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DESIGN AND COMPARATIVE LIFE CYCLE ASSESSMENT OF REINFORCED CONCRETE FRAME STRUCTURES MADE WITH NATURAL AND RECYCLED AGGREGATES

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À minha família e amigos

Tudo vale a pena quando a alma não é pequena

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RESUMO

É do conhecimento geral que o betão é o segundo material mais utilizado no mundo depois da água. O betão é constituído por diferentes componentes, dos quais os agregados formam uma grande parte. O sector da construção é responsável por uma parte significativa das emissões globais de gases com efeito de estufa, pelo que é necessário reduzir as emissões de carbono.

Neste documento, os potenciais benefícios da incorporação de agregados de betão reciclado são avaliados utilizando a metodologia de Avaliação do Ciclo de Vida. Em particular, é analisada uma estrutura de betão armado simples e os seus respetivos impactos ambientais para duas formulações diferentes de betão, sujeitas a dois tipos de ações, verticais e sísmicas. Em questão está um betão normalizado de classe C35/45 e um betão de classe C25/30 com 30% de agregados reciclados. Para simplificar a comparação entre as formulações, a unidade funcional selecionada foi a estrutura central. Os dados do inventário foram obtidos através do dimensionamento da estrutura para garantir que esta cumpre os requisitos descritos nas normas. As categorias de impacto ambiental foram escolhidas, e os indicadores ambientais correspondentes foram calculados com base nas diretrizes definidas nas normas EN 15084 e ISO 21930.

Os resultados mostram que a incorporação de agregados reciclados reduz os impactos ambientais gerados pelo betão e, consequentemente, pode reduzir os do próprio edifício. O estudo da estrutura sujeita a cargas verticais, demonstra que é possível reduzir os impactos ambientais do conjunto total. No entanto, a estrutura sujeita a ações sísmicas dimensionada para betão com componente reciclado apresenta um aumento nos impactos.

Como trabalho futuro, é sem dúvida necessário estudar substituições alternativas para os componentes de betão. As sugestões seriam de substituir uma parte do cimento ou de substituir uma percentagem mais elevada dos agregados virgens, sem comprometer a estabilidade e resistência do betão.

Palavras-Chave: Avaliação do ciclo de vida; Sustentabilidade; Dimensionamento de estruturas; Agregados reciclados, Betão sustentável

ABSTRACT

It is common knowledge that concrete is the second most used material in the world after water. Concrete is build-up of different components, of which aggregates form a large part. The construction sector is responsible for a significant part of the global emissions of greenhouse gases; thus, it is necessary to reduce the carbon emissions.

In this thesis, the potential benefits of incorporating recycled concrete aggregates are assessed using the Life Cycle Assessment methodology. In particular, a typical frame structure and its respective environmental impacts are analysed for two different concrete formulations, submitted to two types of actions, vertical and seismic. In question is a standard concrete of class C35/45 and a concrete of class C25/30 with 30% recycled aggregates. To simplify the comparison between the formulations, the selection of the functional unit was the core structure. The inventory data was obtained by sizing the frame structure to ensure that it meets the construction requirements. The environmental impact categories were chosen, and the corresponding environmental indicators were calculated based on the guidelines defined in the EN 15084 and ISO 21930 standards.

The results show that the incorporation of recycled aggregates reduces the environmental impacts generated by concrete and, consequently, can reduce those of the building itself. The study of the structure submitted to vertical loads shows that it is possible to reduce the environmental impacts of the total structure. However, the structure subjected to seismic actions dimensioned for concrete with recycled component presents an increase in environmental impacts.

As future work, it is undoubtedly necessary to study alternative substitutions for the concrete components. Suggestions would be to replace a part of the cement or to replace a higher percentage of the virgin aggregates, without compromising the stability and strength of the concrete.

KEYWORDS: Life cycle Assessment; Sustainability; Structural design; Recycled Aggregates; Sustainable Concrete

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

C&D - Construction and Demolition waste

EIs – Environmental Impacts

EN – European norm

EP – Eutrophication potential

EPD - Environmental product declaration

FU – Functional unit

GHG - Greenhouse gas

GWP - Global warming potential

ISO – International Organization for Standardization

LCA - Life cycle assessment

LCI – Life cycle inventory

LCIA – Life cycle inventory assessment

LCT – Life Cycle Thinking

NP – Norma Portuguesa

ODP – Depletion potential of the stratospheric ozone layer

POCP – Photochemical ozone creation potential

RC – Reinforced concrete

RCA - Recycled concrete Aggregates

SCMs - Supplementary cementitious materials

VOCs – Volatile organic compounds

1 INTRODUCTION

1.1 OVERVIEW

We live in a world where there are daily calls for a more sustainable, less consumerist, and more environmentally conscious lifestyle. The search for a sustainable and eco-efficient way of living impacts all aspects of human activities and naturally the construction sector also has a significant part to play, as it fulfils a fundamental need of providing shelter to human beings from the elements. Therefore, specific policies and legislative/regulation documents were developed and are currently in force to reduce the sustainability impacts of the construction sector. An example is the EPBD, Energy Performance of Buildings Directive (European Union 2012). This directive aims to increase the energy efficiency of buildings and improve thermal comfort, ensuring a reduction in energy consumption and reducing the consumption of non-renewable resources.

To increase the sustainability of the construction sector, it is fundamental to assess its impact, in order to define measures and/or policies to improve its environmental performance. Thus, currently an increasing number of studies and research are being carried out to identify, assess and reduce the Environmental Impacts (EIs) caused by the various factors that are part of the construction production process. Due to the consumption of raw materials and energy, this is a sector with significant impacts.

It is consensual that these assessments should be made using a Life Cycle Thinking (LCT) (European Commission and Environment Directorate-General 2010), considering all the activities and materials associated with the life cycle of a product or a process. The evaluation itself of the environmental impacts is usually made using the Life Cycle Assessment (LCA) methodology, that allows to determinate the impacts of a process system (material, product, building, etc.) or service, throughout the various stages of its life. The LCA methodology is established by two ISO standard (ISO 14040:2006; ISO 14044:2006), defining a common framework that enables, for example, the comparison between different materials. It allows the identification of the hotspots process system in terms of environmental impacts, and which improvements measures should be considered first.

Concrete is a crucial material in the construction industry, being the most used in all kinds of infrastructures once it is very durable and low cost. It is composed of different constituents, mainly aggregates, cement, and water. The amount of concrete produced in the world highly contributes to carbon emissions and water consumption, having a significant impact on the environment. For example, cement production typically involves the calcination of calcium carbonate, which generates the production of carbon dioxide, whereas these emissions are not linked to the carbon emissions generated by the production of the energy used in the process. Due to the large use of cement worldwide, the cement industry is one of the largest emitters of Greenhouse Gases (GHG).

1.2 DISSERTATION OBJECTIVES

This dissertation will compare a reinforced concrete (RC) structure, designed for two different concrete classes, C25/30 with recycled concrete aggregates and C35/45. The structure will be designed for two

different types of loads: Design for vertical loads (V) and design for seismic demand (E_{cd}). **Figure 1** presents a graph, which aims to illustrate the comparison made. The lower-class concrete is intended to be a greener concrete, i.e., with content of recycled components. To find this material, I analysed several studies, where it was verified that a more sustainable concrete could maintain all its mechanical properties. The RC fame structure has 5 floors and is symmetric in the orthogonal horizontal directions. **Figure 2** shows the described structure.

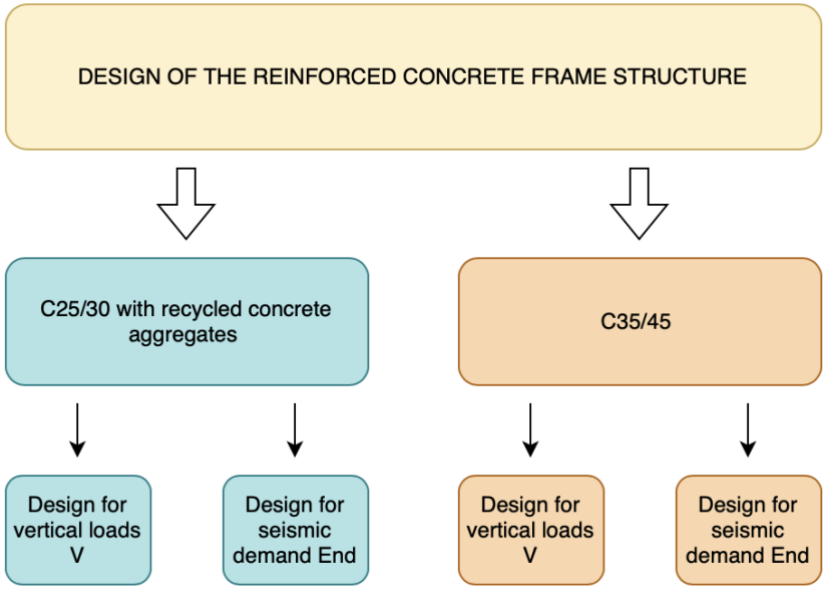


Figure 1 - Comparison of the designed structure for the different scenarios

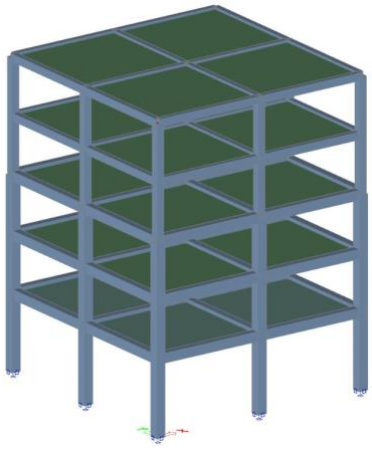


Figure 2 - Designed structure used for this study (Varum and Maranhão 2022)

After the design, it is intended to perform the Life Cycle Analysis of both structures. The objective is to compare the results of the structure dimensioned with concrete class C35/45 and C25/30 with recycled concrete to understand if it is possible to reduce the Environmental Impacts of the structure by using concrete with a lower structural class and recycled material.

1.3 STRUCTURE OF THE DISSERTATION

This dissertation is divided into 6 chapters where the knowledge inherent to this theme will be explored with the aim of better contextualisation and understanding.

The second chapter presents the state of the art, an introduction about the concrete production and the Life cycle thinking approach is made, presenting all the relevant information to this work. The concepts of recycled concrete, recycled aggregates, lightweight aggregates and cement are presented, thus giving a background knowledge of all major aspects.

