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# Environmental assessment of a structural element in a residential building

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## Abstract

The construction industry needs to improve its sustainability. To this end, it is important that during the design phase of a construction, the environmental impacts generated by the designed alternatives are studied. The objective of this research is to determine the environmental impacts that occur when evaluating the concrete and steel reinforcement used in the columns of a residential building. To this end, various alternatives are studied, where the type of cement used (CEM I or CEM II) is varied. Also the characteristic strength of the concrete (25 MPa or 50 MPa), as well as the relationship between the amount of reinforcement steel of the column and its concrete section. The results show great environmental variability among the alternatives. The largest differences indicate average decreases in impacts of 47.7%. In impact categories such as Global Warming Potential, the decrease is 38.4%, which prevents a value of 19.30 $tCO_2$ equivalent from being emitted into the atmosphere or the consumption of 205.23 GJ of energy in the Abiotic Depletion of Fossil Fuels category. This study aims to demonstrate that, although all alternatives are technically viable, some are more environmentally sustainable.

**Keywords:** Concrete; Columns; Cement, Sustainability, Environmental Assessment.

## 1. Introduction

The construction sector must consolidate a more sustainable and efficient development in the next years. The main objective is to promote an industry that is more respectful of the environment and society in general. To this end, more and more research studies are focusing on the environmental characterisation of projects as a whole, or of individual structural elements, building materials, etc., in order to understand them from an environmental perspective. To understand them from a perspective that was previously overlooked due to their low level of importance. This is supported through the changing trend of the current regulations (Structural Code Ministry of Transport, Mobility and Urban Agenda, 2023), where specific points within the project where the sustainability of the alternatives are evaluated are already requested. The results of these new environmental data are gaining weight with respect to the predominant criterion such as the economic one when selecting one project or another. In the near future, it is expected that developers working in the construction sector will have to choose the most environmentally and economically sustainable project alternatives.

Therefore, the aim of this research is to expose and interpret the environmental impacts associated with the production of concrete for the creation of in-situ columns in a residential building located in Spain. For this purpose, several variables will be taken into account, such as the type of cement (CEM I or CEM II). The altitude of the geographical site where the building is located (where the structural loads such as wind, snow, etc. can vary). And finally, the variable amount of steel from the reinforcement per column section. The aim of this research is to show how for a structural element included in a complete project, new execution alternatives can be defined taking into account economic and environmental sustainability.

## 2. State of the art

The above has already been included in previous research. For instance, Ortega et al. evaluate for a hydroelectric power plant structure two alternative materials such as steel or reinforced concrete, and define their respective economic and environmental impacts (Ortega et al., 2022). At the same level, the research by Zhang et al. uses Life Cycle Analysis (LCA) tools to study the impacts of a water treatment infrastructure (Zhang and Ma, 2020). Or applied to the transport sector and specifically to the railway sector, as in the case of Bortoli et al. (Bortoli et al., 2020). Or applied to the residential sector, through the study of various alternatives taking into account environmental, economic and social impacts (Fraile et al., 2015).

Given the background, it should be noted that this research attempts to complement previous results obtained in the research of Fraile et al., (Fraile-García et al., 2019) where they evaluated the environmental impact of in-situ concrete for the columns of a building. However, these environmental results were evaluated for a single environmental impact category and other environmental impact categories were ignored. Therefore, the development of this research is justified as a material to add to the previous research new results more general to the use of concrete in a building.

## 3. Materials and Methods

This section describes the methodology that has been applied to carry out this research, as well as the background that motivates this research.

