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ORIGINAL ARTICLE

Reduction of the environmental impacts of reinforced concrete columns by increasing the compressive strength: a life cycle approach

Redução dos impactos ambientais de pilares de concreto armado ao aumentar a resistência à compressão: uma abordagem de ciclo de vida

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Abstract: The building industry is one of the greatest environmental impact causers in the planet. Cement is the second most used material in the world and the consumption of concrete ranges between 20 to 30 Gt yearly. This demand for the materials ten ds to increase for the next 100 years. The increase of concrete strength to reduce the material consumption is one of the options proposed in literature to reduce the environmental impacts in building industry. However, few studies have been carried about the actual advantages of this strategy in building production. In this paper, a 15-storey reinforced concrete building was designed with three different concrete grades for its columns: 30 MPa, 40 MPa and 50 MPa. The results for the volume of concrete and the amount of reinforcing steel to produce the columns were used to perform a cradle-to-gate life cycle assessment (LCA) to determine the alternative with less environmental impacts in the production stage. Results indicate an advantage to adopt higher strength concretes in columns to reduce environmental impacts and the consumption of materials. Direct effects of higher strength in concretes made possible to reduce the consumption of concrete by 15%. There was also a significant reduction caused by indirect effects of higher strengths in concrete, with the reducing of steel consumption up to 22%. With the combination of the direct and indirect effects of higher compressive strengths, it was possible to reduce the environmental impacts of reinforced concrete in all categories studied in the LCA.

Keywords: reinforced concrete, life cycle assessment, sustainability, concrete columns.

Resumo: A indústria da construção é uma das maiores causadoras de impactos ambientais do planeta. O cimento é o segundo material mais utilizado no mundo e o consumo de concreto varia entre 20 a 30 Gt por ano. Isto faz com que a demanda pelos materiais apresente uma tendência de aumento durante os próximos 100 anos. O aumento da resistência do concreto para reduzir o consumo de materiais é uma das opções propostas na literatura para reduzir os impactos ambientais na indústria da construção. No entanto, poucos estudos têm sido realizados sobre as vantagens reais desta estratégia na construção de edifícios. Neste artigo, um edifício de concreto armado de 15 andares foi dimensionado com três tipos diferentes de concreto para os pilares: 30 MPa, 40 MPa e 50 MPa. Os resultados para o volume de concreto e a quantidade de aço de armadura para produzir os pilares foram utilizados para realizar uma avaliação do ciclo de vida (ACV) do berço ao portão da fábrica para determinar a alternativa com menos impactos ambientais na fase de produção. Os resultados indicam uma vantagem em adotar concretos de maior resistência em pilares de concreto armado para reduzir os impactos ambientais e o consumo de materiais. Os efeitos diretos da maior resistência dos concretos tornaram possível reduzir o consumo de concreto em 15%. Houve também uma redução

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Conflict of interest: Nothing to declare.
Data Availability: The data that support the findings of this study are openly available in Scielo Data in https://doi.org/10.48331/scielodata.BXKHHP.

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significativa causada pelos efeitos indiretos da maior resistência dos concretos, com a redução do consumo de aço até 22%. Com a combinação dos efeitos diretos e indiretos da maior resistência à compressão, foi possível reduzir os impactos ambientais do concreto armado em todas as categorias estudadas na ACV.

Palavras-chave: concreto armado, avaliação do ciclo de vida, sustentabilidade, pilares de concreto armado.

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1 INTRODUCTION

Concrete is one of the most consumed materials in the world. It is estimated a consumption of concrete between 20 to 30 Gt yearly [1], [2]. Cement, the main material of concrete, is most used manufactured material in the world and responsible for large CO_2 emissions. In Brazil, the cement industry was responsible for 23.144 kt of CO_2 emissions in the industrial processes and product use (IPPU) sector in 2020, which represents 22.7% of the emissions from this sector [3].

The production of cement in Brazil is greener than the average worldwide. The estimated CO_2 emissions from cement in Brazil are 564 kg/ton, against the world average of 635 kg/ton [4]. However, efforts aiming to reduce environmental impacts in the construction and cement industry still should be taken.

For the last decades, the demand for cement and concrete was increased and the projected urbanization for the next 100 years is an indicative that this demand will continue to increase for that period. Thus, it is necessary to study strategies to limit the environmental impacts of concrete constructions [5], [6].

Steel, necessary for reinforcement bars in concrete, has a total production of 1.5 Mt yearly. Global steel production is estimated to be around 2.6 $GtCO_2$ per year [7]. Steel production is dependent on non-renewable fuels, making it a material with use of fossil energy and high emissions of CO_2 in the atmosphere [8].

Many alternatives have been proposed to make the concrete and cement industries more sustainable, such as the use of supplementary cementitious materials (SCM) [9]–[11], recycled concrete [9] and the optimization of the mixing design process [12]. Mehta [6] presents three tools to achieve sustainability in concrete and cement industries: (1) to consume less concrete in new structures, (2) to consume less cement in concrete mixtures and (3) to consume less clinker for making cements, as seen in Figure 1. Reducing the concrete volume by enhancing the concrete performance may be one option to reduce the environmental impacts in the building industry. By increasing the concrete strength, less concrete and reinforcing bars will be necessary in building production [13], which may lead to the reduction of environmental impacts.