In the third chapter, "Structural design", the whole calculation phase is described, integrating the necessary selection of a concrete, partially produced with recycled concrete aggregates (RCA). The dimensioning of the reinforced concrete structure is detailed in this chapter.

The fourth chapter deals with the life cycle analysis methodology. The method and materials used are detailed and the categories and indicators analysed in this study are presented. The software SimaPro V9.3.0.3 and database EcoInvent V3.8 were used to obtain the data.

The fifth chapter, "Results and discussion" aims to evaluate the results obtained for LCI and LCIA through the methods applied in the previous chapter. An improvement analysis is also carried out, analysing different solutions to achieve the desired goal.

In the sixth chapter, the conclusions of this study are reported and proposals for future developments are considered.

2
STATE OF THE ART

2.1 INTRODUCTION

2.1.1 CONCRETE

It is well known that concrete is the most widely used material in the construction industry and the second most used material in the world after water (Watts 2019). Concrete is build-up of different components, of which aggregates form a large part. As concrete production increases so do concerns about environmental impacts and the exploitation of natural resources needed for its production to ensure access to all the necessary components. One of the most widely adopted methods for reducing the impacts on the environment is the use of construction and demolition waste as a recycled source of raw materials, thus making it possible to control and reduce some of the EIs created by its disposal in landfill sites and the exploitation of new materials.

According to the (IEA 2019), buildings and construction accounted for 39% of global energy and process-related Greenhouse Gases (GHG) global in 2018. Among them, production of the construction materials, as for example concrete and steel, account for around a third (11% of the global GHG emissions), most of them the result of direct energy consumption. Concrete production constitutes about 4-8% of the world's greenhouse gas emissions. Half of this amount results from the production of clinker, the most energy-intensive part of the production process of cement, which is one of the major constituents of concrete (Watts 2019). To ensure that the cement sector is in line with the Paris agreement it needs to reduce its emissions by at least 16% by 2030. However, cement plays a very important role in the expansion of the built environment, thus creating a conflict (Lehne and Preston 2018). To reduce the emissions associated with cement production there are a number of solutions. The most appropriate solution for the sector under analysis is to mix clinker with alternative materials that allow reducing the amount of clinker in the mixture.

On the other hand, aggregate production has a minimal contribution in terms of EIs compared to cement production. The difference in energy consumption in the production of various types of natural aggregate (NA) and recycled aggregate (RA) has a negligible effect on the total results (Weil et al. 2006). Aggregate production accounts for only 13% to 20% of total CO2 emissions from concrete. However, the use of RA to replace NA in concrete production reduces the consumption of primary resources by up to 44% (Pavlu et al. 2019).

In today's world, the built environment is beginning to overtake the natural one. When it comes to its life cycle environmental impacts, concrete is proving to be very reliable. It is possible to control and monitor its entire life cycle, unlike certain materials, such as those used for packaging production (plastics, metal, cardboard, etc.) which often end up in the sea or other natural environments. Perhaps this is the reason for the undervaluation and lack of concern about the impacts that this material can cause, even though its production is much higher than that of plastic (Watts 2019). A big problem of concrete and construction is the destruction of Nature and natural resources without restoring the

functions they perform which are necessary for the well-being of humanity, directly or indirectly. It also contributes to the biodiversity crisis by converting nature into infrastructure. Yet, the (Portland Cement Association 2019) considers concrete to be a very sustainable building material. There are several reasons mentioned by them, starting with the longevity of a concrete structure, the low life cycle cost and the safety, reliability, and resilience that the structures provide.

2.1.2 LIFE CYCLE THINKING

Every day we consume products that contribute to our wellbeing. However, we are reminded by consumers, producers and even companies of the levels of unsustainability we are reaching and the significant impacts that each of these products has on the environment (European Union 2010). The LCT approach seeks to identify ways in which a good or service can be improved to reduce its economic, environmental, and social impacts. This includes reducing the number of resources used at all stages of its life cycle, from extraction of natural materials to recycling. Life cycle approaches support the transition to a green economy, are transversal to all sectors and allow the analysis of different impact categories and indicators, analysing both social and environmental impacts (Life Cycle Initiative 2022).

One of this tools is the Life cycle assessment. LCA makes it possible to assess the environmental or social impacts of a product or system, at different levels, in a quantitative way. The inclusion of certain life stages in the ACL study is defined by system boundaries, which can be cradle-to-gate, cradle-to-grave, gate-to-gate, or gate-to-grave (Jacob-Lopes 2018). This evaluation method will be described in more detail later in this work.

2.2 RECYCLED CONCRETE

Although we hear a lot about recycled concrete, its use can still a challenge. The huge lack of confidence on the part of those involved in the construction world, the absence of an adequate recovery system with quality control measures for processing and reselling at regulated prices and the lack of regulations to understand what effects the use of recycled materials has on the performance of concrete are some of the aspects mentioned by Silva et al. 2018. Nonetheless, recycled concrete has three main advantages that should be mentioned. As (Colangelo et al. 2018) points out, concrete recycling significantly reduces the demand for new resources; it reduces energy production costs; and it gives new life to waste that would otherwise end up in a landfill. Despite the environmental challenge that this process represents, there are already several case studies presented in various articles.

2.2.1 STATE OF THE ART RESEARCH

A search in the Scopus database for "Life Cycle Assessment and concrete" yielded 1663 results. The search was made applying the following filters: "Article Title"; "Abstract"; "Keywords". The first publication was made in 1996 and the last in 2022 (research period), the year 2021 surpassed all others with a total of 233 publications. The countries with the highest number of publications were, to little surprise, the United States (280), China (191) and Italy (120).

The search was narrowed down to "LCA and recycled concrete" using the same filters. A total of 95 results were obtained starting in the year 1998 and ending in 2022. The year with the most publications was 2021 with a total of 19 publications. Although it is still a little explored area, the increase in the number of publications since the year 2017 is visible and reflects the growing concern with the subject in recent years.

2.3 AGGREGATES

2.3.1 RECYCLED AGGREGATES

Recycling concrete is a relatively simple process. The aim is to use Construction and Demolition Waste (C&D waste) as new construction material, thus obtaining a recycled concrete aggregate and increasing the durability and lifespan of materials. The quality of recycled aggregates produced through C&D waste can vary greatly, facilitating their use in various civil engineering works. This contributes to economic and environmental sustainability.

Many of these new processes arise from the evolution of environmental regulations in developed countries. Tam et al. 2018 addresses this very issue by comparing data from 24 developed countries. All these countries are dedicated to promoting the use of recycled concrete aggregates, reducing the use of landfills and the consumption and extraction of virgin materials. In not so recent legislation ("DIRECTIVE 2008/98/EC") the European Union stated that its member states should prepare for the reuse, recycling, and recovery of a minimum of 70% by weight of their non-hazardous construction waste, excluding the natural ones.

2.3.2 LIGHTWEIGHT AGGREGATES

Lightweight aggregates and lightweight concrete are materials that have a long history. Their first applications can be seen in the Pantheon and Coliseum in Rome. Lightweight concrete is produced using lightweight aggregates (e.g., expanded clay or EPS; density < 2000kg/m^3). Its use is common for filling, thermal and acoustic insulation or even in places where it is necessary and/or desirable to reduce the weight of a structure. The properties of expanded materials are almost identical to those of natural materials, besides the fact that they are less dense, thus allowing the creation of a lighter concrete.

However, nowadays, we are witnessing increasing attention to this type of concrete. The research sector has focused immensely on finding new sources of lightweight aggregates to develop a more sustainable, eco-efficient and cost-effective production.

2.4 CEMENT

The majority of the cement produced in the world is used as a binder in the production of concrete. Cement is responsible for ensuring the stability of concrete. Cement production has a great impact on CO_2 emissions, not only because it is a process with a high thermal consumption, but also because CO_2 is produced in the transformation of the raw material.

There are several associations that provide information on ways to reduce CO_2 emissions in the cement industry. One of these initiatives was developed by the World Business Council for Sustainable Development (WBCSD), called the Cement Sustainability Initiative (WBCSD 2022). It brings together 24 concrete producers in 100 different countries with the focus of managing and minimising the impacts generated by cement production. There are several goals proposed for the development of this initiative. Some are to identify actions and steps that companies can take in order to accelerate sustainable development, others are to create a framework for more cement companies to get involved in this project.

The European Cement Association aims to find a solution that allows the reduction of CO_2 emissions in concrete production considering the technologies available today (CEMBUREAU 2013). They believe that with a common effort it is possible to reach the goal of an 80% carbon emission reduction by 2050.

The Portland Cement Association (PCA) supports initiatives that promote cement production with a focus on reducing the carbon footprint (Portland Cement Association 2019). With the commitment of several PCA members to reduce carbon emissions, the PCA aims to develop a roadmap to enable member companies to achieve carbon neutrality by 2050. Over the past 40 years producers have already

reduced energy consumption by ca. 40%. These initiatives are important to ensure a more environmentally efficient cement and therefore concrete production.

3 STRUCTURAL DESIGN

3.1 CHOICE OF RECYCLED CONCRETE - C25/30

The first step in the design phase was the choice of a recycled concrete of class C25/30. After an extensive analysis it was concluded that the Article (Meddah 2020) proved to be the most suitable. The parameters to be considered in this analysis were that the mechanical properties should remain identical to the EC2 standard concrete.

In the referred paper, coarse recycled concrete aggregates were used in three different proportions of 30%, 50% and 100% to produce concrete. Tests were carried out for different degrees of compressive strength and various w/c ratios. The values for workability, mechanical and durability performances are analysed.

The C25/30 concrete class showed quite different behaviours for the various proportions of RCA. Both the 30% and the 50% showed an ideal behaviour in almost all the parameters analysed. However, the durability performances decreased when the RCA content was increased beyond 30% and, for this reason, the grade of concrete C25/30 with 30% RCA was selected.

The properties of the recycled concrete aggregates used as a substitute for the natural aggregates (NA) are as described in the table below:

Table 1 - Properties of the aggregates (Meddah et al. 2020)

Properties	Coarse Recycled Concrete Aggregates (RCA)
Nominal size (mm)	20
Specific gravity	2,43
Dry-rodded Unit weight (kg/m^3)	1280
Water Absorption (%)	5,3
Fineness modulus	6,7
Crush value	23,4

3.1.1 WORKABILITY

Regarding workability, the results obtained in the slump test were within the defined limits. The compaction factor reached 0.98, a value slightly higher than expected. However, both are within the limits of the S1 and S2 slump classes.