### 3.1. Background

The research which is taken as a reference (Fraile-García et al., 2019) modelled an 8-storey residential building, with a total of 36 columns as shown in Figure 1. The columns have a square section typology. The building is calculated for slab loads (4.1 kN/m$^2$), floor loads (1 kN/m$^2$), partition walls (1 kN/m$^2$) and serviceability overload (2 kN/m$^2$). The building was also modelled for three altitudes, zone A (0 m.a.s.l.), zone B (400 m.a.s.l.), zone C (600 m.a.s.l.). Finally, the last variable studied to obtain the results is the $A_S/A_C$ ratio. Where the $A_S$ value represents the steel reinforcement section of the column, and the $A_C$ value represents the concrete section. As the performance of the concrete improves, the smaller the steel section of the reinforcement will be required. Conversely, the larger the reinforcement area, the smaller the concrete section.

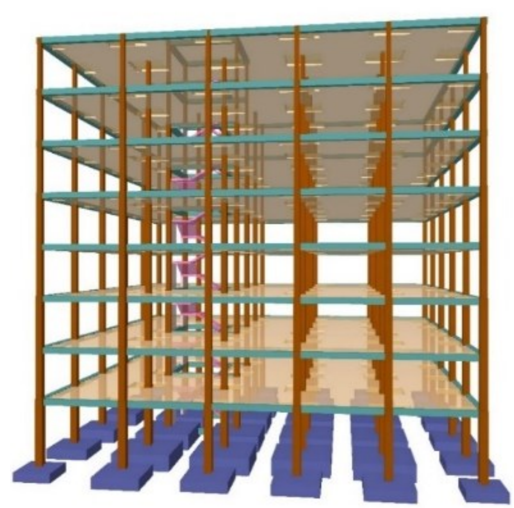

**Figure 1:** 3D modelling of research residential building (Fraile-García et al., 2019).

The results of the research (Fraile-García et al., 2019), analysed only the environmental impacts of the Global Warming Potential impact category (unit: kg of $CO_2$), and their respective economic cost (monetary unit: €) for the 108 modelling scenarios that include the above variables. However, this previous research did not consider the environmental impacts of the ready-mix concrete, i.e. the impacts associated with the use of fine and coarse aggregates, water and cement, in addition to assessing other environmental impact categories. To these overall results of using the ready-mix concrete, it was decided to add the environmental impacts of creating and using the reinforcement. This is intended to generate more general environmental results from the use of concrete in a structural element.

Due to the extent of the various simulations of previous research (Fraile-García et al., 2019), it was decided to analyse a specific case study, which could be replicable to the rest of the case studies. This is the case where the building is located in an altitude zone of 400 m.a.s.l. with a wind zone B (Structural Code Ministry of Transport, Mobility and Urban Agenda, 2023), and for extreme concrete characteristic strength levels ($N/mm^2$) of 25 MPa and 50 MPa. In the case that the materials that make up the concretes are CEM I and CEM II type cements on the one hand.

To this first classification is added the variable of the $A_S/A_C$ ratio, which will be studied for values of 1 and 2. It is justified to choose these ratio values ($A_S/A_C$) because it is in this interval where the best optimisation for costs and environmental impacts is shown (Fraile-García et al., 2019).

To improve the interpretation of the results, a codification of the alternatives evaluated in the research is created as follows; HA-X-Y-Z. Where: HA: Represents that it is a reinforced concrete alternative. X: Represents the characteristic strength values, 25 MPa or 50 MPa. Y: Represents the $A_S/A_C$ ratio with values of 1 and 2. Z: Represents the type of cement. CEM I or CEM II.

For instance, the alternative HA-25-I-CEM I, specifies that it is a reinforced concrete with a characteristic strength of 25 MPa with an $A_S/A_C$ ratio of 1 and uses a CEM I cement.

## 3.2. Life Cycle Assessment

The LCA is developed using the UNE-EN ISO 14040 (UNE-EN ISO 14040, 2006.) and UNE-EN ISO 14044 (UNE-EN ISO 14044, 2006) standards. To obtain the environmental data, the LCA programme SimaPro (SimaPro-LCA Software, 2023) is used. In its databases such as Ecoinvent v.3 (Ecoinvent v3.0, 2023.) the manufacturing processes of ready-mix concrete mixtures can be modelled. In addition to varying the various processes of the raw materials that compose the concrete.