The production of higher strength concretes has been increasing in the last years to improve the performance of the structures [14]–[16]; however, the increased strength is achieved by higher amount of cements, which increase the environmental impacts of the concrete mixture.

Different studies found in literature use the strategy of increasing the concrete strength to reduce the environmental impacts by assessing the impacts of individual columns [17], bridge girders [18] or variations of both design strategies and the adoption of different compressive strengths along the length of the columns [19].

Increasing the concrete strength will certainly reduce the cross section of the structural members and the volume of concrete and consumption of steel in reinforced concrete buildings. The consumption of concrete and reinforcing steel can be reduce by 5.4% and 38.6%, respectively, changing the compressive strength of RC columns from grade C30 to grade C60 [13].

However, as cement is the main contributor for CO_2 emissions of concrete, it is important to quantify and verify if the reductions of material consumption are enough to compensate the higher environmental impacts from the higher amount of cement in the concrete mixture.

Life cycle assessment (LCA) is a powerful sustainability assessment tool to quantify the environmental impacts of a product or a system [20]. The LCA methodology is based on ISO 14040 [21]. LCA is considered to be one promising technique more ecological design of products [22].

This study aims to evaluate the feasibility and validity of the option to increase compressive strength of concrete to lower the environmental impacts of the structure. A reinforced concrete (RC) residential building was designed with columns in three different concrete grades of strength (f_{ck}s) to obtain the quantitative results of volume of concrete and steel reinforcement weight. With the quantitative values, a LCA was performed to assess and compare the environmental impacts for the different scenarios considered and the contribution of each material present in reinforced concrete in different impact categories.

2 METHODOLOGY

2.1 Building design

The object of study of this paper was based on an architectural design of a 15-store RC residential building (Figure 1) located in Belo Horizonte, Minas Gerais, Brazil. Building design was performed using Cypecad software. The design of the structure followed the method stablished by Brazilian standard NBR 6118 [23].

Three different models were designed with different concrete characteristic strengths for columns (f_{ck}s): 30 MPa (C30), 40 MPa (C40) and 50 MPa (C50). Slabs and girders defined with compressive strengths of 30 MPa for all the situations, as shown in Table 1.

To determine service loads of the building, this study followed de recommendations of NBR 6120 [24]. The procedures presented by NBR 7480 [25] were followed for requirements of reinforcing steel bars in structural members. For combinations of actions in the structure, the methods presented in NBR 8681 [26] were adopted. For wind load, a speed of wind of 35 m/s was considered for the city of Belo Horizonte MG, following the procedures of NBR 6123 [27].

For reinforcement of the structural members, the area of steel reinforcement (A_s) was defined as the minimum calculated area of steel reinforcement (A_{smin}). Detailed information and the calculation logs of this study are openly available in Scielo Data.

Table 1. Compressive strengths of structural members

Model	Slabs	Girders	Columns
C30	30 MPa	30 MPa	30 MPa
C40	30 MPa	30 MPa	40 MPa
C50	30 MPa	30 MPa	50 MPa