3.1.2. MECHANICAL PROPERTIES

For this concrete and according to (Meddah 2020) the values for the mechanical properties are as described below:

Table 2- Mechanical Properties

C25/30 with 30% RCA	
Description	Value
Mean compressive strength (MPa)	32,5
Modulus of Elasticity (GPa)	25
Flexural strength (MPa)	3,5
Splitting tensile Strength (MPa)	2,55

3.1.3 DURABILITY PERFORMANCES

The durability of concrete produced with RCA was evaluated according to porosity, resistance to carbonation and Chloride Permeation. For the porosity, the results of the ISAT-10 for the concrete with 30% RCA replacement was 0,52 ml/m^2/s. For the same concrete strength, with 0% RCA replacement the result was 0,40 ml/m^2/s. It can be stated that the difference between the two values is very slight and not significant. The remaining values can be found in the figures below.

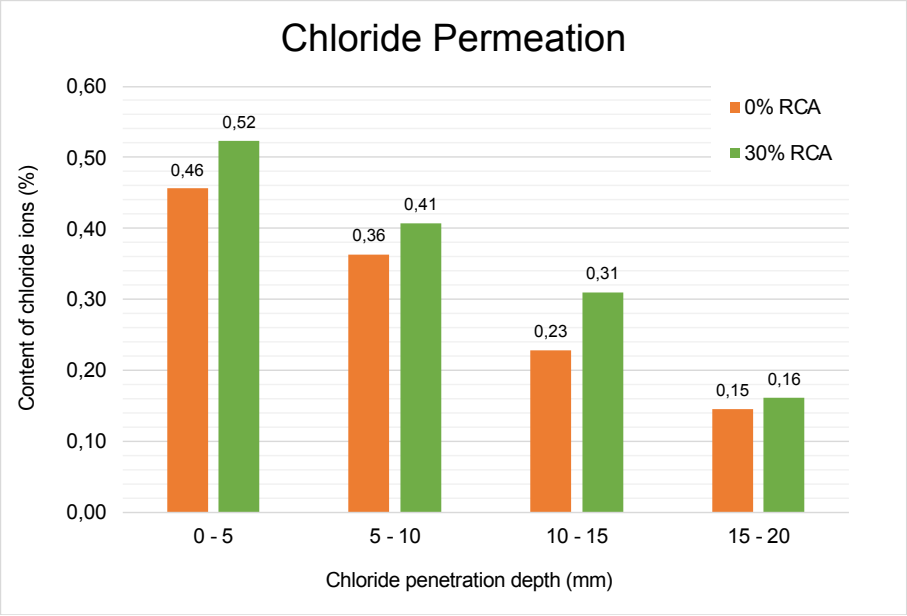


Figure 3 - Chloride penetration depth

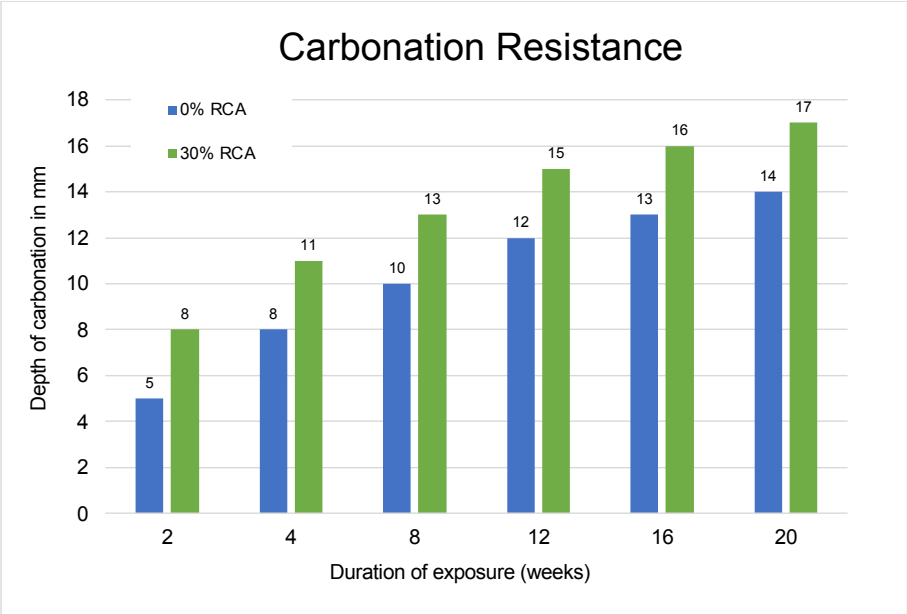


Figure 4 - Depth of carbonation vs Duration of exposure

3.2 STRUCTURAL ANALYSIS AND DESIGN

The structure was designed for two structural classes of concrete (C25/30 e C35/45) regarding two different loading cases. In the first case, the structure was designed considering only the vertical loads (*V*). In the second case, the structure was designed according to the vertical and seismic load cases according to EN 1998-1:2004 (EC8) (E_{CD}). The structural analysis was made with the software *Scia Engineer* and all design calculations were made using Excel. The designed structures refer to calculation examples from Helder Maranhão's PhD work, so all aspects and information mentioned during this chapter are taken from (Varum and Maranhão 2022).

The RC structure is a structural frame system in which the vertical and lateral loads are resisted by spatial frames, composed of 2 bays in each direction, spanning 6,0 m long in the X direction and 5,0 m long in the Y direction, isotropic in the orthogonal horizontal directions. The structure has 5 floors where the ground floor is 3,5 m high, and the remaining floors are 3.0 m high. All these dimensions are described in figure 4. For reasons of simplification, it shall be mentioned that only the central frame of the building structure has been designed, and it was assumed as planar, highlighted in pink in figure 6.

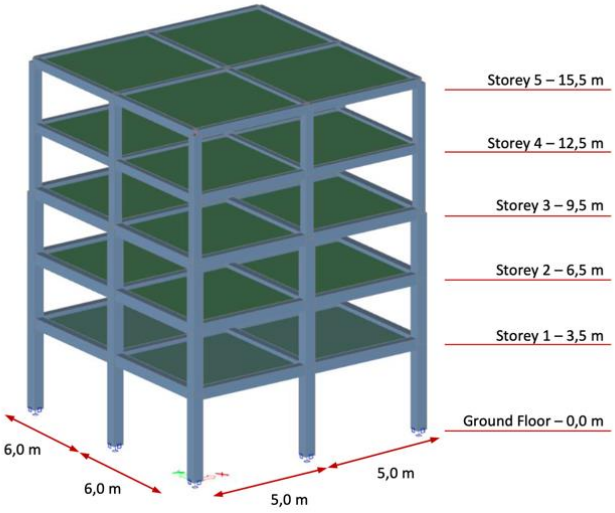


Figure 5 - Building Geometry

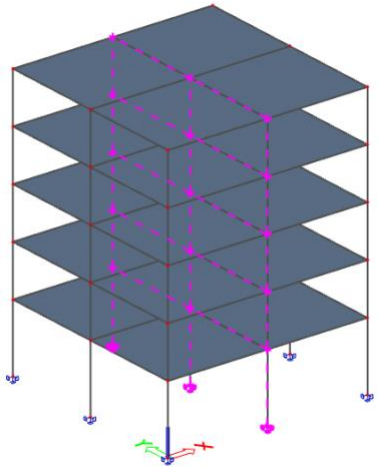


Figure 6 - Central Frame

3.2.1 MODELLING ASPECTS

The structure was designed and analysed for earthquake demand in one direction only. Global torsional effects were not considered in the design and analysis and pure translational response was considered.

The contribution of the slab stiffness was not considered in the model and the columns and beams were modelled on their central axis. The stiffness of the joints was not modelled. Concrete stiffness in cracks was also assumed: for flexural and shear stiffness properties of concrete elements, half of the corresponding stiffness of non-cracked elements was taken, as proposed in NP EN 1998-1:2004 4.3.1(7)

Regarding the masses:

a. Masses of the slabs, other permanent loads, and live loads with the quasi-permanent value, were assumed uniformly distributed on the floors;
b. Masses of the frame elements (beams and columns) were considered automatically by the software (distributed along the axis of the elements)

No redistribution of bending moments was adopted in this study, even though according to NP EN 1998-1:2004 (EC8) it is allowed (following the specifications of NP EN 1992-1-1:2004 (EC2))

3.2.2 DESIGN ASSUMPTIONS

The nominal concrete cover c_{nom} is calculated by adding the minimum cover c_{min} and the allowance in design for deviation Δc_{dev}.

Related to the environmental conditions and according to NP EN 206-1:2007, the assumed exposure class was XC1, and therefore c_{nom}=3,0 cm

The structures are assumed to be regular in plan and in elevation. Thus, no reduction of the q-factor was adopted.

The steel reinforcement in beams, columns and joints was calculated according to EC2 and with specific detailed requirements in Eurocode 8 (EC8).

In the design of the structural elements, it was intended to obtain the optimum dimensions of the structural elements at design forces, without adopting typical rules of common practice, such as constant section in columns throughout their height, etc. However, a rule was imposed that the cross-section dimension of the columns should not be increased in height.

Moderate reinforcement ratios ρ = [1.0-2.5%] for columns, ρ = [0.5-1.0%] for bottom reinforcement in beams and, ρ = [1.0-1.5%] for top reinforcement in beams were adopted and also a balanced reinforcement on both faces of beams as defined with (EC8), section 5.4.3.1.2 (4-b).

3.2.3 LOAD VALUES AND THEIR DISTRIBUTION

The structure's self-weight (G_{k1}) was defined by considering that all RC elements have a volumetric weight γ=25 kN/m^3. The columns and beams masses were generated by the Finite Element software. The slabs were calculated according to the tributary areas and assumed as uniformly distributed loads on the beams.

The other permanent loads (G_{k2}) are divided between the loads on the current storeys, 1st to 4th floors, and those on the roof, the 5th floor. For the current storeys, the external walls and partitions are considered to have a contribution of 3,0 kN/m per unit of wall length. According to section 6.3.1.2 point 8 of EN 1991-1-1 (EC1), the uniformly distributed load on the floors is dependent on the self-weight of the partitions and takes, in this case, the value of 1,2 kN/m^2. For the floor finishing, a uniformly distributed load of 1,3 kN/m^2 is assumed. The 5th floor has as finishing a uniformly distributed load of 1,0 kN/m^2.