First of all, the system boundaries of the investigation must be defined in order to determine the scope of the investigation. For construction products, according to the above-mentioned standards, a series of stages are indicated. In this investigation, only the stages from the production of the materials (A1) that compose the concrete, their transport to the concrete production plant (A2) and finally the mixing process (A3) will be taken into account. It is decided to exclude subsequent phases of the system boundary such as the commissioning phase (A4-A5), the product phase (B1-B7), and the demolition and recycling phase (C1-C4) since it is assumed that all the alternatives are structurally viable and therefore there is no difference in their behaviour throughout their useful life (Los Santos-Ortega et al., 2023). Furthermore, the functional unit (FU) is defined as the amount of concrete ($m^3$) and steel reinforcement (kg) required for the creation of the columns of the residential building in Figure 1. The boundary conditions are shown schematically in Figure 2.

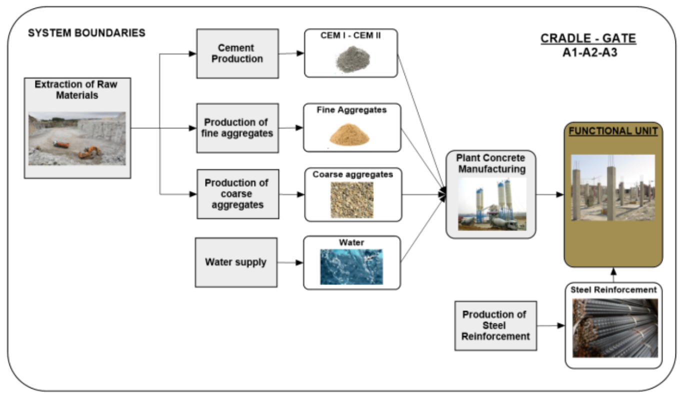


**Figure 2.** System boundary from the cradle to gate for the production of the concrete and steel reinforcement for the construction of the columns.

One step in the LCA methodology is to determine the Life Cycle Inventory (LCI), i.e. the collection of all raw materials involved in the creation of the FU. The LCI for this research is shown in Table 1.

**Table 1.** Concrete and steel amount for building columns using CEM I and CEM II.

| Concrete Strength (MPa) | $A_s/A_c$ | Reinforced Steel (kg) | Concrete ($m^3$) |
|---|---|---|---|
| 25 | 1 | 9552 | 92.08 |
| | 2 | 17078 | 73.96 |
| 50 | 1 | 6838 | 61.88 |
| | 2 | 10359 | 59.12 |

To create the concrete creation process in SimaPro, two processes were chosen according to their characteristic strength. These are Concrete, 25 MPa {RoW} concrete production 25 MPA | Cut-off, U, for the case of 25 MPa concrete. And on the other hand, the process Concrete, 50 MPa {RoW} concrete production 50 MPA | Cut-off, U for the 50 MPa strength alternatives. Finally, for steel reinforcement, the reinforcing steel {RER} production | Cut-off, U process was selected.

One aspect that was taken into account is that the above-mentioned concrete production processes contain a different type of cement than the one used in the investigation. Therefore, it was decided to modify that process to that of a cement which is in line with the production of CEM I and CEM II. These were, for CEM I the process, Cement, Portland {Europe without Switzerland} market for | Cut-off, U. And for CEM II, the process Cement, alternative constituents 6-20% {Europe without Switzerland production} market for | Cut-off, U. Table 2 shows the quantities of cement used to create concretes with a strength of 25 MPa and 50 MPa.

