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Minimizing environmental impact from optimized sizing of reinforced concrete elements

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Abstract. The construction field must always explore sustainable ways of using its raw materials. Studying the environmental impact generated by reinforced concrete raw materials during their production and transportation can contribute to reducing this impact. This paper initially presents the carbon dioxide emissions from reinforced concrete raw materials, quantified per kilo of raw material and per cubic meter of concrete with different characteristic strengths, for southern Brazil. Subsequently, reinforced concrete elements were optimized to minimize their environmental impact and cost. It was observed that lower values of carbon dioxide emissions and cost savings are generated for less resistant concrete when the structural element is a beam, and that reductions in the cross section dimensions of the beams, sized based on the use of higher strength concrete, may not compensate for the increased environmental impact and costs. For the columns, the behavior differed, presenting lower values of carbon dioxide emissions and costs for higher concrete strengths. The proposed methodology, as well as the results obtained, can be used to support structural projects that have less impact on the environment.

Keywords: environmental impact; reinforced concrete; CO_2 emission; optimization; structures

1. Introduction

Concern for the environment is increasing, either by spontaneous awareness or by current legislation, demonstrating an evolution in the treatment of issues related to environmental impact. Bringing this culture to all companies producing large- and small-scale construction materials, as well as to designers, can greatly contribute to minimizing the environmental impact generated by reinforced concrete structures.

To minimize the damage to the environment and human health, several methodologies have been employed to study the environmental impact of buildings, including the Life Cycle Assessment (LCA), which is a method that allows for a detailed study of all stages of the building, from the extraction and production of materials, construction, use, and maintenance to the end of the service life (demolition and landfill or possible recycling).

There are several ways to assess environmental impact, with CO_2 emissions being one of the most used. According to Gan *et al*. (2019), the construction sector generates one third of global greenhouse gas emissions, with the embedded CO_2 in reinforced concrete being recognized as a significant source of these emissions. Therefore, developing low-carbon reinforced concrete construction is an important strategy for achieving long-term sustainability in cities.

The data on CO_2 emissions corresponding to building materials varies significantly, depending on the life cycle assessment, the country, and the time of the data collection. Data found in the recent literature indicates that the percentage difference in CO_2 emissions for concrete and steel, as two typical building materials, were 267% and 863%, respectively. These variations cause significantly different results in the search for sustainable structures (Oh *et al*. 2017).

The importance of obtaining data specific to the place of production of the materials is related to the energy matrix, which directly influences emissions. In European countries, the average carbon dioxide emission for the production of 1 kWh of energy is 0.475 $kgCO_2$, ranging from zero for Norway, where hydropower energy is mostly used, to 0.753 $kgCO_2$ in Denmark, where coal is the main source of power generation (Pommer and Pade 2005). In Brazil, the National Energy Balance (2018) indicates that the average emission of carbon dioxide for the production of 1 kWh is 0.1044 $kgCO_2$.

Hájek *et al*. (2011) in their study show that the use of optimized concrete structures could potentially increase the quality of construction and consequently reduce its environmental impact. Thus, any improvement in concrete design principles, evaluation methodologies, and construction and demolition technologies, and the management of the operation and use of concrete, greatly contributes to the overall objective of sustainable development.

It was observed a growing application of optimization techniques to civil engineering, especially in the last decades (Dede *et al*. 2019), related to different structures such as bridges (Bolideh *et al*. 2019), buildings (Boscardin

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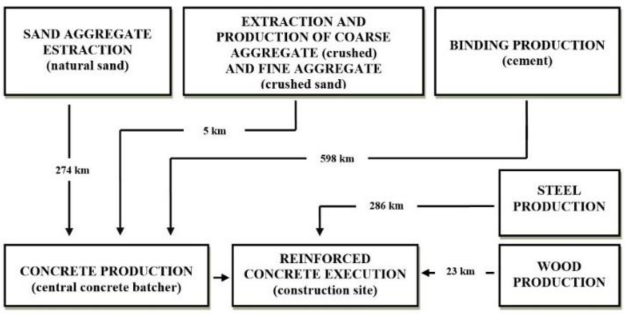