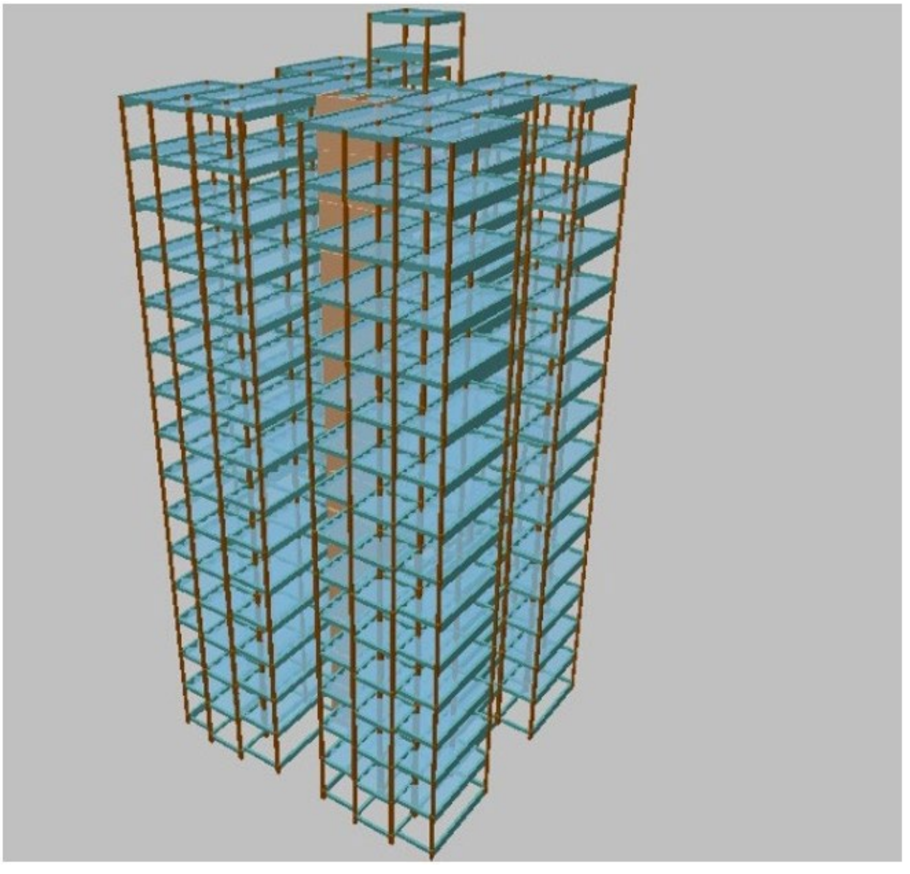

Figure 1. Structural model of the residential building

After verification and error correction of the structure, quantitative tables were generated to obtain the values of concrete consumption (m^3) and the weight of reinforcement (kg) to produce the columns. From this, it was possible to compare the variations of concrete materials (cement, sand, gravel, water and superplasticizer) and steel reinforcement with the changes in the f_{ck}.

2.2 Concrete mix design

To achieve the goal of this study, the definition of concrete composition was necessary for each design model developed in 2.1. The mix design is presented in Table 2.

The mix design was produced following the method presented by Thomaz [28]. In this method, data from over 200 concrete mixes available in the literature were selected to perform correlations between water/cement ratio, water amount, aggregates, superplasticizers and compressive strength. From this, it was possible to estimate the amount of materials to achieve the desired f_{ck}s.

The compressive strength (f_c) to achieve the desired f_{ck}s was used as the input to obtain the quantitative of cement, sand, gravel, water and superplasticizer in a Microsoft Excel spreadsheet. The mix design data from the spreadsheets are available in Scielo Data.

Equation 1 gives the relation between fc and f_{ck}:

$$f_c = f_{ck} \times 1.65 \times sd \quad (1)$$

Where,

f_c: Target mean compressive strength of the concrete mixture;

f_{ck}: Characteristic compressive strength of the concrete mixture;

sd: Standard deviation of the distribution, defined as 4 with a better technological control in the production.

Table 2. Mix design formulations for the concrete columns

Components	C30	C40	C50
Cement (kg/m^3)	345	394	432
Gravel (kg/m^3)	1042	1057	1067
Sand (kg/m^3)	751	733	721
Water (kg/m^3)	186	178	171
Superplasticizer (kg/m^3)	0	0,1	3,3

2.3 Life Cycle Assessment (LCA)

The LCA was performed in four steps, as recommended by ISO 14040 [21]: Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation of the results.

2.3.1 Goal and scope

The LCA performed in this study aimed to quantify and compare the environmental impacts of columns of RC buildings designed and produced with different characteristic strengths (f_{ck}s): 30 MPa (C30), 40 MPa (C40) and 50 MPa (C50). The OpenLCA software was chosen to perform the LCA [29] was chosen for being free and open source and for having the collaboration of researchers from all over the world for the improvements LCA studies, which makes it a transparent tool.

Since the construction phase is the main contributor for the environmental impacts of a building [19], [30], system boundaries were set from cradle to gate, i.e., from material extraction to the finished product. The boundaries and stages considered are indicated in Figure 2.

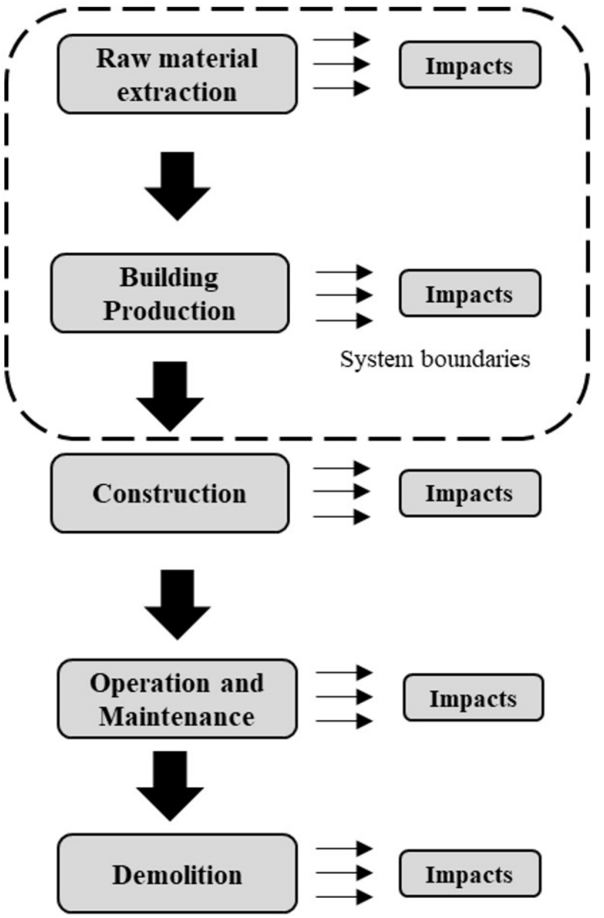

Figure 2. System boundaries of the LCA

Two sets of analysis are presented for a better understand of the impacts in concretes, with two functional unities. First considering a functional unity of 1 m^3 of concrete to analyze the impacts of conventional concrete and the influence of its components in the results.

Additionally, for the second set of analysis, the impacts of the total amount of concrete and reinforcing steel to produce the columns for the building were analyzed. For this purpose, a functional unity of 1 item, equivalent to the total amount of columns combined, was adopted.