According to table 6.1 of EC 1, for the current storeys, this building is classified under use category A "Areas for domestic and residential activities". Table 6.2 of section 6.3.1.2 of the same standard provides the value of the live loads for that category as q_k = 2,0 kN/m^2. The roof category is H “Roofs not accessible except for normal maintenance and repair” (section 6.3.4 of EC 1) and the value provided for the live load is q_k = 1,0 kN/m^2.

For the vertical loads, the structure was designed for the combination of actions for persistent or transient design situations (fundamental combinations) (EN 1990:2002) (EC0):

$$\sum_{j\geq 1} \gamma_{G,j} G_{k,j} + \gamma_{Q,1} Q_{k,1} + \sum_{i>1} \gamma_{Q,i}\, \psi_{0,i} Q_{k,i} \qquad (1)$$

With $\gamma_{G,j} = 1{,}35$ and $\gamma_{Q,1} = 1{,}5$. In this study wind, snow and thermal actions were not considered.

For seismic action, the calculations were performed on the basis of a horizontal response spectrum, figure 7.

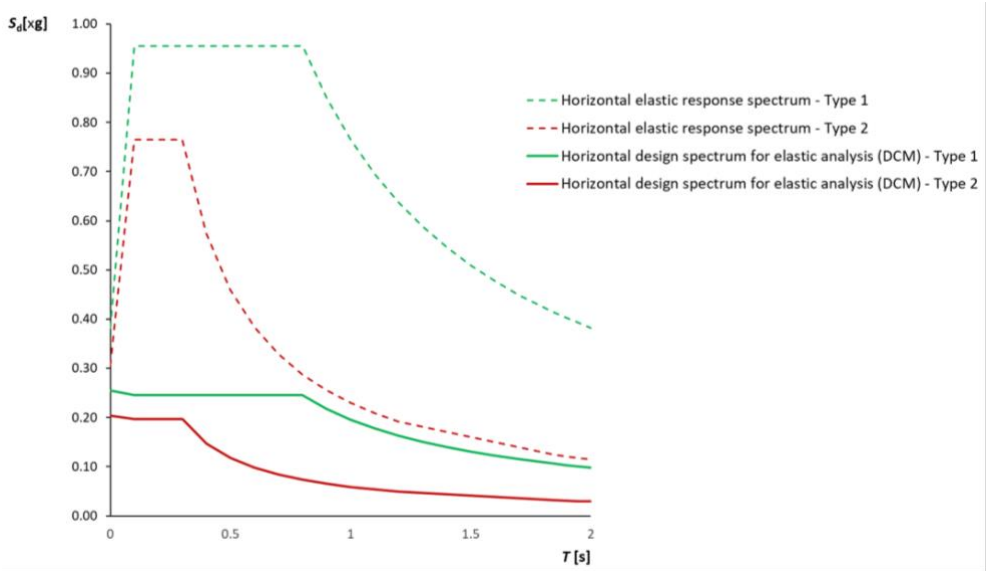


Figure 7 - Horizontal elastic response spectrum and horizontal design response spectrum for linear analysis

All parameters used in the analysis were taken from EC8. It was assumed that the structure was located in the city of Lagos, in the south of Portugal. The importance factor was defined as $\gamma_1 = 1,0$. The values describing the elastic response spectrum for type 1 and type 2 were taken, assuming a soil type (D), from the respective tables. The ductility class for which the building was design is DCM, Consequently, the behavior factor q is defined regarding the structural type and the ductility class considered. The behavior factor for horizontal seismic actions is defined as follows according to EC8 (5.2.2.2).

$$q = 3{,}0 \cdot \alpha_u/\alpha_1 \tag{2}$$

Based on the fact that this building is a multistorey building, with multi-bay frames the value $\alpha_u/\alpha_1=1{,}3$ may be used. The assumed value for the behavior factor is $q = 3{,}0 \cdot 1{,}3 = 3{,}9$. This way, it was possible to define the horizontal design response spectrum for elastic analysis.

For the seismic action, the structure was designed for the combination of actions for persistent or transient design situations (fundamental combinations) (EN 1990:2002) (EC0):

$$\sum_{j\geq 1} G_{k,j} + A_{Ed} + \sum_{i>1} \psi_{2,i} Q_{k,i} \tag{3}$$

3.2.4 Measurement Rules for final material quantities

The rules to be adopted for measurements will be as follows:

a. The concrete volumes will be measured at the axes of the structure.
b. The steel volumes will be measured at the axis of the structure including the transverse reinforcement.
c. The transverse reinforcement of the beams is measured at their axis. (**fig. 8**)
d. The transverse reinforcement of the columns is measured at their axis. (**fig. 9**)
e. In the case of columns with more than one type of stirrup (in E_{CD}) these must be calculated in accordance with the longitudinal reinforcement bars. (**fig. 10**)

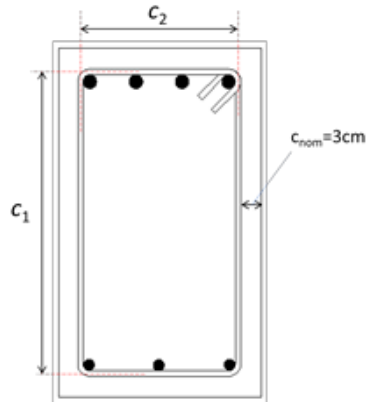


Figure 8 - Beam stirrups

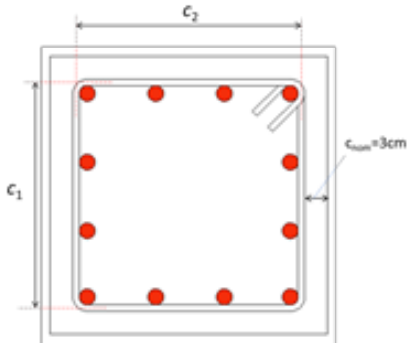


Figure 9 - V Column stirrups

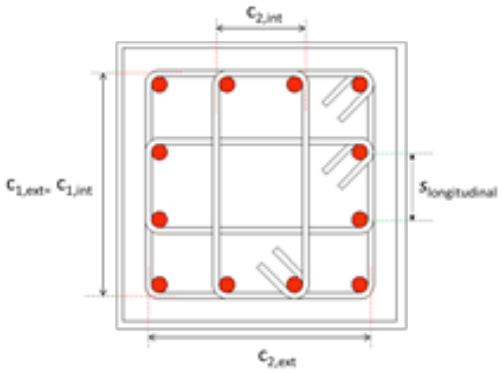


Figure 10 - ECD Column stirrups

3.3 STRUCTURAL DESIGN FOR C25/30 CONCRETE

3.3.1 DESIGN FOR VERTICAL LOADS (*V*)

Initially, the dimensions of the cross-sections were defined. All values are described below.

- Beams: 300 x 400 mm (At all storeys)
- Columns: 400 x 400 mm (1st storey)
  350 x 350 mm (2nd and 3rd storey)
  300 x 300 mm (4th and 5th storey)

Using the fundamental combinations and the design software, all forces, to which the structure was subjected (axial, shear, bending moments), were calculated. Following the EC2 guidelines and the previous calculations, the necessary reinforcement was calculated for both flexural and shear actions in beams and columns. All the results are available in the annex A1

3.3.2 Design for seismic demand considering the global ductility condition: Capacity Design (*ECD*)

According to EC8 paragraph 4.4.2.3, in a multi-storey building, the formation of a soft-storey plastic mechanism shall be prevented. In frame buildings the following condition should be verified at all joints of primary and secondary seismic beams with primary seismic columns:

$$\sum M_{Rc} \geq 1.3 * \sum M_{Rb} \quad (4)$$

For the structure to comply with the capacity design criteria it is necessary to: (i) increase the amount of reinforcement in the columns; (ii) increase the cross-section of the columns. The dimensions adopted for this scenario are as follows:

- Beams 400 x 600 mm (1st, 2nd and 3rd storey)
  400 x 500 mm (4th and 5th storey)
- Columns: 550 x 550 mm (1st storey)
  500 x 500 mm (2nd and 3rd storey)
  450 x 450 mm (4th and 5th storey)

Following the EC8 guidelines and using all the previously mentioned data the reinforcement was calculated for both flexural and shear actions and the results are presented in the table in annex A2.

3.4 Structural Design for C35/45 concrete

The calculations performed for the C35/45 structure were the same as for the lower-class structure, however the dimensions of the structure were adapted and are presented in the following sections.

3.4.1 Design for vertical loads (*V*)

The values of the cross-sections used for the design are as follows:

- Beams 300 x 400 mm (At all storeys)
- Columns: 400 x 400 mm (1st storey)
  350 x 350 mm (2nd and 3rd storey)
  300 x 300 mm (4th and 5th storey)

The structure was designed as mentioned in section 3.3.1, for vertical loads, designed for the fundamental combinations, following the (EC2) guidelines. The results for the required reinforcement are presented in the attached table (A3).

3.4.2 Design for seismic demand considering the global ductility condition: Capacity Design (E_{CD})

As previously (3.2.2), in order to meet the capacity design criteria, the cross-section of the beams and columns were increased. The dimensions are the following:

- Beams 400 x 500 mm (1st, 2nd and 3rd storey)
  350 x 450 mm (4th and 5th storey)
- Columns: 550 x 550 mm (1st storey)

500 x 500 mm (2nd and 3rd storey)
450 x 450 mm (4th and 5th storey)

According to the (EC8) the structure was dimensioned, and the necessary reinforcement defined. The results are presented in annex (A4).

4
LIFE CYCLE ASSESSMENT

4.1 INTRODUCTION

When evaluating the sustainability of product, process, or service, the most objective way to do it is to use a LCT perspective (European Commission and Environment Directorate-General. 2010), that considers all relevant associated activities, materials and energy consumed throughout its life cycle, in a systemic approach. This way, all relevant environmental, economic, and social impacts, either positive or negative, are properly considered. To evaluate the environmental impacts the LCA methodology is commonly used and based on the results obtained in the LCA study it is possible to assess the sustainability of a product, process, or service.

The definition of the life cycle of a product, as the name suggests, refers to the sequence of events in the life of a product. In general, it starts with raw materials extraction, followed by production (including auxiliary materials not incorporated in the product and the energy used), packaging and distribution, use, end of use, that may involve waste treatment and/or recovery/recycling (TOMRA 2020). The described process reflects a linear economy, also known as a cradle to grave life cycle. Nowadays it is desired to turn this linear model of production into a circular one (cradle to cradle life cycle) **(fig. 11**). The goal is to keep, as much as possible, the added value of a product while eliminating its waste (Sariatli 2017).