Fig. 1 Raw material displacement distances

Table 1 CO_2 emissions from the raw material

Raw material	CO_2 Emissions		
	Extraction/Production	Transport	Total
Coarse Aggregate (gCO_2/Kg)	4.22	0.57	4.78
Natural Fine Aggregate (gCO_2/Kg)	3.46	23.24	26.70
Crushed Fine Aggregate (gCO_2/Kg)	4.22	0.62	4.84
Binder (gCO_2/Kg)	371.00	47.18	418.18
Steel (gCO_2/Kg)	1014.00	31.24	1045.24
Wood (gCO_2/m^3)	38124.89	6652.11	44777.00

et al. 2019) and earth-retaining walls (Molina *et al*. 2017). In recent years, several studies aiming to reduce the environmental impact of reinforced concrete structures have been conducted. Among the studies that employ optimization techniques, those by Payá-Zaforteza *et al*. (2009), Yeo and Gabbai (2011), Yepes *et al*. (2012), Park *et al*. (2013), Medeiros and Kripka (2014), Kim *et al*. (2016) can be highlighted. As expected, the results differ depending on the country and the parameters considered. However, all the authors are unanimous in highlighting the importance of employing optimization techniques to achieve effectively sustainable structures. Moreover, it is observed that, from the studies carried out, a small portion refers to the sizing of the structures. Considering the different phases of the life cycle, Santoro and Kripka (2017) found that the main lines of study are mostly (approximately 50%) distributed in the concrete production phase, taking into account its strength and the cement additions, 31% in the design phases and the remaining 19% in the broad life cycle, also including the carbonation of the concrete during its service life.

The present work proposes the optimization of structural reinforced concrete elements based on the data obtained for the study region (southern Brazil). Initially, a survey was carried out to understand the CO_2 emissions generated by concretes of different characteristic strengths and steels and wood used in the extraction, production, and transport phases of the raw materials, and also those generated during concrete production in a concrete batcher and transportation to the site. Then, to create structures that have less impact on the environment, an optimized design of reinforced concrete beams and columns was carried out, according to the emission parameters obtained in the study and, in parallel, in relation to the costs. Behaviors related to the environmental impact and costs resulting from the use of different concrete characteristic strengths are presented, with the purpose of identifying parameters that can be employed by designers in the sizing of these elements.

2. CO_2 emissions from the extraction, production, and transport of raw materials, and the production and transport of reinforced concrete to the site

The study on the environmental impact of reinforced concrete structures was conducted with the raw materials used by a concrete batcher, which is located in the southern region of Brazil with displacement distances as shown in Fig. 1.

Subsequently, the methodology used to determine the environmental impact in terms of CO_2 emissions for the different materials, as well as the corresponding values, was briefly described. This allowed for a more detailed verification of the phases defined in Santoro and Kripka (2016).

The study considered the CO_2 emissions generated by the fuel and electric energy consumptions of the machines and equipment involved in all the processes. The CO_2 emission values for fuels (diesel and gasoline) were obtained from the National Inventory of Atmospheric Emissions by Road Motor Vehicles (2014), and the CO_2 emission values from the production of electric energy consumed in the processes were obtained from the National Energy Balance. (2018).

The survey considered the extraction, production, and storage activities at the mining companies, as well as the transportation of the coarse aggregate (gravel), natural fine aggregate, (sand) and crushed fine aggregate (crushed sand).

The CO_2 emissions from the formwork were obtained from the phases of planting, handling, cutting, processing, and transportation the wood.

Regarding the stages of production of the binder (cement) and the steel, data from the Second Brazilian Inventory of Emissions and Anthropic Removal of Greenhouse Gases-Industrial Processes for Cement and Iron and Steel Metals Production (2010) was used; CO_2 emissions from their transportation were calculated from the distances to be traveled to the concrete batcher and the construction site.

The final values of CO_2 emissions, obtained from the extraction/production of raw materials and transport, are presented in Table 1 below.

From the data in Table 1, it can be observed in Fig. 2 that the transport of raw materials, even with some considerable displacement distances, represents less than 15% of the final total values. Fig. 2 also presents the transport contribution, considering the duplicated distances. Even so, the transport share still accounts for a maximum of about 26% of the total emissions. An exception is observed only for the natural fine aggregate (sand) because the extraction/production of CO_2 emissions values is low for this aggregate when compared to those of other raw materials that have large displacement distances.