2.3.2 Life Cycle Inventory (LCI)

For the LCI, the Ecoinvent database was used to provide the inventory for the materials of this study. The processes used LCI are shown in Table 3.

Table 3. Processes in the Life Cycle Inventory

Material	Process
Cement	market for cement, Portland | cement, Portland | APOS,U - RoW
Gravel	market for gravel, crushed | gravel, crushed | APOS,U - RoW
Sand	market for silica sand | silica sand | APOS,U - GLO
Water	market for tap water | tap water | APOS,U - RoW

The superplasticizer inventory is not present in the ecoinvent database. Thus, it was necessary to insert manually the inventory available in the EFCA Environmental Declaration of superplasticizing admixtures [31]. The input of raw materials and the processes used for 1 kg of superplasticizer in the LCA are presented in Table 4.

Table 4. Raw inputs for superplasticizing admixture

Raw material	Value	Process
Coal (g)	62	market for hard coal | hard coal | APOS,U - RoW
Crude oil (g)	91	market for petroleum | petroleum | APOS,U - GLO
Crude oil (g)	74	market for heavy fuel oil | heavy fuel oil | APOS,U - RoW
Natural gas (dm^3)	0.13	market for natural gas, vented | natural gas, vented | APOS,U - GLO
Natural gas (m^3)	0.21	market for petroleum | petroleum | APOS,U - GLO
Water (kg)	7.4	market group for tap water | tap water | APOS,U - GLO

2.3.3 Life Cycle Impact Assessment (LCIA)

The Impact World+ method with an endpoint indicator was chosen for the LCIA step of this study. The method was designed as a joint update to traditional methods IMPCAT 2002+, EDIP and LUCAS and with the goal to create a regionalized method that covers the entire world [32]. The impact categories covered by the method are indicated in Table 5.

Table 5. Impact categories of the Impact World+ LCIA method

Impact Category	Unity
Climate change, long term	kg CO_2 eq (long)
Climate change, short term	kg CO_2 eq (short)
Fossil and nuclear energy use	MJ deprived
Freshwater acidification	kg SO_2 eq
Freshwater ecotoxicity	CTUe
Freshwater eutrophication	kg PO4 P-lim eq
Human toxicity cancer	CTUh
Human toxicity non cancer	CTUh
Ionizing radiations	Bq C-14 eq
Land occupation, biodiversity	m2 arable land eq .yr
Land transformation, biodiversity	m2 arable land eq
Marine eutrophication	kg N N-lim eq
Mineral resources use	kg deprived
Ozone Layer Depletion	kg CFC-11 eq
Particulate matter formation	kg PM2.5 eq
Photochemical oxidant formation	kg NMVOC eq
Terrestrial acidification	kg SO_2 eq
Water scarcity	m3 world-eq

Calculations for all the impact categories available in the methodology were made for this study. However, for further analysis, five impact categories were selected for a deeper look in the results and to understand of the roles of each material in the environmental impacts: climate change (long term), fossil and nuclear energy use, freshwater eutrophication, mineral resources use and ozone layer depletion.

For the first set of the analysis, the m^3 comparison of the three concrete grades, results were detailed for cement, sand, gravel, water and superplasticizer. For the comparison of the columns productions, results were detailed by concrete and reinforcing steel.

2.4 Cement and environmental efficiencies

Cement efficiency is a factor present in different studies to assess the relation of the characteristic strength of the concretes designed and the amount of cement to produce them [17], [33], [34]. Cement efficiency was calculated as the ratio of the cement content in 1 m^3 of concrete and the concrete strength obtained in MPa, as shown in Equation 2:

$$E_c = \frac{C}{f_{ck}} \quad (2)$$

Where,

Ec = Cement efficiency;
C = Cement content for 1 m^3 of concrete;
f_{ck} = Characteristic strength

A parameter called environmental efficiency was also calculated to analyze the results of the LCA. In this case, the results for the Climate change category, i.e., CO_2 emissions, were considered. The environmental efficiency of cement was calculated as follows:

$$Eco_c = \frac{CO_2}{f_{ck}} \tag{3}$$

Where,
Eco_c = Eco-efficiency of cement;
CO_2 = Environmental impacts from the climate change (long term) category.

3 RESULTS AND DISCUSSIONS

3.1 Building Design

For this study, a 15 store residential building was designed and the quantitative results for concrete and reinforcing bars were extracted. Results are shown in Table 6. The quantitative results for cement, sand, gravel, water and superplasticizer are shown in Table 7.

The adoption of higher concrete grades made the reduction of the consumption of both concrete and reinforcing bars to produce the columns in the building possible. When comparing the results for grade C30, reductions in the amount of concrete by 3.8% and 11.2% were possible for C40 and C50 grades, respectively. For reinforcing bars, reductions of 13.7% and 22.3% were achieved for C40 and C50 grades. This result is similar to what was found previously when comparing columns produced with grade C30 concrete and grade C60 [13].

To achieve higher concrete strengths, it is necessary to increase cement content and to reduce the w/c ratio. In this study, the reduction of concrete observed in grades C40 and C50 was not enough to reduce the cement content in the RC columns.