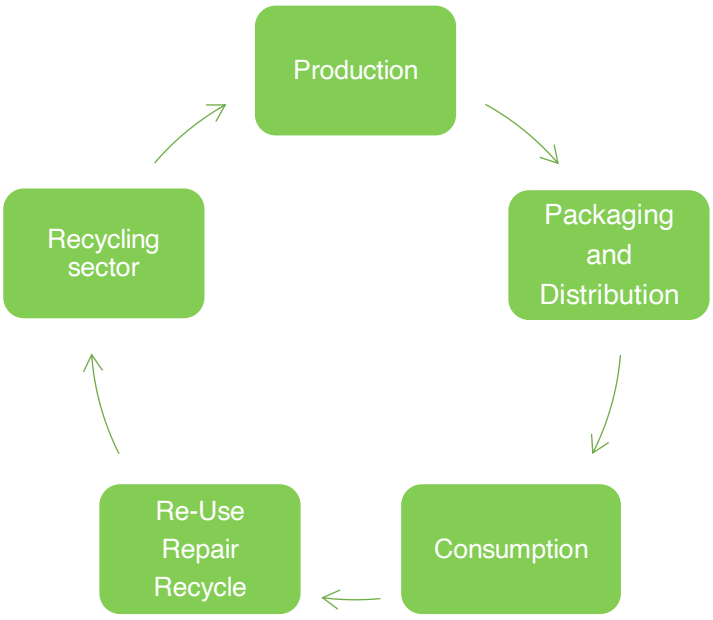


Figure 11 - The circular economy model

The LCA guidelines are defined in accordance with the ISO standard ISO 14040:2006 and ISO 14044:2006. The LCA methodology is divided, according to the standards, into four steps as shown in fig 12: Goal and scope definition; Life cycle inventory (LCI) analysis; Life cycle Impact assessment (LCIA); and Interpretation of the results. To ensure that the study is made in the best possible way, it is necessary to establish the four phases correctly and identify the various stages of production. The first stage (Goal and scope), provide the framework for LCA research. The second step, the Life Cycle Inventory (LCI), gathers the necessary data and information to be able to evaluate the potential environmental impacts in the next step, the Life Cycle Impact Assessment (LCIA). The interpretation step is considered to be the fourth and final step. This is where the results of the study are analysed and it is possible, for example, to identify which are the hotspots in the process or to compare them with similar process systems. However, the interpretation step is also common to the other steps, since the study hypothesis, boundaries and other aspects may have to be adjusted during the execution of the study.

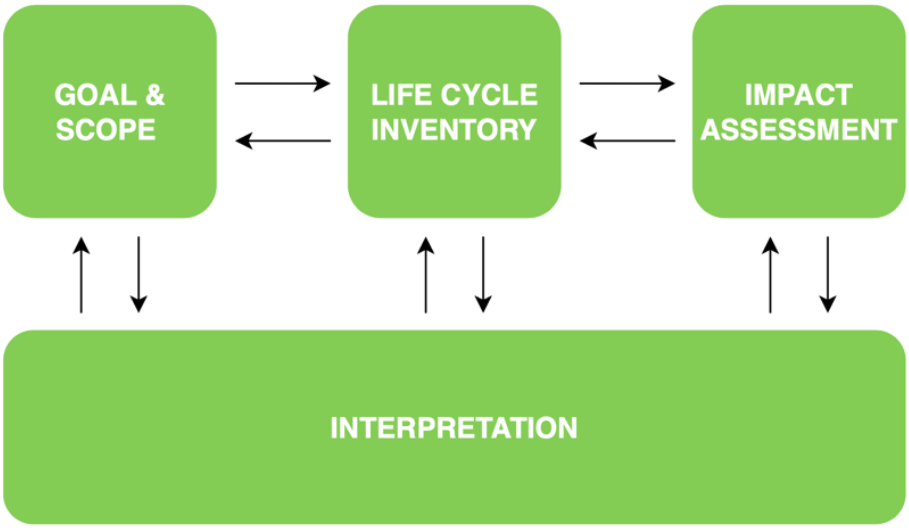


Figure 12 - Four phases of LCA

4.1.1 Goal and scope definition

The Goal establishes the purpose and the aim of the study, and, at this stage, it should be made clear to whom the results of the study are intended. It is important that the formulation of the problem and the context of the study are clearly specified to be sure to achieve the result intended (Henrikke Baumann and Anne-Marie Tillmann).

Regarding the scope definition, it is important to define the product to be studied, the functional unit, the system boundaries (which processes are included), the impact categories and method of impact assessment, data requirements and some other specified in the standards. The selection of all these parameters is an essential step towards the LCA. Since this technique is iterative, it is possible that changes may have to be made during its execution to ensure that the objective of the study is achieved.

The goal and context of the study should be formulated in detail and thus be able to determine the relevant methodological decisions in the formulation of the subsequent model. After this, the functional unit can be defined. The functional unit shall describe a reference flow to which all input and output flows are related. This quantitative value should allow LCA results to be compared with several products of identical functional unit, which makes this choice extremely critical. The categories and method of impact assessment depend largely on the product being analysed.

4.1.2 LIFE CYCLE INVENTORY (LCI)

In the inventory phase, data is collected, and calculations are made to quantify the system input and output flows of the product to be analysed. The inputs and outputs may be energy and mass flow, as well as data on emissions to the air, land, and water. There are many available databases to obtain generic data for the LCI. In an European context Ecoinvent is considered to be the leading database and so the most used as well.

The LCI can be divided into phases: data collection; data calculation; flow allocation and emissions and discharges. As already mentioned, this process is iterative and, as one learns and researches about the system, new constraints or requirements may be identified. To meet the objectives of the study it may be necessary to make changes to the data collection procedures.

4.1.3 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

In this phase of the LCA the objective is to describe and assess the environmental consequences of the aspects quantified in the LCI. Each value is associated with a specific environmental impact category and a category indicator. This phase is important as it provides information for the next phase of interpretation.

The aim is to make the results more environmentally relevant, more understandable, and easier to communicate. Through LCIA it is possible to reduce the number of parameters by grouping environmental loads into environmental impact categories. It is also useful to make the results more comparable.

4.1.4 INTERPRETATION

The inventory phase is the fourth and final phase of the LCA study. In this phase the results of the inventory and the impact assessment are taken into consideration together. The results provided should be in accordance with the goal and scope initially defined and should also draw conclusions, explain limitations, and make recommendations.

It is important to mention at this stage that the LCIA results are based on relative approaches and that all reported environmental effects are only potential. No actual effects are predicted in final impacts by categories, exceedance of limit values or safety margins or risks. The interpretation also aims to provide a comprehensive, complete, and coherent presentation of the LCA results.

The results of the life cycle interpretation should reflect the results of the product evaluation.

4.2 METHODOLOGY APPLICATION

4.2.1 GOAL AND SCOPE DEFINITION

The main goal of this study is to evaluate the environmental impacts of the structure defined in figure 2 dimensioned for two different structural classes of concrete, and compare the results obtained.

The functional unit was defined as the central frame of the structure in, to facilitate data management as well as its application. The decision to select this functional unit was made to make the comparison of the final impacts of the structures easier and more understandable. Even though the functional unit is the dimensioned structure, the quantities of materials considered in terms of mass or volume depend on the type of material.

The LCA study is a cradle to gate study, i.e., it includes the extraction of raw materials, and the production of the construction materials, in this case considered to be mainly concrete and steel. The construction of the structures is not considered, as it is similar regardless the type of concrete and

structure. Also, it is considered that for the transportation to site, use and demolition phase, the impacts of both structures will be identical. This means that the analysis will be purely based on the raw materials of each structure.

The system boundaries are given in figure13. Figure 14 details the virgin concrete production phase and the recycled concrete production phase is presented in figure 15.