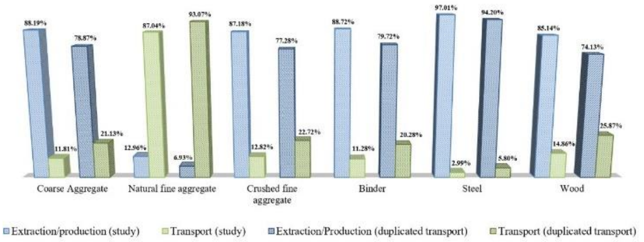

Fig. 2 Transport contributions to CO_2 emissions

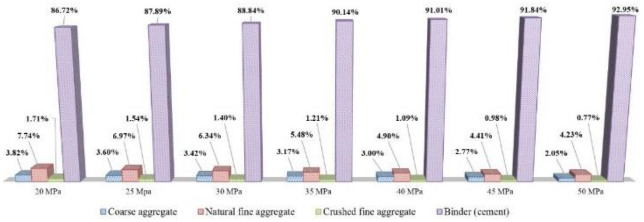

Fig. 3 CO_2 emissions contribution for one cubic meter of concrete

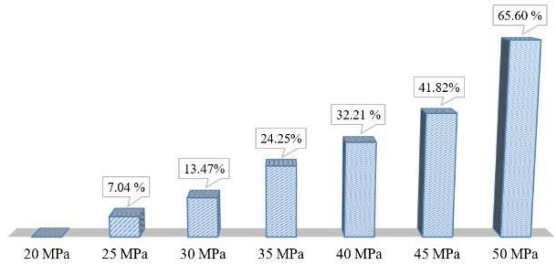

Fig. 4 Increased CO_2 emissions with increased concrete strength

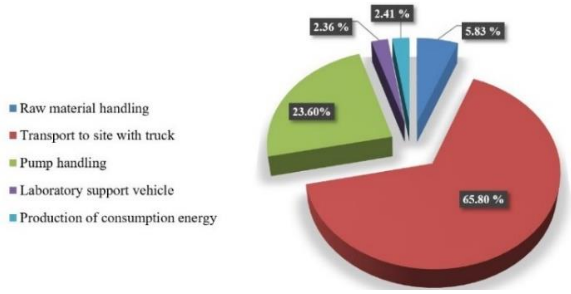

Fig. 5 Contributions of the production process steps

Finally, with the surveys of each raw material, the CO_2 emissions were calculated from the batching plant guidelines for the production of one cubic meter of concrete samples with different characteristic strengths, and these are presented in Table 2.

The contribution of each raw material used in the production of the concrete samples with different characteristic strengths to CO_2 emissions, can be seen in Fig. 3, where the binder is the largest contributor, reaching values close to 93% of the total.

Fig. 4 illustrates the percentage variation of emissions for different strengths, considering the 20 MPa concrete as a reference. A significant increase in emissions for higher strength concretes can be observed, which can reach a maximum of 65.60%.

The influence of the different raw material transport distances was evaluated for the production of one cubic meter of concrete with different characteristic strengths. It was found that doubling the distances generates an increase in the final emissions of between 14 to 18%.

In addition to the CO_2 emissions from the raw materials used in the production of reinforced concrete, the CO_2 emissions generated in the production processes and transport from the batching plant to the construction site were quantified (Table 3), and the contribution of each step in the process was verified, as shown in Fig. 5.

By adding the CO_2 emissions values of the raw materials for different concrete characteristic strengths to the values generated by the batcher in the production and transport of the concrete, we obtained the final values of the CO_2 emissions for the study region (Table 4).

3. Optimization of reinforced concrete elements to minimize environmental impact and costs

As higher strength concretes will be used in smaller volumes, conclusions about the possible advantage of using one strength value or another should be based on the appropriate sizing of the structural elements. In this sense, the results obtained from the cross-section optimization of concrete beams and columns according to the environmental impact criteria are presented, based on the values determined through the methodology previously described and the costs in the study region.