Table 6. Total of materials consumed in columns

Concrete grade	Concrete (m^3)	Δ	Reinforcing bars (kg)	Δ
C30	260	-	38773	-
C40	250	3.8%	33480	13.7%
C50	222	11.2%	30132	22.3%

Table 7. Total of materials consumed in the concrete used in the columns

Material	C30	C40	Δ	C50	Δ
Cement **(ton)**	**89.7**	**98.5**	10%	**95.9**	7%
Gravel **(ton)**	**27.1**	**26.4**	-2%	**23.7**	-13%
Sand **(ton)**	**19.5**	**18.3**	-6%	**16.0**	-18%
Water **(ton)**	**48.4**	**44.5**	-8%	**38.0**	-22%
SP **(ton)**	0	**98.5**	-	**0.73**	2830%

3.2 Life Cycle Impact Assessment

3.2.1 m^3 comparison

Results were normalized in relation to the 30 MPa class of concrete. A preliminary comparison considering the impacts of 1 m^3 of concretes was performed. As expected, the higher amount of cement in concretes C40 and C50 resulted in higher environmental impacts in all categories, as seen in Figure 3. This is explained by cement being the material with most environmental impacts in concrete. To achieve higher compressive strength, higher amounts of cement are necessary and, as consequence, when the functional unity of 1 m^3 is evaluated, the concretes with higher compressive strength present higher environmental impacts.

Further analysis was necessary understand the roles of the materials in the environmental impacts of the concrete. For that purpose, five categories were selected: Climate change (long term), Fossil and nuclear energy use, Freshwater eutrophication, Mineral resources use and Ozone layer depletion. Results are presented in Figure 4.

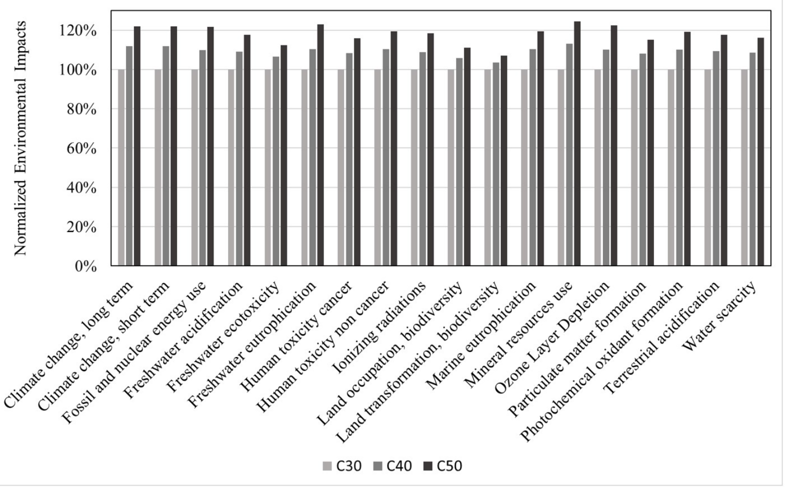

Figure 3. Normalized LCA results for 1 m^3 of concrete

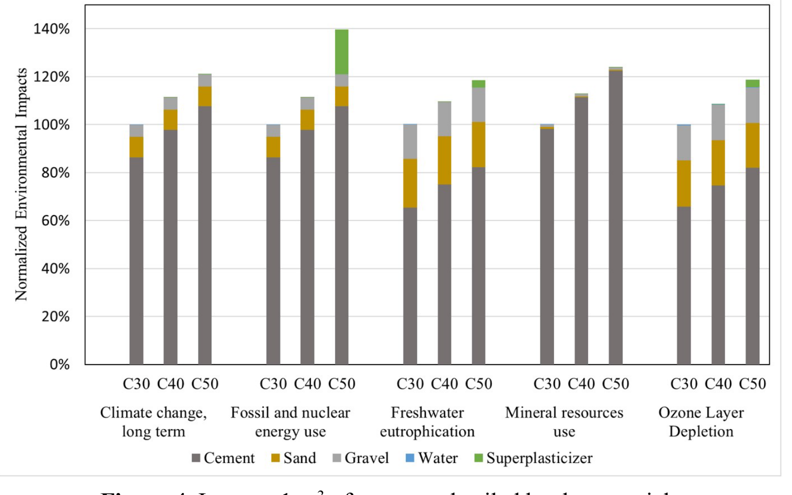

Figure 4. Impacts 1 m^3 of concrete detailed by the materials

The LCA results for concrete indicate the predominance of cement in the environmental impacts when compared to the other materials (gravel, sand, water and superplasticizer, cement). In this study, cement is present in the concrete mix in average of 16.5% by weight of the materials and is responsible, in average, for 68% of the environmental impacts of concrete.

In contrast to the use of cement, sand and gravel represent 76% of the materials in concrete by weight and are responsible, in average for 32% of the environmental impacts to produce 1 m^3 of concrete. Impacts of sand and gravel are caused mostly by transportation. Average distances of transportation are accounted in the market process chosen in the LCI phase of this study [35].

The high values of climate change for concrete are due to carbon dioxide emissions to air originated by clinker production and from the use of petrol and coke to power the furnaces in cement factories. This use of petrol and coke is responsible also for the higher values of environmental impacts in fossil energy.