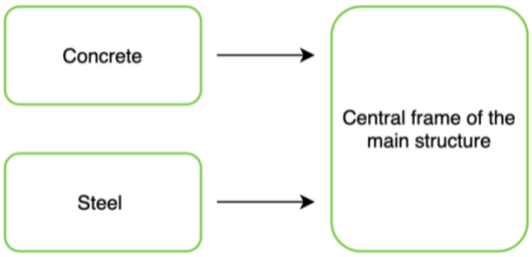


Figure 13 - System boundaries

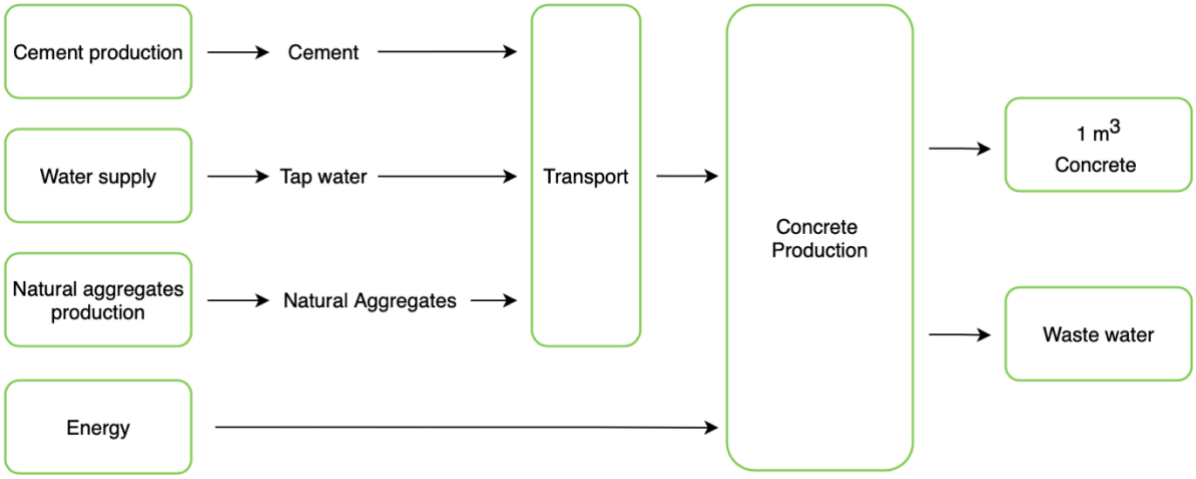


Figure 14 - Virgin Concrete system boundaries

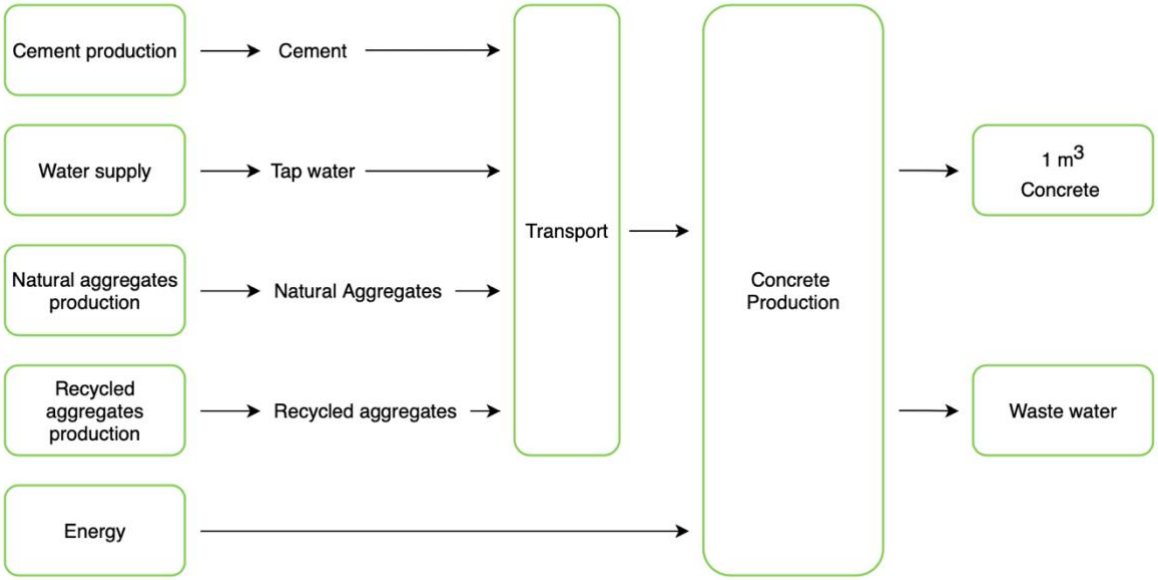


Figure 15 - Recycled Concrete system boundaries

The LCA study is an attributive study, as the environmental impacts are attributed to the functional unit directly. Whenever possible European conditions will be considered, in particular for the energy supply and the production of the raw and construction materials. If not possible, information and data valid for regions will similar technologic and economic development was used. Regarding time coverage, present day conditions and state of the art technologies are considered, and the results are valid in time frame of at least 10 years.

4.2.2 Inventory Analysis

In this stage the inputs and outputs of the system through the system boundaries are considered. As mentioned above, the main inventory terms are concrete and steel, and the total quantities needed for each structure and load is determined by the design of the structure, as described in Chapter 3. For concrete the quantities will be calculated in m^3, and for steel in ton. Even though the data cannot be considered as primary, as it was not obtained from the construction of real structures, the dimensioning procedure is based in rigorous modelling, and can therefore be considered as a good approximation of a real structure.

To be able to evaluate the environmental impacts information concerning the production of concrete and steel a search was made in the available LCA databases. For concrete C35/45 and steel the information was obtained from the Ecoinvent V3.8 life cycle inventory database, integrated in Simapro V 9.3.0.3.

For concrete C25/30 with 30% substitution of natural aggregates by recycled aggregates the process was not so simple. Through available articles and from Environmental Product Declarations (EPD) it was possible to obtain an inventory of the emission values related to the impacts of recycled concrete aggregates. The used EPD refers to an American product produced with 100% renewable energy (Argent Materials Inc. 2021). Their chosen functional unit for the recycled aggregates was 1 metric tonne, which corresponds to 1000kg.

The inventory values for common concrete C25/30 were taken from the Ecoinvent V3.8 database. The software Simapro V9.3.0.3 made it possible to analyse the impacts of each component individually and thus reduce the amount of natural aggregate by 30% and replace it with the equivalent amount of recycled aggregates, the impacts of which were provided by (Argent Materials Inc. 2021).

The choice of all inventory values took into consideration the geographical region to which they referred. The selection of the data took into account its relevance for Portugal or that it was of interest from the point of view of sustainability. Therefore, the values used for the life cycle analysis of concrete are based on the North American country Canada and for steel, we used values referring to the world and European average.

The inventory results are presented in the next chapter and in annex A5.

4.2.3 LIFE CYCLE IMPACT ASSESSMENT

Several standards exist to assess and certify the sustainability of building construction. In particular, the ISO standards ISO 21930:2007 and EN 15804:2012 cover the principles on how to do the environmental product declaration of building products, including in particular recommendations in which environmental impact categories should be selected. In section 8.2.2.1 of ISO 21930:2007 the following environmental impacts categories for LCIA are presented as adequate to assess the environmental impacts of buildings and construction materials:

Table 3 - Environmental impact categories

Impact Category		**Unit**
Acidification of land and water sources		mol H^+ eq
Climate change	Fossil	kg CO_2 eq
	Biogenic	kg CO_2 eq
	Land use and land use change	kg CO_2 eq
Depletion of the stratospheric ozone layer		kg CFC11 eq
Eutrophication	Freshwater	kg P eq
	Marine	kg N eq
	Terrestrial	mol N eq
Formation of tropospheric ozone (photochemical oxidants)		kg NMVOC eq.

The causes of each of these impacts are detailed below. Air pollution is one of the factors with the greatest negative impacts, being responsible for environmental acidification, eutrophication, and the formation of ozone at ground level (Agência Portuguesa do Ambiente 2021 a)

Acidification is the name given to the reduction of pH in soils and waters, which can reach levels where flora and fauna are damaged. The emission of sulphur and nitrogen compounds into the atmosphere contributes to the reduction of pH levels, and acidification of these environments occurs. The pH level of water can decrease if CO2 in the atmosphere reacts with water and this reaction releases hydrogen ions. The water then becomes acidic (Marah Hardt and Carl Safina 2008).

The main cause of climate change are the emissions of greenhouse gases (GHG), which are measured in kg CO_2 equivalent. These gases absorb heat and trap it in the atmosphere. (United States Environmental Protection Agency). Carbon dioxide is the most emitted gas and is produced by burning fossil fuels, industrial production and land use and land use change. Other greenhouse gases are methane, nitrous oxide, and fluorinated gases (Hannah Ritchie et al. 2020).

Figure 16 shows the evolution of greenhouse gas emissions over the years in the world and in the European Union. Although the emissions in the world continue to increase, it is noted that in the European Union the value of emissions in recent years tend to decrease. These results show the will of the EU to achieve a more sustainable future.

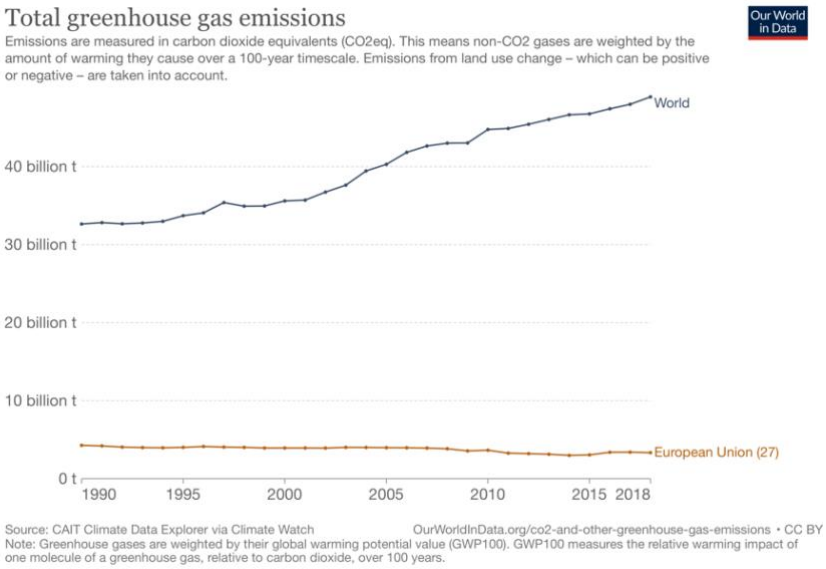


Figure 16 - Greenhouse gas emissions (World & EU) (Hannah Ritchie et al. 2020)

Ozone is a gas naturally present in the stratosphere. It plays a vital role in filtering ultraviolet solar radiation and protecting life on earth (Agência Portuguesa do Ambiente 2021 b).

The depletion of the ozone layer (ODP) is probably one of the impacts we hear about most. This environmental impact refers to the slow thinning of the ozone layer. Ozone depletion occurs when chlorine and bromine atoms come into contact with ozone in the stratosphere. There are compounds which, when exposed to UV radiation, release these same atoms. Ozone is destroyed faster than it is naturally created (European Environment Agency 2021).

However, in the troposphere, ozone is considered a pollutant. For this reason, the formation of the photochemical ozone (POCP) is listed as an impact category. Its formation is caused by volatile organic compounds (VOCs) and carbon monoxide in the presence of nitrogen oxides and sunlight (The European commission 2013). The concentration of this gas in the troposphere has several negative effects on human health, vegetation, and materials. In the construction sector, VOCs emissions are mainly caused by cement production and super plasticizers (Gursel et al. 2016).

Eutrophication consists of an increase in nutrients and minerals in an aquatic or terrestrial system, leading to excessive growth of plants or algae. This process has occurred naturally for years, but human activities have accelerated it. The main contributors to eutrophication are nitrogen and phosphorus (Malone and Newton 2020).

The environmental impact categories listed above will be used to classify the inventory to items, hence this phase is called classification (Colangelo et al. 2018).

After the classification, a calculation methodology to evaluate the corresponding environmental indicators must be selected. In this work it was chosen the calculation methodology in the standard EN 15804 + A2 method. The A2 refers to a revision of the standard, where the methodology was aligned with the Environmental Footprint (EF) method under development in the European Union (EF 3.0 Method). Since the values of the Environmental Impacts of recycled concrete aggregates were calculated based on information obtained on an EPD, it made sense to calculate the remaining EIs in the same way. The second reason is to make the results easier to compare and analyse, as it is used a standardized method that has been used throughout the various EPDs in this area.

5
RESULTS AND DISCUSSION

5.1 INVENTORY ANALYSIS

The inventory analysis was discussed previously in section 4.2.4. The quantities of concrete and steel were based on the dimensioning of the structure and will be presented in tables 4 and 5. The final inventory values for concrete are shown in annex A5.