In all cases, the objective was to minimize the CO_2 emissions and also the total cost of the section, which is related to the costs of concrete, the steel, and the wood formwork.

The CO_2 emission values considered for the structural materials are those shown in Table 4, with concrete given per unit volume, steel in newtons, and shape in square meters.

The cost values considered for structural materials in Table 5 are averages for the market in the study region.

Table 2 CO_2 emissions for each cubic meter of concrete

Raw Material	20 MPa $KgCO_2/m^3$	25 MPa $KgCO_2/m^3$	30 MPa $KgCO_2/m^3$	35 MPa $KgCO_2/m^3$	40 MPa $KgCO_2/m^3$	45 MPa $KgCO_2/m^3$	50 MPa $KgCO_2/m^3$
Coarse Aggregate	4.99	5.03	5.07	5.15	5.18	5.14	4.44
Natural Fine Aggregate	10.12	9.75	9.40	8.89	8.47	8.17	9.16
Crushed Fine Aggregate	2.24	2.16	2.08	1.96	1.88	1.81	1.66
Binder	113.33	122.94	131.73	146.36	157.24	170.20	201.14
TOTAL Emissions	130.68	139.88	148.27	162.37	172.76	185.32	216.40

Table 3 Central batcher CO_2 emissions

Pan Loader $KgCO_2/m^3$	Truck concrete mixer $KgCO_2/m^3$	Pressure pump $KgCO_2/m^3$	Support Vehicle $KgCO_2/m^3$	Electric Energy $KgCO_2/m^3$	TOTAL $KgCO_2/m^3$
0.55	6.17	2.21	0.22	0.23	9.38

Table 4 Final CO_2 emission values

Material	CO_2 Emissions
Concrete - 20 MPa	140.05 $KgCO_2/m^3$
Concrete - 25 MPa	149.26 $KgCO_2/m^3$
Concrete - 30 MPa	157.65 $KgCO_2/m^3$
Concrete - 35 MPa	171.74 $KgCO_2/m^3$
Concrete - 40 MPa	182.14 $KgCO_2/m^3$
Concrete - 45 MPa	194.70 $KgCO_2/m^3$
Concrete - 50 MPa	225.78 $KgCO_2/m^3$
Steel - CA 50 / CA 60	1.05 $KgCO_2/Kg$
Formwork	1.78 $KgCO_2/m^2$

Table 5 Reinforced concrete costs in the study region

Material	Cost
Concrete - 20 MPa	330.00 R$/m³
Concrete - 25 MPa	350.00 R$/m³
Concrete - 30 MPa	360.00 R$/m³
Concrete - 35 MPa	370.00 R$/m³
Concrete - 40 MPa	390.00 R$/m³
Concrete - 45 MPa	400.00 R$/m³
Concrete - 50 MPa	420.00 R$/m³
Steel - CA 50	3.82 R$/Kg
Steel - CA 60	4.15 R$/Kg
Wood formwork	28.05 R$/m²

3.1 Optimization of reinforced concrete beams

For the optimized design of the beams, the software employed by Medeiros and Kripka (2013) was used. The software, developed in the Fortran language, associates the matrix structural analysis by the Displacement Method with the Simulated Annealing optimization method, a heuristic developed by Kirkpatrick *et al*. (1983) in analogy to the process of metal annealing. In the analysis, the beams can be considered in isolation or forming a grid.

The formulation of the problem aims at minimizing the total cost of the beam, and in the present work, was also adapted to minimize the environmental impact. The design variables consist of the height or groups of the elements, considering only discrete values and complying with the restrictions regarding the ultimate serviceability limit states, these being: checking the maximum sagging of each element considering the long term effects, the maximum crack width, the minimum and maximum rates of reinforcement in relation to the cross-sectional area, and the verification of the shear, torsion and both combined, as well as the minimum steel rate for both effects, according to the Brazilian Norm ABNT NBR-6118/2014. A detailed formulation and computational implementation can be obtained from Medeiros and Kripka (2013).