**Table 2.** Amounts of CEM I and CEM II for the characteristic's strengths of the concrete.

| Concrete strength (MPa) | CEM I or CEM II (kg) |
|---|---|
| 25 | 250 |
| 50 | 400 |

The aim of this research is to study other categories of environmental impact that, although they are less known than $CO_2$ emissions, are also relevant to know the environmental impacts generated by the cement material. These impact categories are those covered by the Environmental Product Declaration (EPD) methodology. This environmental assessment methodology is widely used in the construction sector, because EPDs are created for products. These serve as a method of comparing and contrasting products in order to assess their respective sustainability and the impacts of the use of the material or product. The impact categories are listed in Table 3.

**Table 3.** Environmental impact categories in the EPD methodology.

| Impact Categories | Unit |
|---|---|
| Acidification | kg $SO_2$ eq |
| Eutrophication | kg $PO_4$ eq |
| Global Warming Potential | kg $CO_2$ eq |
| Photochemical Oxidation | kg NMVOC |
| Abiotic Depletion Elements | Kg Sb eq |
| Abiotic Depletion of Fossil Fuels | MJ |
| Water Scarcity | $m^3$ |
| Ozone Layer Depletion | kg CFC-11 eq |

## 4. Results and Discussion

The results are shown in Figure 3, for each of the environmental impact categories of the EPD methodology. As can be seen, the ordinate axis shows the percentage (%) of impact of each alternative studied. For a better understanding of the results, the first step is to explain the environmental differences involved in using CEM I and CEM II cements for the alternatives evaluated. Subsequently, the importance of the $A_S/A_C$ ratio is developed.

Whether analysing the HA-25 or HA-50 alternatives for an $A_S/A_C$ ratio of 1 or 2, the same pattern is obtained. That is, the environmental impacts decrease in all impact categories for the alternatives using CEM II. The biggest differences are found in the comparison of the HA-50-I-CEM I alternative with respect to the HA-50-I-CEM II alternative where the average decrease of all environmental impacts is 4.09%. This is most notable in impact categories such as Global Warming Potential with a decrease of 9.7%, which is equivalent to a reduction of 4856.04 kg $CO_2$ emissions. Other impact categories are also improved such as Acidification (-4.9%), Eutrophication (-5.0%), Ozone Layer Depletion (-4.5%), Photochemical Oxidation (-3.9%), Abiotic depletion elements (-0.1%), Water Scarcity (-1.3%) or Abiotic Depletion of Fossil Fuels (-1.3%) which corresponds to avoiding consuming an equivalent of 3.98 GJ of energy from non-renewable energy sources such as fossil fuels.

It should be noted that the difference in the amount of cement used in 50 MPa and 25 MPa concretes is 150 kg/$m^3$. Despite this increase, a better environmental assessment and sustainability of CEM II over CEM I is achieved. This is justified because CEM II contains a lower percentage of clinker (65%~79%), the remaining percentage being components from industry, such as silica fume, fly ash, pozzolans, etc., i.e. waste that can be reused in cement due to its properties. On the other hand, CEM I has a very high clinker content (95%~100%). And in order to produce clinker, it involves high energy consumption and, associated with this, the emission of large quantities of environmentally harmful substances. Hence the differences explained above.

Once the major environmental differences between the CEM I and CEM II alternatives are exposed, the cases in which there is still an environmental benefit, but with a lower average impact, are discussed. Such is the case between HA-50-II-CEM I and HA-50-II-CEM II (-3.90%), HA-25-I-CEM I and HA-25-I-CEM II (-1.16%) and finally between HA-25-II-CEM I and HA-25-CEM II (-1.04%).