5.1.1 MATERIAL QUANTITIES FOR C25/30 WITH 30% RECYCLED AGGREGATES

After having performed the dimensioning presented in section 3.3, I proceeded to calculate the total quantities of materials for each structure. The amount of concrete was calculated, for columns and beams, in m^3. The longitudinal and transverse reinforcement of both columns and beams was calculated in tons, assuming a density of 7,8 ton/m3.

Table 4 - Total quantities for the C25/30 concrete class structure with 30% RCA

C25/30 w/ RCA	Total Volume of structural Members (m3)			Total weight of steel reinforcement (longitudinal and transversal) in structural members (ton)				
	Columns	Beams	Total	Columns		Beams		Total
				Long.	Trans.	Long.	Trans.	
V	5,51	7,2	12,71	0,55	0,11	1,12	0,17	1,95
Ecd	11,32	13,44	24,76	1,40	0,55	1,14	0,42	3,51

5.1.2 MATERIAL QUANTITIES FOR C35/45

The total quantities of the materials are shown in table 4. The calculations of the total quantities were carried out as in 5.1.1.

Table 5 - Total quantities for the C35/45 concrete class structure

C35/40	Total Volume of structural Members (m3)			Total weight of steel reinforcement (longitudinal and transversal) in structural members (ton)				
	Columns	Beams	Total	Columns		Beams		Total
				Long.	Trans.	Long.	Trans.	
V	5,51	7,2	12,71	0,55	0,11	1,06	0,17	1,91
Ecd	11,32	10,98	22,30	1,28	0,38	1,27	0,35	3,34

Although, for the structure designed for vertical actions, the cross sections do not change for the two proposed scenarios, there is a variation in the amount of steel required to ensure the safety of the structure. However, as a simplification, it is assumed that the amount of concrete is the same.

5.2 LIFE CYCLE IMPACT ASSESSMENT

The subsequent stage can be referred to as characterisation. The main goal at this point is to allocate impacts to the previously presented impact categories. As mentioned above, this phase of the LCA is important as it allows to assess the magnitude of environmental impacts

The first aspect to bear in mind is that, analysing the different classes of concrete per m^3, the lower class (C25/30) always presents lower impacts when compared to a higher grade of concrete, whether or not it has a percentage of recycled aggregates. A higher concrete class offers higher strength and to make this possible, the amount of some components in the mix is increased, which causes the EIs to increase. Figure 16 illustrates the comparison of the three types of concrete studied. The results are presented as percentages, normalized to class C35/45. The impact values for concrete of class C35/45 in comparison with other types of concrete are displayed in green in the graph.

A comparison is made between normal concrete C25/30 and concrete C35/45. The difference in values is always remarkable, being in some categories higher than others. Concrete class C25/30 shows values ca. 10% lower than the upper concrete class in the categories of climate change, acidification, and freshwater eutrophication. For the remaining categories, the values vary between 6.5% and 8%, being the lower concrete always more advantageous in terms of EIs i.e., more sustainable.

When analysing this figure, it is understood that the replacement of virgin aggregates by recycled ones, effectively enhances the reduction of environmental impacts. The chosen recycled aggregates have very low environmental impact values. Argent Materials Inc. 2021 has chosen to use only energy from renewable sources (50% solar, 50% wind) which also contributes to a reduced value of greenhouse gas emissions.

The comparison of recycled concrete with higher grade concrete shows even more appealing results. For all categories, recycled concrete shows 10% lower values than concrete C35/45, and even 12% lower values in the categories of climate change and water eutrophication.

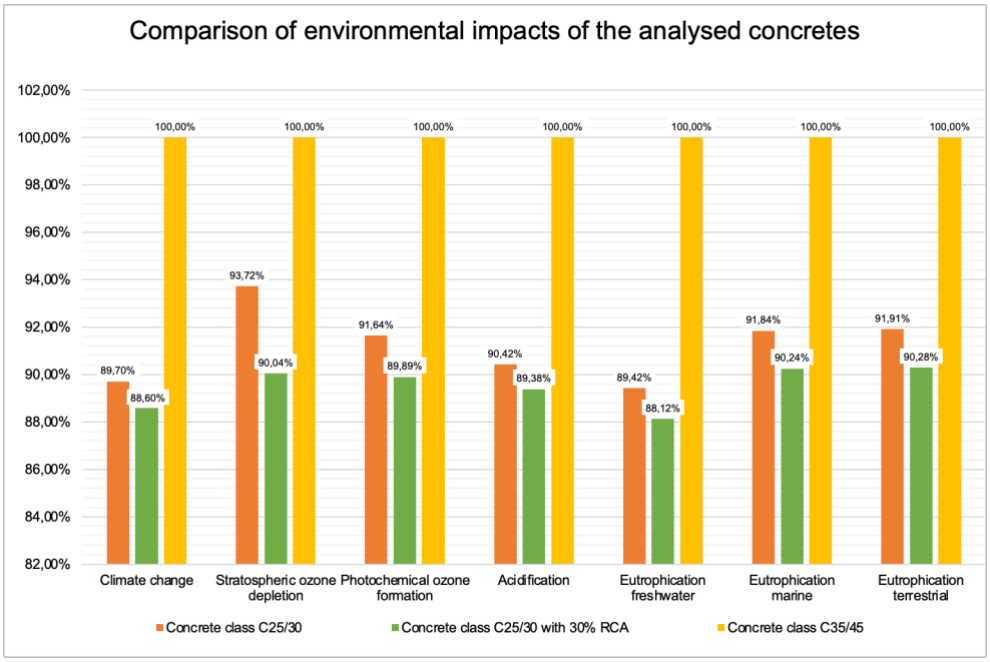


Figure 17 - Comparison of environmental impact of all analysed concrete types

The following figure shows a graph with the analysis of the environmental impacts of class C25/30 concrete with 30% recycled concrete aggregates. The graph illustrates the contribution of each component to the respective environmental impact. It should be noted that cement is, in all

environmental impact categories, the largest contributor, taking values between 68% and 90%. However, it can also be observed that the second largest contributor to EIs is aggregates, both fine (sand) and coarse (gravel). In this case, replacing virgin coarse aggregates with recycled concrete coarse aggregates substantially reduces the individual impact of gravel, as will be detailed later.

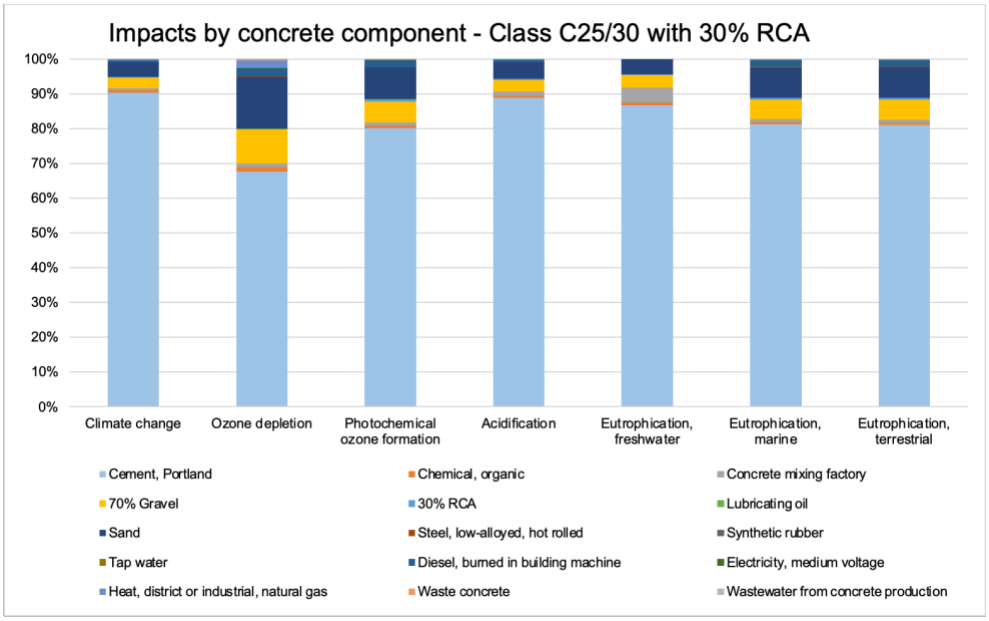


Figure 18 - Impacts by component of concrete class C25/30 with 30% recycled concrete aggregates

As mentioned earlier, to obtain a higher concrete class it is necessary to increase the amounts of certain components, one of them being the cement. The following figure (18) presents the contribution of each component to the various environmental impact categories. As can be seen, cement is, once again, the largest contributor to all impact classes. It assumes values between 68% and 90% in the various categories, the most notable being climate change and acidification.

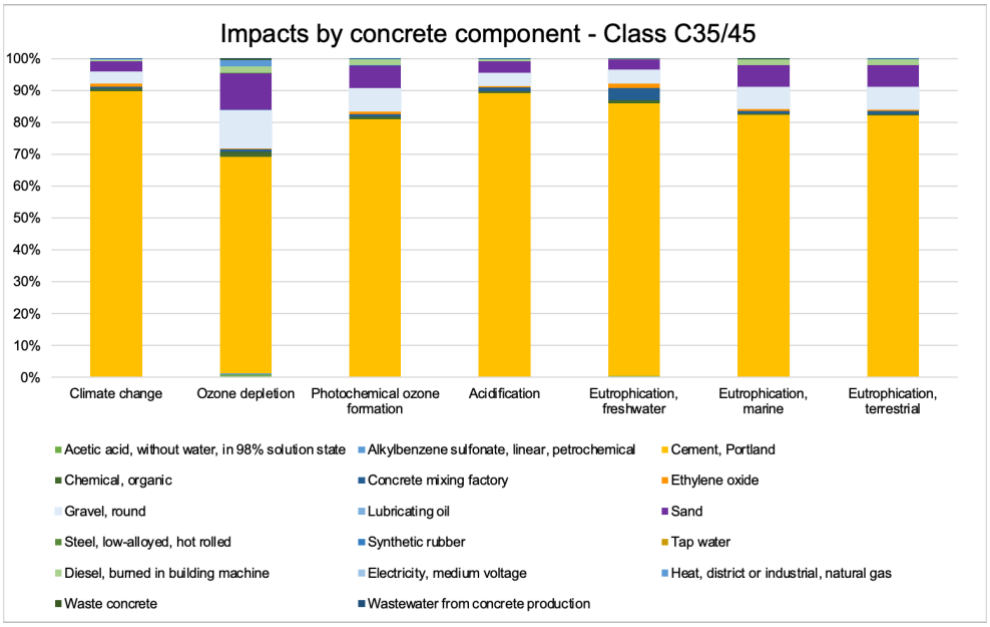


Figure 19 - Impacts by component of concrete Class C35/45

The reduction of the amount of natural aggregates does not show, in the final scenario, such a remarkable impact as in the case of replacing a percentage of cement by a more sustainable material. In fact, the reduction of the amount of natural aggregates does not show, in the final scenario, such a remarkable impact as in the case of replacing a percentage of cement by more sustainable materials. However, the fact that there is a reduction in impacts shows how this solution has a sustainable character.