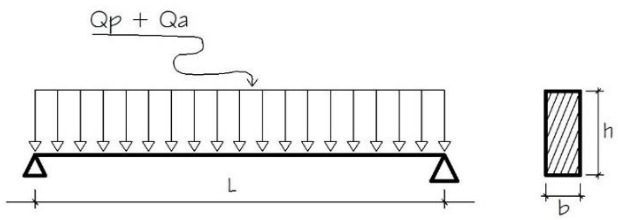

Fig. 6 Optimized simply supported beam

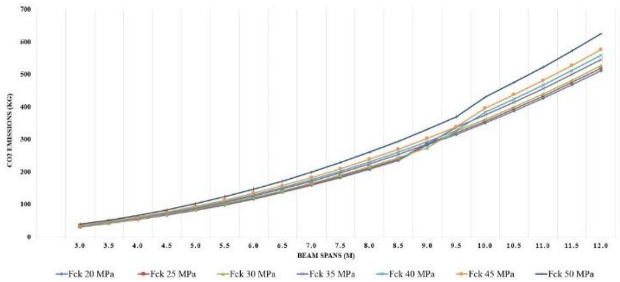

Fig. 7 CO_2 emissions from optimized reinforced concrete beams

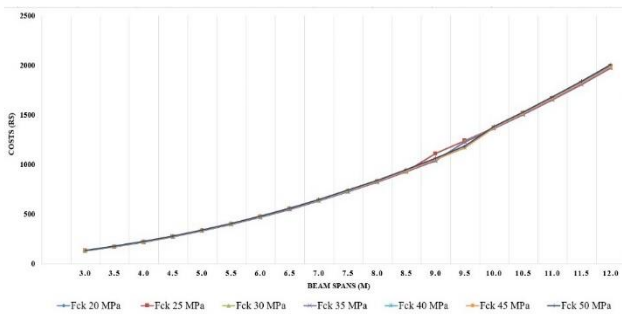

Fig. 8 Costs of optimized reinforced concrete beams

The objective function is composed of CO_2 emissions and costs of steel in mass (kg), concrete in volume (m^3), and forms in area (m^2), given by Eq. (1), where C_t corresponds to the emission or total cost of the beam analyzed, P_A, P_{aw}, A_F, and V_C refer to material quantities (500 MPa steel weight, 600 MPa steel weight, area of formwork and volume of concrete), while C_A, C_{Aws}, C_F and C_C represent the CO_2 emissions obtained in the present study, or average unit costs of the study region for each material (longitudinal reinforcement, transversal reinforcement, formwork and concrete, respectively).

$$C_t = [(P_A + P_{Asw}).C_A] + (A_F.C_F) + (V_C.\ C_C) \quad (1)$$

Two-way beams with free spans (*L*) ranging from 3 to 12 m in 0.5 m increments were studied. The initial design height (*h*) for all beams was taken approximately as one tenth of their free span. The adopted width (*b*) of the beams was fixed at 0.2 m. The permanent load used was 9.5 kN/m (*Qp*) and the live load 2.0 kN/m (*Qa*), according to Fig. 6. In this case, the problem was restricted to a single project variable.

The results obtained from the optimized sizing taking into account CO_2 emissions, and the costs for each of the different concrete strengths can be seen in Figs. 7 and 8, respectively, where the variations in the function values are observed for the different spans considered.