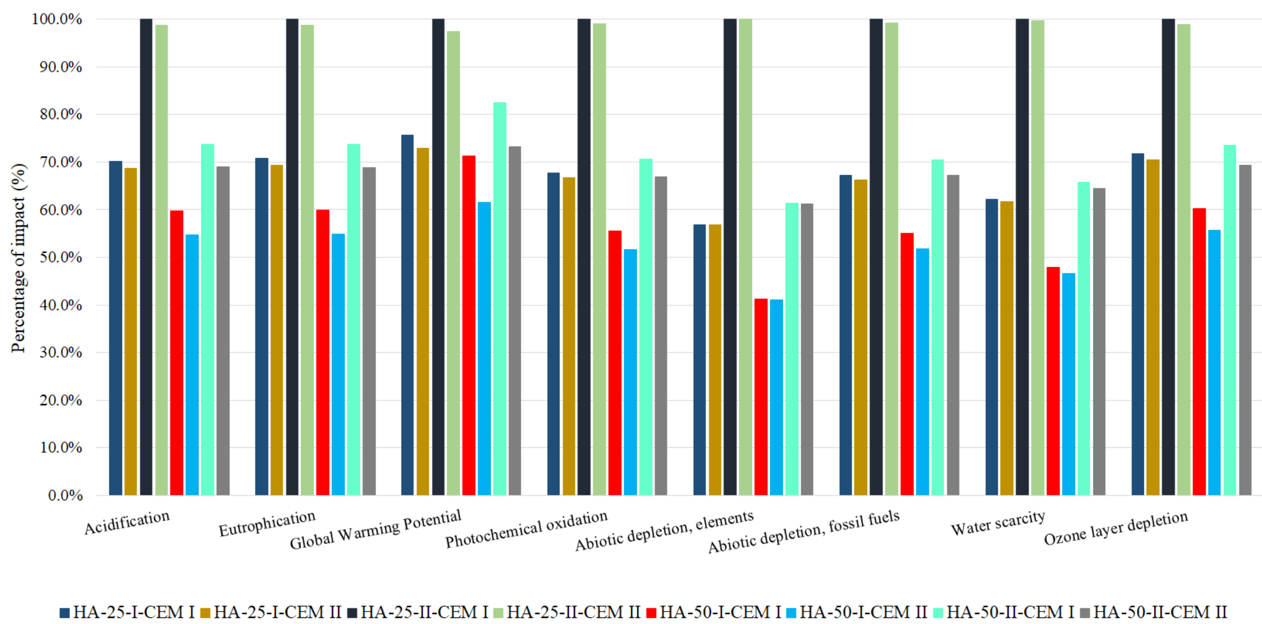


**Figure 2:** Environmental results according to the impact categories assessed for the various simulations.

Once the environmental differences obtained from the simulation between CEM I and CEM II cements have been discussed, the results are evaluated from the perspective of the $A_S/A_C$ ratio. That is, whether an $A_S/A_C$ ratio of value 1 implies worse environmental results than a value 2.

As shown in Figure 3, specimens with an $A_S/A_C$ ratio of 2 perform worse in all impact categories compared to an $A_S/A_C$ ratio of 1. This is justified since increasing the $A_S/A_C$ ratio requires higher amounts of steel reinforcement. For instance, in the case of characteristic strength of 25 MPa the increase in kg of steel reinforcement is 7526 kg (increase of 44.06%), even though the amount of concrete to be used between the two ratios decreases by 8.12 $m^3$. The same is true for the 50 MPa characteristic strength, with an increase of 3521 kg of steel reinforcement and a decrease of 2.76 $m^3$ of concrete. These results conclude that the environmental impacts associated with concrete production are lower than those of steel reinforcement production for the case study. For instance, if the alternatives HA-25-I-CEM I and HA-25-II-CEM I in Figure 2 are visualised, there is 32.2% more impact for the impact categories evaluated. This increase is solely due to the increase in reinforcing steel reinforcement and the environmental cost of producing it. Specifically in the Global Warming Potential impact categories, the increase is 24.4%, equivalent to emitting 12249.42 kg of $CO_2$ for the use of 7526 kg of steel, which requires increasing the AS/AC ratio by one unit. Similarly, in the Abiotic Depletion of Fossil Fuels category there is a notable increase of 32.8% (increase in energy consumption of 139.70 GJ). Figure 4 shows for the HA-25-CEM I alternative discussed above how the steel reinforcement production process and the concrete production process influence the impact contribution, for $A_S/A_C$ ratios 1 and 2.