The mineral resources use impact categories have cement as the predominantly responsible component for the environmental impacts. Cement is accounted for 98.3% for C30 concretes, 99.7% for C40 and 99.8% for C50. Those impacts are caused by mining and extraction of clay and limestone to produce clinker.

The contributions of superplasticizer in the environmental impacts of concrete are not relevant in the production of 1 m^3 of concrete. This is the result of the lower content of 0 kg, 0.1 (0.01% of the total weight) kg and 3.1 kg (0.43% of total weight) in 1 m^3 of concrete in C30, C40 and C50, respectively.

It is important to note that superplasticizers should be a concern in concrete production. As seen in Table 3, superplasticizers' raw materials are petroleum based, which explain the influence in the results in fossil and nuclear energy use. Analyzing the categories, values of impacts of 18.6% and 2.90% were noticed in relation to the total impacts of the C30 grade concrete if only 3 kg of superplasticizers are added in the mixture.

3.2.2 Cement efficiency and eco efficiency.

Cement efficiency and eco-efficiency of the concretes are shown in Table 8.

The increase of compressive strength in the concretes resulted in a better efficiency and a lower amount of cement necessary to reach 1 MPa. That means that, besides having a higher content of cement for higher strength concretes, this amount is used in a more efficient way to improve the mechanical the mechanical properties.

Results for the eco-efficiency followed the trend observed in cement efficiency. Although the emissions of CO_2 observed for concretes C40 and C50 are higher, less CO_2 is emitted in the atmosphere to achieve 1 MPa of compressive strength in concretes. This result is an indicator that higher compressive strengths and, thus, the reduction of the volume of concrete and the weight of reinforcing steel bars, lead to the reduction of the environmental impacts.

Similar results are found in the literature. Pacheco et al. [17]. The efficiency of concrete increased with higher compressive strengths, varying from 12.20 kg/m^3/MPa in C20 concretes to 5.75 kg/m^3/MPa in C80 concretes. Miranda de Souza et al. [36] found similar trends for the eco-efficiency of concretes with different concrete grades. results of 15.72 kgCO_2eq/MPa were found for C20 concretes, whereas values of 12.28 kgCO_2eq/MPa were found for C30 class concretes

Table 8. Cement efficiency

Concrete grade	f_{ck}	Cement (kg)	Efficiency (kg/m^3/MPa)	eco-efficiency (kgCO_2eq/MPa)
C30	30	345	11,50	11,58
C40	40	414	10,35	9,71
C50	60	465	9,30	8,48

3.2.3 Columns

The LCA for the columns was performed using the results of the building design and the mix design chosen for the concrete. The first set of analysis aimed to compare the results of the columns produced in three different grades: C30, C40, C50. For that, the results were normalized in relation to the C30 columns. Results are presented in Figures 5 and 6.

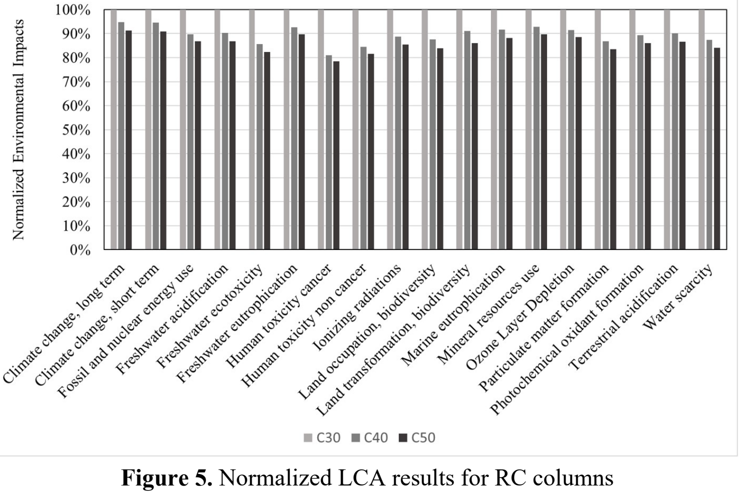

Figure 5. Normalized LCA results for RC columns

For further analysis, and to understand the roles of the materials, now including reinforcing steel, the same five impact categories selected for the m^3 analysis were studied for the RC columns.

The analysis of the proportions of the materials in the results of impact categories was important to understand the influence of the impacts of reinforcing steel. It is important to acknowledge the effect the indirect advantages of the increased concrete strength to produce the RC columns.

It is possible to note in the five highlighted impact categories that the environmental impacts accounted for the concrete portion of RC present some reduction for the different concrete grades, even with the reduction of volume of concrete in C40 and C50 columns.

CO_2 emissions (Climate change impact category) from grade C50 columns were 10% lower than the grade C30 RC columns. Habert and Roussel [37] estimates that this reduction can be up to 30% if the strategy to increase strength is combined with cement replacement. As observed in Table 6, the cement consumption increases for C40 and C50 grade mixes of concrete in relation to the C30 grade. To reduce the environmental impacts of the concrete portion of the RC columns, it would be necessary to reduce the cement content cement in concrete mixtures.

Rohden and Garcez [19] and Peyroteo et al. [38] state that the reduction of steel is an advantage concerning the environmental impacts of the building. Reinforcing steel, as can be seen in Figure 6 is the greater responsible for the environmental impacts of RC columns. Thus, the reduced need for reinforcing bars in the column results in the lower environmental impacts of RC columns produced is C40 and C50 concretes.