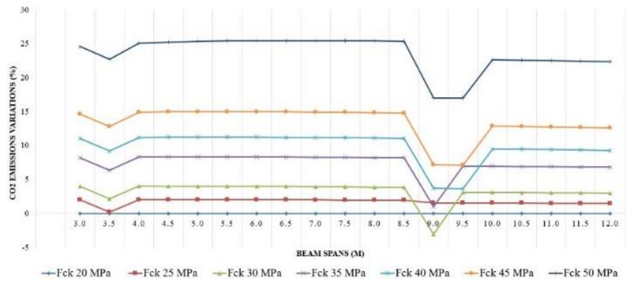

Fig. 9 CO_2 emissions variations with increasing resistance

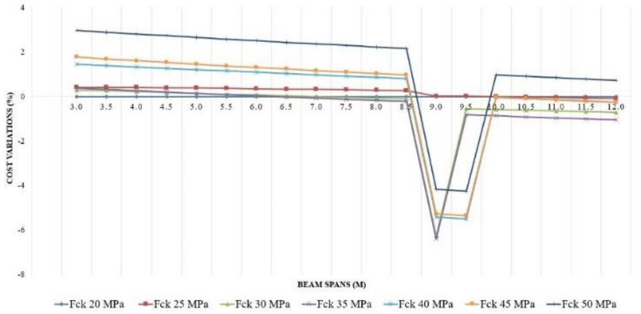

Fig. 10 Cost variations with increased strengths

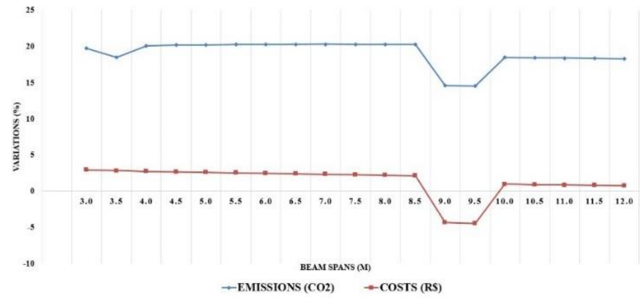

Fig. 11 CO_2 emissions and cost variations

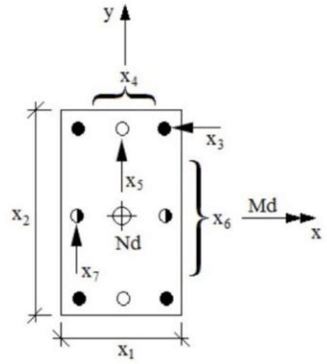

Fig. 12 Design variables

When analyzing the variations in CO_2 emissions from the increase in the design strength, it can be seen in Fig. 9 that beams optimized with lower concrete strength generate lower CO_2 emissions, and that each increase in strength tends to generate an increase in emission variations. An oscillation of variation (decrease) values is also observed in the spans between 9 and 10 m, owing to the use of skin reinforcement in the beams.

Fig. 10 shows that the cost variations are smaller than those of CO_2 emissions, indicating that the lower strengths generate lower costs for beams with spans of up to 8.5 m. There is also fluctuation (decrease) in the values in the spans between 8.5 and 10 m, owing to the use of skin reinforcement. For larger spans, from 10 m onwards, there is a tendency for higher strength values to improve in relation to the costs, with the exception of the 50 MPa strength, which for all spans has the highest cost.

For the values considered, it was observed that invariably, the best situation corresponds to the lower strength concrete, and this behavior can be verified from Fig. 11, where the CO_2 emissions and cost variations are presented for the comparison between the lowest and highest strengths of the studied concrete.

Overall, for both environmental impact and cost minimization, the optimized section reinforcement rates were very close to the minimum required by the standard. This is true even for higher loads, considering the same spans and characteristic strengths.

3.2 Reinforced concrete column section optimization

The cost and environmental impact minimizations were also evaluated for sections of reinforced concrete columns subjected to uniaxial bending. For the present study, a base program developed by Bordignon and Kripka (2012) was used that associated the optimization with the use of the Simulated Annealing method with a routine for the verification of the columns' strength capacity.

The formulation of the optimization problem was based on consideration of some input parameters, i.e., stresses acting on the section (Nd and Md), the characteristics of the materials involved, and the CO_2 emissions or costs. The stresses Nd and Md are the final values adopted for the verification, without any amplification due to column slenderness. The design variables were considered as discrete, with the values related to the concrete cross-section sizing (x_1 and x_2) varying with each centimeter and the reinforcement areas, quantities, and arrangement (x_3, x_4, x_5, x_6, and x_7) limited to commercial values, as shown in Fig. 12. The dimensions b and h (x_1 and x_2) are discrete variables represented by the intervals $b \in (20, ..., 200)$ and $h \in (20, ..., 1000)$. Lower values were indicated by standards and the higher values were large enough so as to prevent them to interfere in the optimal solution. The variables x_3, x_5 and x_7 represent the longitudinal steel bars, and were restricted to the following diameters, in mm: 10.0, 12.5, 16.0, 20.0, 22.0, 25.0, 32.0 and 40.0.

The objective function seeks to find a configuration for the column section that corresponds to the minimum cost or environmental impact and, at the same time, allows the generated section to withstand the applied stresses and to meet the limits specified by the Brazilian Standard ABNT NBR-6118/2014, which is related to the strength criteria and construction provisions.