As can be seen regardless of the impact category, the $A_S/A_C$ ratio of value 2 generates higher environmental impacts compared to the ratio of 1. If the $A_S/A_C$ ratio of 2 is analysed, the steel reinforcement production process has the highest impact weight compared to the concrete production process. For instance, for the impact categories of Abiotic Depletion Elements it has an impact of 98.34%, Water Scarcity 89.14%, Photochemical Oxidation 78.49%, Acidification 74.29%. Therefore, it can be concluded that the production process of steel production for column reinforcement is the main responsible for environmental impacts. If the values of the $A_S/A_C$ ratio are increased, e.g. above 3, the environmental impacts would increase exponentially.

The average differences in environmental impacts for the $A_S/A_C$ 1 and 2 ratios as a function of the type of characteristic strength and type of cement used are shown in Table 4.

**Table 4.** Average decreases in environmental impacts and $A_S/A_C$ ratio.

| Differences between $A_S/A_C$ (1,2) | Average decrease in impacts |
|---|---|
| HA-25-CEM I | -32.2% |
| HA-25-CEM II | -32.4% |
| HA-50-CEM I | -15.09% |
| HA-50-CEM II | -15.27% |

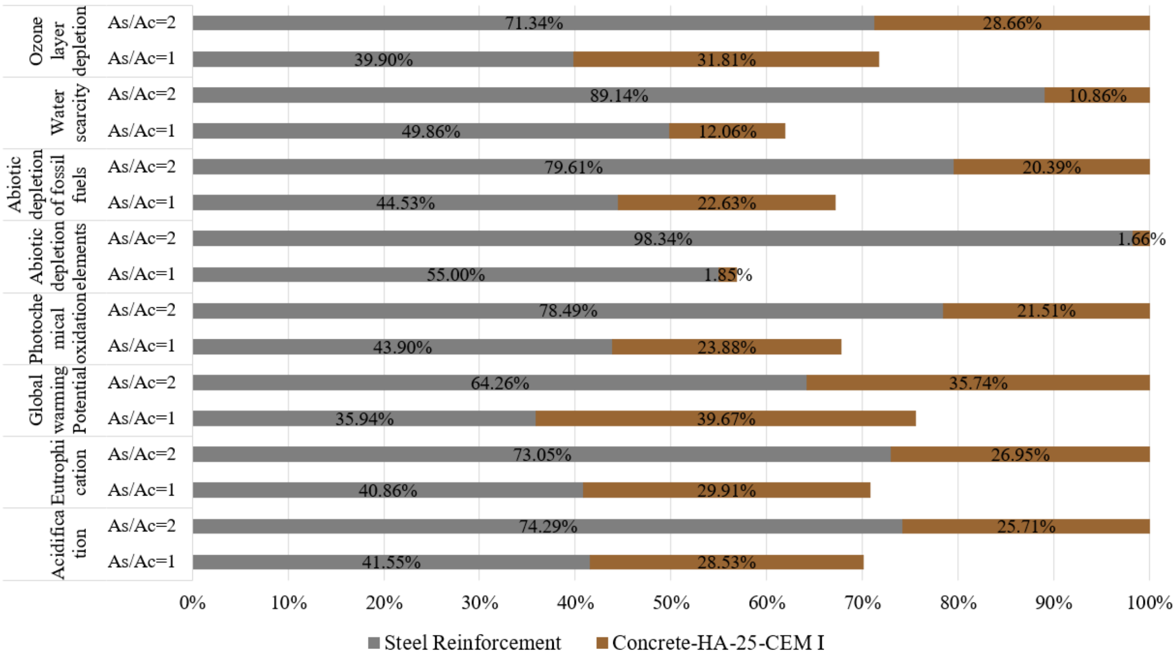


**Figure 3:** Results of steel reinforcement and concrete production processes as a function of the $A_S/A_C$ ratio for HA-25-CEM I alternatives.