Figures 7, 8, 9, 10 and 11 show the tendencies of the environmental impacts of concrete and reinforcing steel in contrast to the total environmental impacts for categories. It can be seen in the figures that even with the reduction in the volume of concrete in the structure, not much variation is observed in the portion of the environmental impacts of concrete in the RC columns. The lower environmental impacts caused by the reduction of reinforcing bars in the columns was essential to the reductions found in this study.

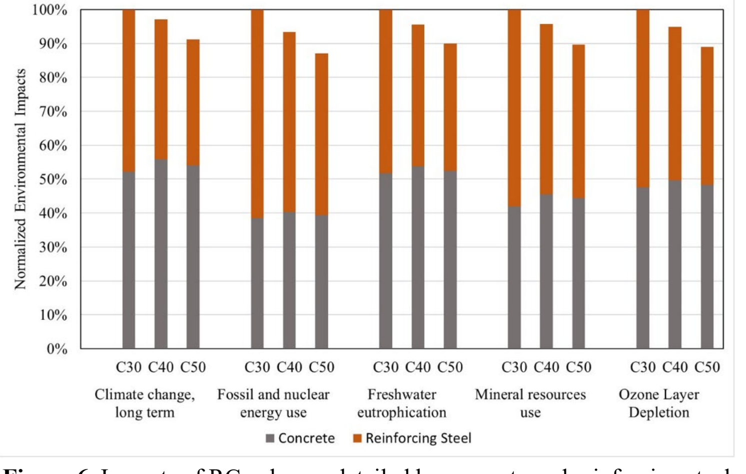

Figure 6. Impacts of RC columns detailed by concrete and reinforcing steel

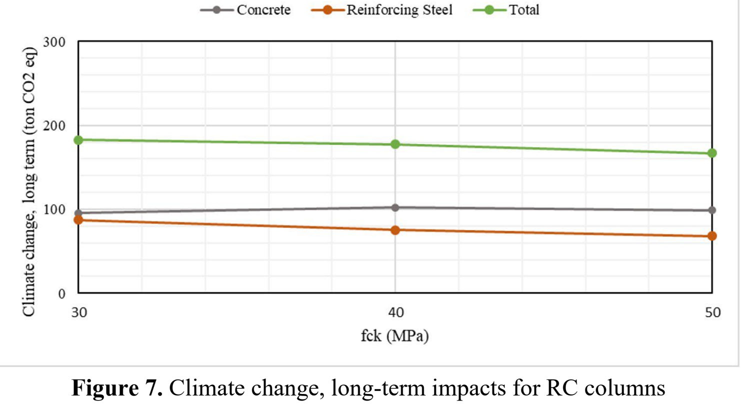

Figure 7. Climate change, long-term impacts for RC columns

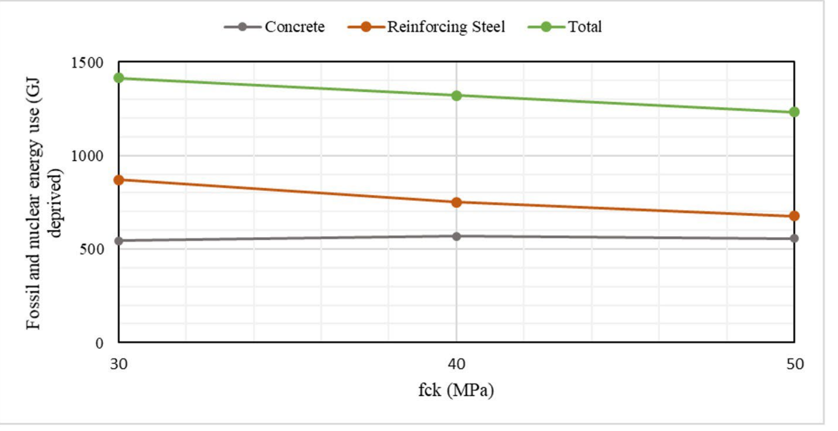

Figure 8. Fossil and nuclear energy use for RC columns

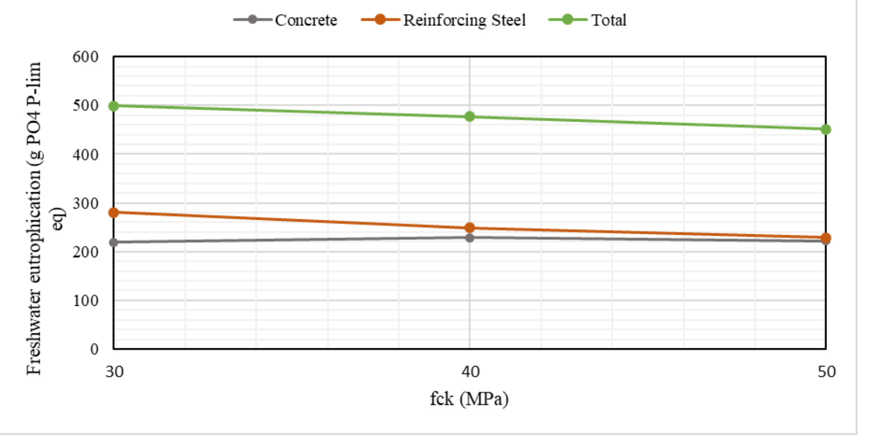

Figure 9. Freshwater eutrophication impacts for RC columns

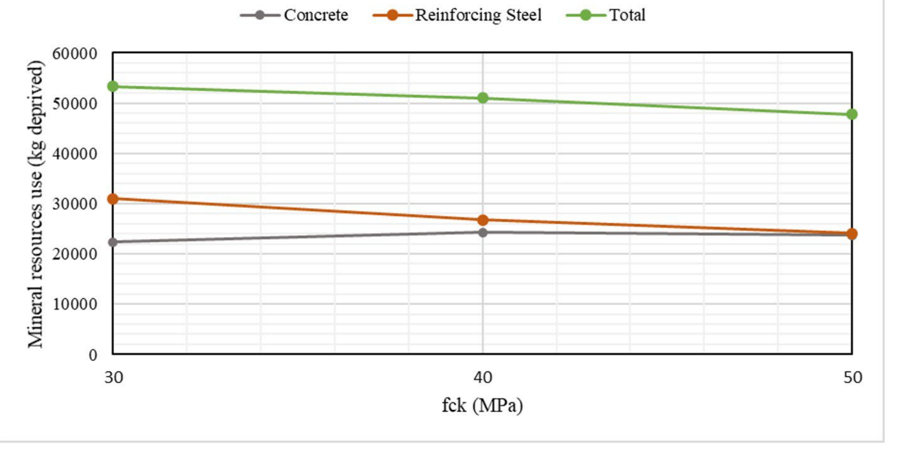

Figure 10. Mineral resources use for RC columns

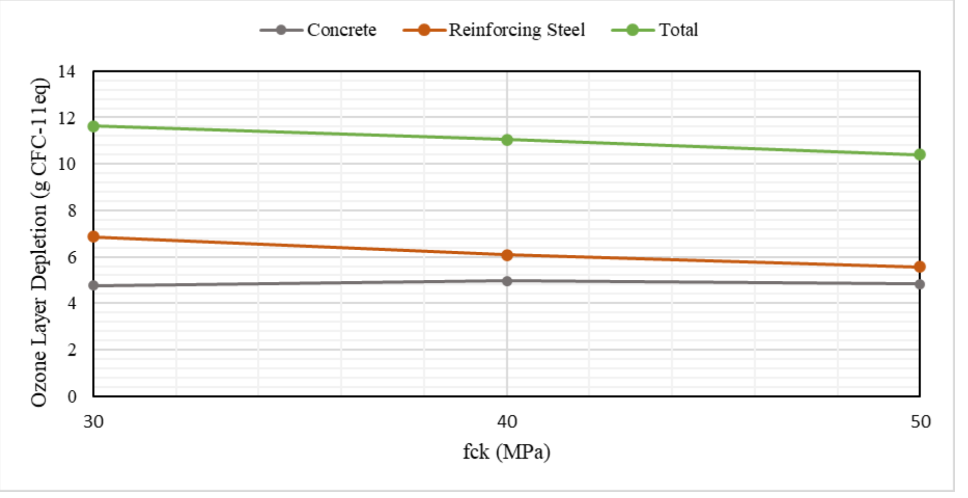

Figure 11. Ozone layer depletion for RC columns

4 CONCLUSIONS

In this study, a cradle to gate LCA was performed to assess the possibility of increasing the concrete strength of RC columns to reduce the environmental impacts.

First, three concrete mixes of different grades were selected as basis for input in the LCA: 30 MPa, 40 MPa and 50 MPa. Then, the LCA was performed for two sets of analysis: the production of 1 m^3 of concrete and the production of the RC columns.

Results show great influence of cement in the environmental impacts of concrete. The process of production with mining and extraction of materials and the use of non-renewable energy in cement plants.