Therefore, the emission or cost function to be minimized in the optimization process considers the emissions or total cost of concrete, steel, and wood materials, which can be expressed by Eq. (2).

$$F = (A_{con}).\ Cc + (A_{s\ Total}).\ C_s + 2.\ (b+h).\ C_f \qquad (2)$$

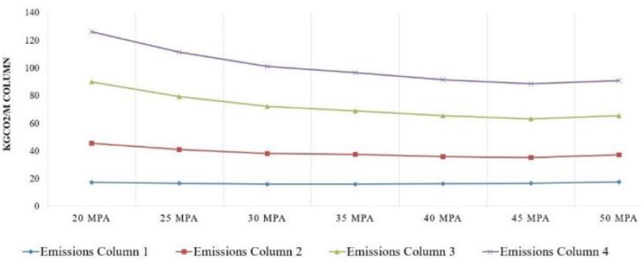

Fig. 13 CO_2 emissions for each concrete characteristic strength

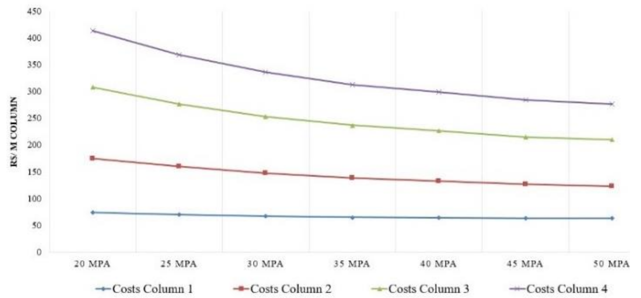

Fig. 14 Costs for each concrete characteristic strength

Table 6 Values of stresses in the sections

COLUMN	N (kN)	M (kN.cm)
P1	500	6250
P2	2250	28125
P3	5000	62500
P4	7250	90625

The first portion of the function represents the emissions or cost of concrete, where C_c is given per unit volume; the second represents the emissions or cost of the longitudinal reinforcement, where C_s is given by unit of mass and $\mathbf{g}_s$, the specific weight of steel; and the last portion represents the emissions or cost relative to the form, where C_f is given per unit area. All provide a relative value for each unit of optimized element length.

In this manner, the final formulation to be employed in the process can be rewritten as a function of the variables according to Eq. (3).

From this formulation, the CO_2 emissions and costs of four column sections were optimized with the acting and increasing stresses indicated in Table 6.

$$\text{Minimize } F(x) = (x_1.x_2).\ C_c + (4.x_3 + 2.x_4.x_5 + 2.x_6.x_7).(\boldsymbol{\pi}/4).\ \mathbf{g}_s.C_s + 2.(x_1+x_2).C_f \quad (3)$$

The behavior of the final values obtained in the optimization of the CO_2 emissions and reinforced concrete costs per linear meter of column, varying the characteristic strength of the concrete and the acting forces, are presented in Figs. 13-14. These values presented, in both cases, optimized section reinforcement rates very close to the minimum required by the standard.

When analyzing the variations in CO_2 emissions from the increase in strength, it can be seen in Fig. 15 that most columns made with higher strength concrete generate lower CO_2 emissions, with the best result obtained for the 45 MPa concrete strength. It is also noted that the increase in the forces acting on the column together with the increase in the concrete characteristic strength, cause a greater variation in the CO_2 emissions.