Steel production is generally carried out in smelting furnaces, which work with electrical energy. This energy comes from a grid which is supplied from renewable energy sources (hydro, solar, biomass), but also from non-renewable energy sources such as coal, natural gas, diesel, etc. Therefore, the emission of harmful substances in the production of this electricity has an impact on an increase in categories such as Ozone Layer Depletion (32.2%), Photochemical Oxidation (32.2%). Likewise, the production of steel means that the raw material of iron has to be extracted through mining processes, which increases the exploitation of raw materials and is reflected in the impact category of Abiotic Depletion Elements (43.2%). These processes have high water consumption reflected in the increased Water Scarcity category (28.3%).

It should be noted that all the alternatives shown in this research are feasible in terms of strength and can be implemented in the building (Fraile-García et al., 2019). Therefore, we will finally highlight which alternative is the most environmentally viable. This is the alternative HA-50-I-CEM II. Logically, it is the alternative with the lowest $A_S/A_C$ ratio of value 1 and therefore the lowest amount of steel reinforcement. It also uses the higher characteristic strength of 50 MPa and therefore the amount of cement is higher (see Table 2). However, using CEM II creates less environmental impacts compared to CEM I despite the increased amount of cement.

A comparison between environmentally extreme alternatives (HA-25-II-CEM I and HA-50-I-CEM II) shows large percentage differences in impact categories such as Acidification (-45.2%, -76.98 kg $SO_2$ eq), Eutrophication (-45.1%, -10. 30 kg $PO_4$ eq), Global Warming Potential (-38.4%, -19.299 $tCO_2$), Photochemical Oxidation (-48.4%, -101 Kg NMVOC), Abiotic Depletion Elements (-58.9%, -0. 10 kg Sb eq), Abiotic Depletion of Fossil Fuels (-53.4%, -205.23 GJ), Water Scarcity (-44.2%, -6483.78 $m^3$), Ozone Layer Depletion (-47.7%, -1.20E-3 kg CFC-11 eq). The explanation for these decreases originates from what has been explained throughout this section, such as the use of more sustainable cements, as well as a lower consumption of steel reinforcement due to a better optimisation of the $A_S/A_C$ ratio.

## 5. Conclusions

As has been demonstrated, the design of a structural element such as the columns of a residential building does not have a single solution. Instead, various alternatives can be designed where several variables intervene, such as the use of the type of cement (CEM I, CEM II), the characteristic resistance of the concrete (25 MPa, 50 MPa) and finally the relationship between the amount of steel reinforcement and the section of the $A_S/A_C$ column (1, 2). All this leads to the fact that the alternatives that are produced have a greater or lesser environmental impact.

These impacts may represent a new decision item for choosing an alternative from among all those available, since more and more structural regulations are requiring a sustainability study of the project to be carried out. Consequently, environmental assessment is gaining importance and weight within the construction sector. It also provides valuable information that was previously overlooked.

Specifically, for the research case, an average reduction of -47.7% of the environmental impacts in the studied categories between HA-25-II-CEM I and HA-50-I-CEM II alternatives is demonstrated. The most environmentally efficient solution would be the HA-50-CEM II concrete configuration for the building columns.

In addition, when it is possible to use CEM II cements in projects compared to CEM I, this should be done, as its environmental sustainability is evident. For the specific case of the research, a variable decrease in the range of -1.16% to -4.09% is shown, conditioned by the characteristic strength of the concrete, as well as the $A_S/A_C$ ratio.

It should also be noted that a lower $A_S/A_C$ ratio helps to achieve better environmental results, as the amount of steel reinforcement is more optimal. Consequently, the environmental impacts generated as a result of the steel production process are lower. In the case of the research, an average decrease of -32.2% of the impacts is evidenced by increasing the $A_S/A_C$ ratio by one unit, keeping the type of cement used and its characteristic resistance constant.

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