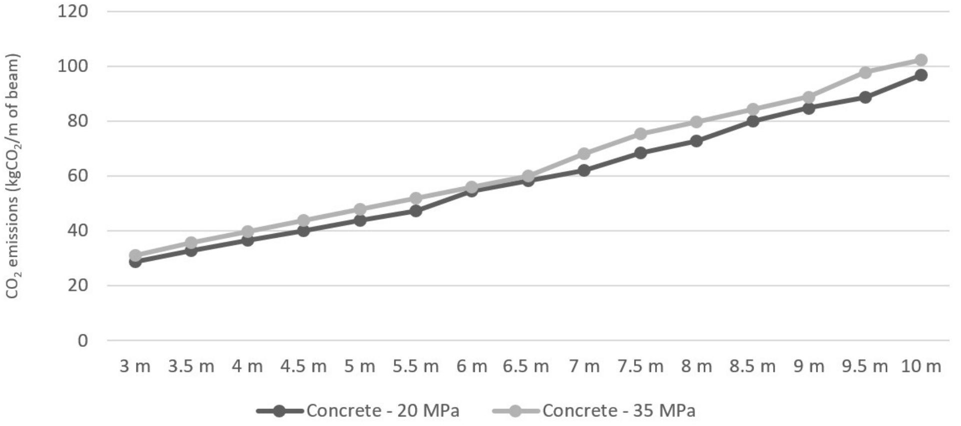


Figure 9. CO_2 emissions of reinforced concrete beams.

In the analysis of the results, it is observed that CO_2 emissions/m of beam increase progressively as the span of the beam increases. Contrary to what was observed for the columns, the lower-strength concrete produced less impact for all the spans analyzed. The beams dimensioned with 35MPa concrete presented an impact between 3 and 10% greater, with an average value of 7.5%. A similar trend had been obtained by Medeiros and Kripka [37] considering the cost of the beams.

Figure 10 shows the percentage of CO_2 absorbed during the life of the columns in relation to CO_2 emissions during their production.

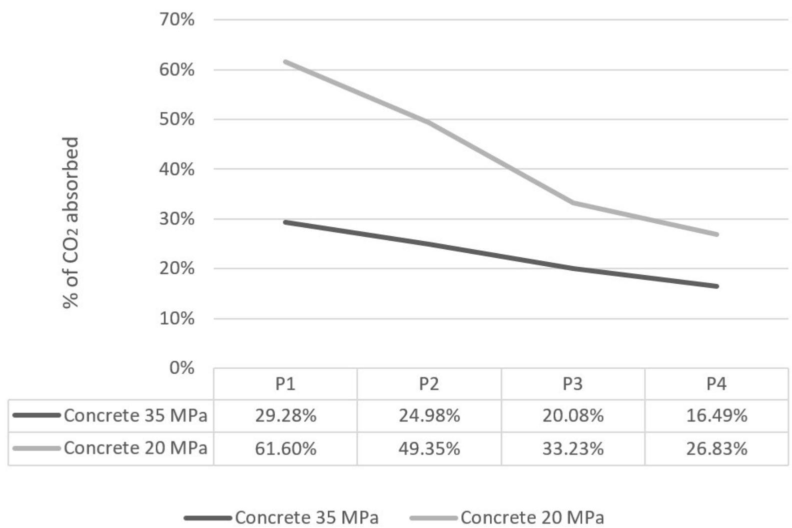
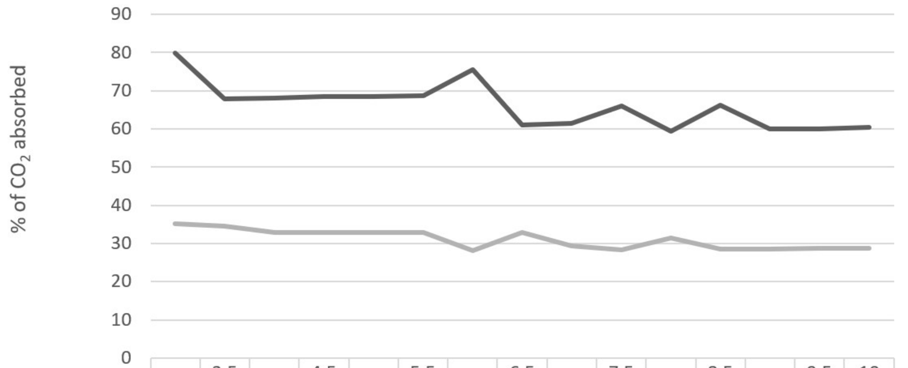


Figure 10. CO_2 capture during the useful life of columns designed with 20 and 35 MPa concrete.

The average carbonation for the columns with 20 MPa concrete was on average around 42%, which means that the columns absorbed approximately 42% of the CO_2 emitted during the entire process of material extraction, transport, and production. For the columns optimized with 35 MPa concrete, the average absorption was about 22% of the CO_2 produced. It was observed that, with the increase of the compressive strength of the concrete, the depth of carbonation of the concrete decreases, and consequently, the amount of CO_2 absorbed by the structural element also decreases.