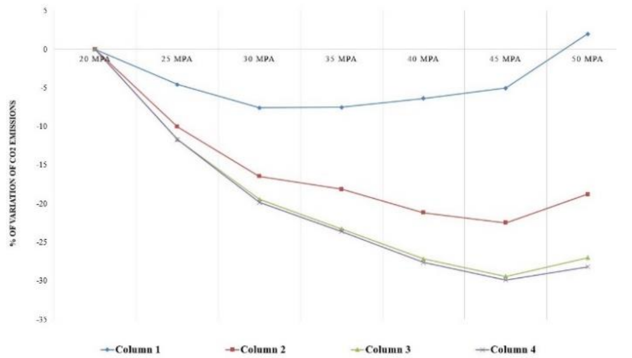

Fig. 15 CO_2 emissions variations with increasing concrete strength

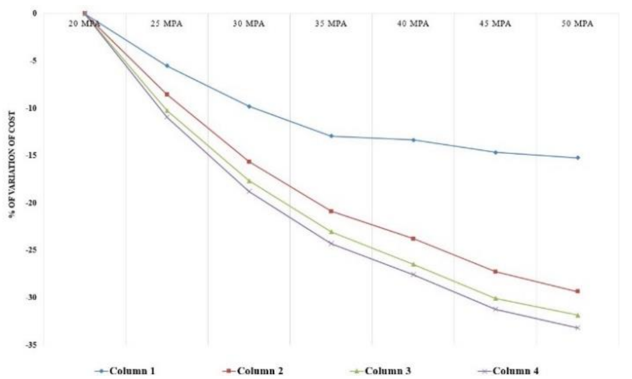

Fig. 16 Cost variations with increased strength

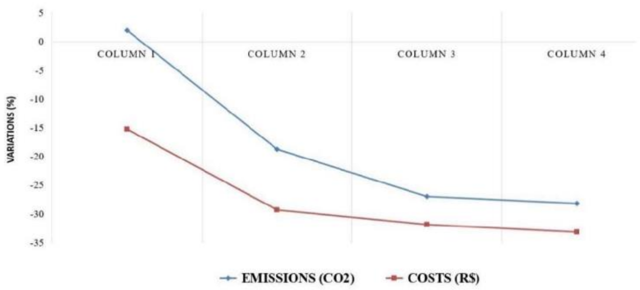

Fig. 17 CO_2 emissions and cost variations

The cost variations with the increase in the concrete strength are presented in Fig. 16, showing a similar behavior to that of the CO_2 emissions, with the higher strength generating a lower production cost, but with larger variation percentages. Likewise, the increase in the stresses acting on the column together with the change in the concrete characteristic strength, results in an increase in the cost variations.

Finally, the variation in the CO_2 emissions and costs were corroborated when comparing the results of the smallest and the highest concrete strengths studied, as shown in Fig. 17. It was observed that the most satisfactory results correspond to the use of the highest concrete strength, and that columns with higher acting stresses ($P4$) present these larger variations in percentage terms.

4. Conclusions

The objective of the present work was to optimize reinforced concrete elements, beams and columns based on data obtained for the study region. To this end, the environmental impact generated by steel, wood formwork, and concrete of different strengths in the extraction, production, and transport phases, measured in terms of carbon dioxide emissions, were determined. Subsequently, these elements were optimized according to the parameters obtained and the costs of the study region.

In general, it was observed that the results obtained are highly dependent on the parameters employed, as well as on the origin of this data, which justifies the need to obtain actual values for the region under study.

Evaluating the results obtained for the region under study, it can be concluded that producing concrete with higher characteristic strength will generate a greater amount of CO_2 in the environment, and a variation of up to 65.60% can occur when comparing the lowest and the highest strengths.

By optimizing the beams' sections, both in relation to CO_2 emissions and costs, it is shown that even when using higher strength concrete in smaller volumes, the environmental impact and costs are still high. It was also found that the reinforcement rates for the optimized sections, in both cases, remain close to the standard minimums.

As for the optimized column sections, it was observed that when higher strength concrete is used, lower values of both CO_2 emissions and costs are obtained.

The relationships obtained seek to support the design of low-cost structures that have minimal impact on the environment. Given that beams and columns are just some of the component elements of building structures, an evaluation of the global behavior of the building in terms of environmental impact would be interesting.

The values obtained from the present study are for a specific country and region. Therefore, to obtain the exact values for other regions, it is important that specific emissions are determined. However, it is understood that the methodology employed here can be easily adapted, and furthermore, it is believed that the conclusions regarding the behavior of each structural element should not vary much between regions of study.

In this study the optimization was performed by using the Simulated Annealing method, once it was adopted successfully by the authors in several previous studies. On the other hand, it is growing the use of other new heuristics to structural optimization, such as Jaya (Dede 2018) and Teaching Learning Based Optimization (Bolideh *et al.* 2019).

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