Even though there is a greater utilization of sand and gravel by weight, the impacts to extract the materials were not as significant as cement, which is present in lower amounts per m^3 of concrete.

Superplasticizers are produced with petroleum-based raw material that can be relevant in environmental impacts such as fossil and nuclear energy use and for increase of freshwater ecoxoticity, with higher biological and chemical oxygen demands. However, the impacts in RC columns are overshadowed by the impacts of cement and steel when the results RC columns are analyzed.

The increase of concrete strength to produce the RC columns showed as a good alternative to reduce the total environmental impacts in to produce the building. However, the reduction of impacts is not caused by the reduction of the volume of concrete in the columns, but by the reduction of reinforcing bars, as steel production are responsible for a great portion of the environmental impacts of RC.

The increase of the concrete strength is also positive when cement efficiency and eco-efficiency were assessed. Concrete grades C40 and C50 increased the cement efficiency in 10% and 19.1%, respectively to produce 1 m^3 of concrete.

As of eco-efficiency, higher compressive strengths increased the eco-efficiency, the ratio between the CO_2 emissions for 1 m^3 of concrete and the compressive strength. In relation to C30 concretes, results were 16.1% and 26.8% for C40 and C50 concretes, respectively.

As seen in the three tools proposed to achieve sustainability in building construction, the reduction of concrete in structures can be a viable option, but the high amount in cement in concrete mixture is still an obstacle, since the environmental impacts of the concrete portion of RC slightly increased.

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