Figure 11 presents the results of the carbonation calculation for the reinforced concrete beams. It was observed that the beams dimensioned with concrete of 35 MPa absorbed an average of 31% of the emitted CO_2 and that the beams dimensioned with concrete of 20 MPa absorbed an average of 66%.



	3m	3.5 m	4m	4.5 m	5m	5.5 m	6m	6.5 m	7m	7.5 m	8m	8.5 m	9m	9.5 m	10 m
Concrete 20 MPa	79.8	67.8	68.1	68.4	68.5	68.7	75.5	60.9	61.3	66.0	59.3	66.1	59.9	60.0	60.3
Concrete 35 MPa	35.1	34.4	32.8	32.8	32.8	32.8	28.1	32.8	29.4	28.3	31.4	28.4	28.5	28.6	28.7

Figure 11. CO_2 capture during the service life of beams dimensioned with 20 and 35 MPa concrete.

Figure 12 shows the carbonation of the beam with an intermediate span (beam V8, with a span of 6.5m), with a useful life ranging from 10 to 100 years.

Through the analysis of Figure 12, it is possible to see that the capture of CO_2 increases in percentage when considering the longer useful life of the reinforced concrete structure. For example, for a lifetime of 50 years, the beam absorbs approximately 31.97% of the CO_2 emitted during its entire manufacturing process. For the 100-year lifespan, the absorption rises to about 45.34% of the CO_2 emitted (an increase of 41.8%). Furthermore, the 20 MPa concrete beam would absorb almost twice as much CO_2 as the 35 MPa beam in the same period.

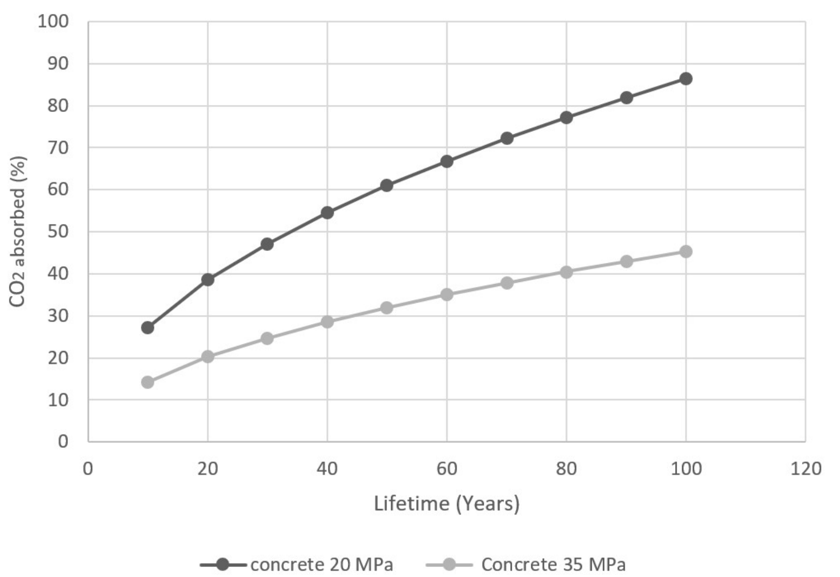


Figure 12. Comparison of the carbonation of the beam with a span of 6.50 m for a useful life ranging from 10 to 100 years.

6 CONCLUSIONS

The present work aimed to evaluate the environmental impact of reinforced concrete structures from the determination of CO_2 emissions in optimized structures. This assessment was conducted based on the emissions determined for the City of Chapecó, SC, Brazil. Based on data provided by a concrete batcher in the region, the emissions of concrete with two different characteristic strengths were determined, in addition to steel and wood formworks. In general, it was observed that these values are significantly different from those obtained in a study conducted in another city in the southern region, evidencing the influence of factors such as distances and dosage of concrete. Mainly due to the greater amount of cement used, the 35MPa concrete presented emissions about 20% higher than the 20MPa concrete.

The emission values obtained were used in the optimization of beams and columns, considering the emissions of concrete, steel, and formworks. In general, it was observed that in columns it is interesting to use higher-strength concrete. To the beams, on the contrary, the lowest total emissions were obtained with concrete of lower strength.

Finally, the influence of the concrete carbonation process on total CO_2 emissions was evaluated. It was observed that, invariably, the percentage absorbed compared to that emitted is quite significant, and must be considered in the global assessment of impacts. It is interesting to observe that the lower strength concrete, even producing the lowest emission per unit volume, is also the one that absorbs the most CO_2, which increases its positive impact compared to the higher strength concrete.

In general, the present study aimed to identify the main factors that influence the impacts produced by reinforced concrete structures, as a subsidy for the designers and decision-makers. In addition to the results presented, it is suggested as a guideline for the mitigation of impacts the study of substitutes for portland cement, as well as the use of raw materials that require a shorter transport distance.

As a continuation of the study, concretes with other characteristic strengths will be evaluated, as well as the influence of the selected impact category on the results. In addition, although the behavior regarding carbonation agrees with the observed in the literature, it is important to deepen the studies related to factors that allow a better estimate that total percentage of reduction.

Although the present study was developed with data obtained for a specific region of the country, it is understood that the proposed methodology can be easily adapted to other locations.

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Author contributions: JJA and MK: conceptualization, methodology, formal analysis, writing; JFS: methodology, formal analysis

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