5.2.1 AGGREGATES

Figure 19 illustrates the reduction in the potential EIs when replacing 30% of coarse aggregates with recycled aggregates. The use of recycled aggregates reduces the impacts of all the categories analysed, some being more significant than others.

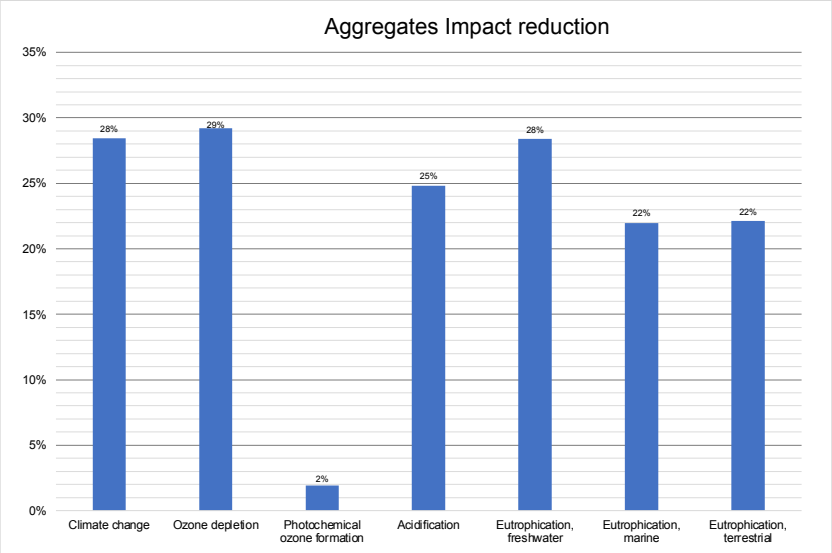


Figure 20 - Reduction of environmental impacts by replacing 30% of virgin aggregates with recycled aggregates

Regarding the climate change impact, to produce 1.0 m^3 of concrete, the amount of virgin aggregates used, emits approximately 12 kg CO^2 eq. (figure 20). This value is reduced by 28%, to 8.51 kg CO^2 eq., when 30% of the virgin aggregates are replaced by RCA.

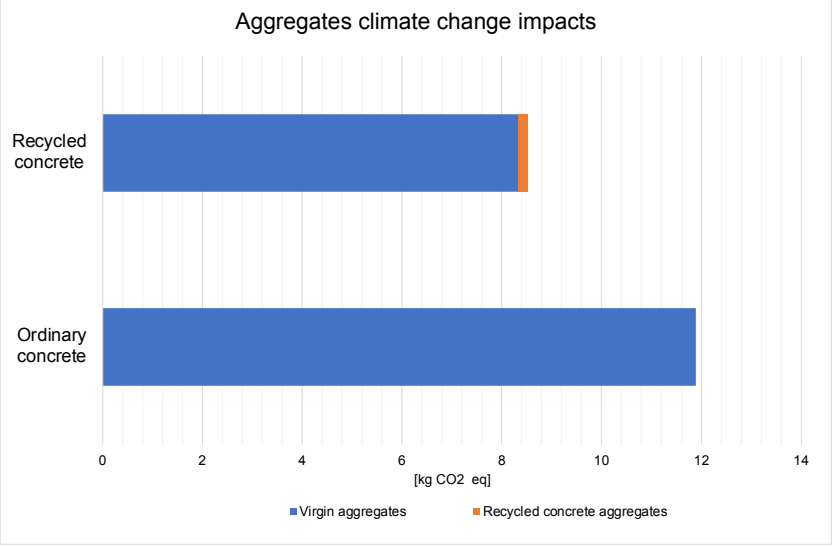


Figure 21 - Climate change impact comparison

In the production of recycled aggregates, chlorine and bromine are emitted less and consequently contribute to the reduction of the destruction of the ozone layer (Park et al. 2019). Figure 19 shows a reduction of almost 30% of the potential impact for the ozone depletion.

The photochemical ozone formation exhibits rather low impact values for all case scenarios. As in the production of aggregates, VOCs occur to a very reduced extent, this impact, as well as its reduction, is quite low.

The potential environmental impact values of acidification were reduced by 25%, corresponding to 0.0215 mol H+ eq. The reduction of virgin aggregates and therefore of carbon dioxide, reduces acidification.

Regarding eutrophication**,** a 30% reduction in natural aggregates reduces the amount of dumped waste, so the values of the potential impacts of this category are thus reduced.

5.2.2 REINFORCED CONCRETE FRAME STRUCTURES

The final potential impacts of the designed and analysed structure are presented below. The analysis is made according to the functional unit, i.e., the central frame of the structure, considering all the data necessary for its production.

5.2.2.1 STRUCTURES DESIGNED FOR VERTICAL LOADS

Initially, a comparison of the structure subjected to vertical loads is made. The structure, as mentioned throughout the study, was dimensioned for concrete class C35/45 and C25/30 (recycled concrete). The comparison considers all the base materials necessary for the production of the structure (steel and concrete).

Figure 22 illustrates this comparison; the blue bars represent the lower concrete class, and the green bars represent the higher class. The first aspect that can be noted when analysing the graph is that concrete produced using recycled materials has a lower environmental impact in all categories. In this structure, a significant part of the impacts is caused by the amount of steel used. Figures 23 and 24 represent the contribution in percentage of each material to the final impacts value. In the case of figure 23, it can be said that steel is responsible for 50% or more of the environmental impacts, with the exception of the impact of acidification. In this first scenario for the different designs, the cross sections remained the same. In order to guarantee that the lower-class structure complied with all the safety rules, the amount of reinforcement was increased. This increase is evident in the graphs of Figures 23 and 24. Comparing the steel contribution in each of the scenarios, it is noted that in the case of the upper-class concrete structure, the steel contribution is lower.

For this type of application, where the applied loads are relatively constant, it is possible to obtain a slightly more sustainable solution, without compromising the stability and safety of the structure.

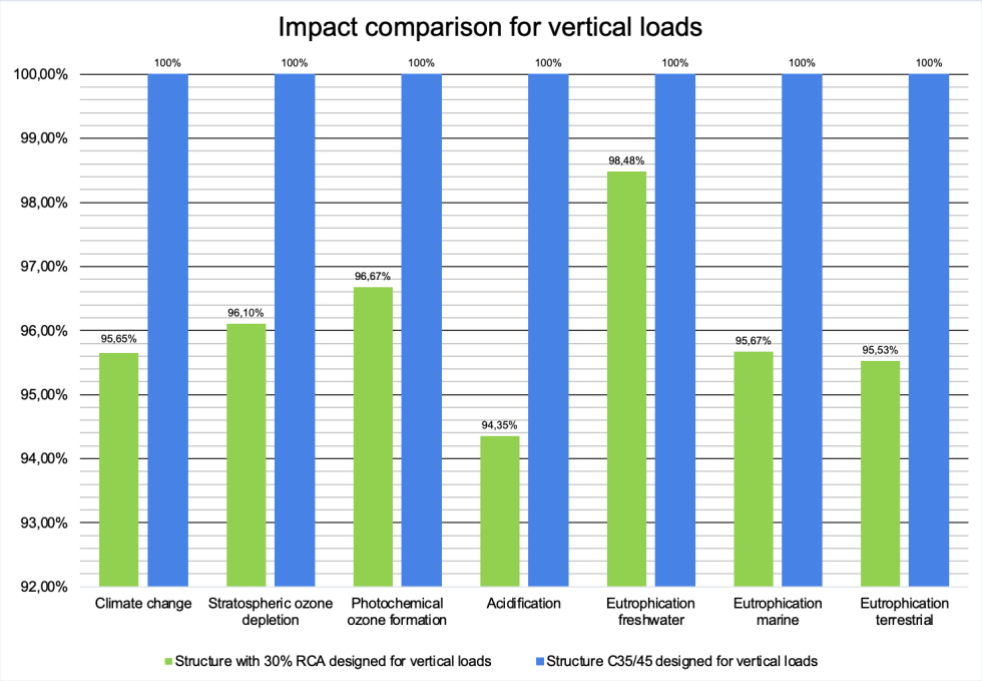


Figure 22 - Potential environmental impacts normalised to concrete class C35/45 for the scenario designed for vertical loads

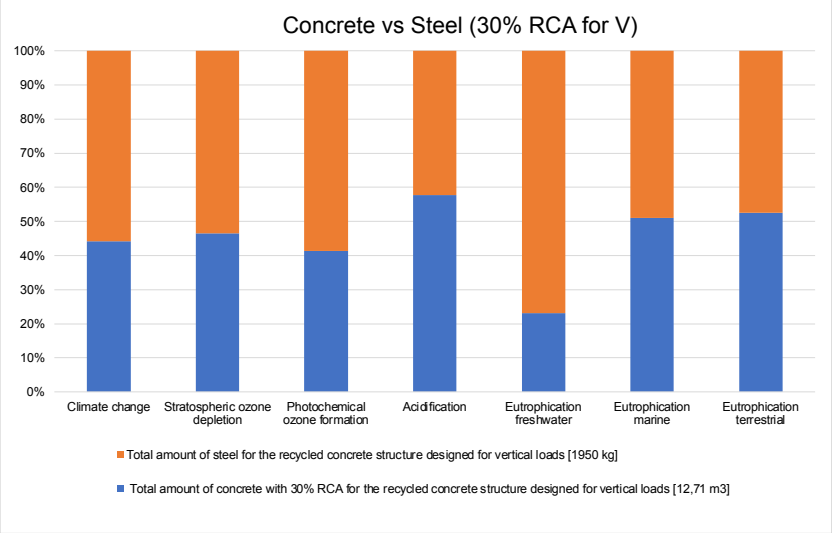


Figure 23 - Comparison of environmental impacts of steel and concrete according to functional unit for the recycled concrete structure designed for vertical loads

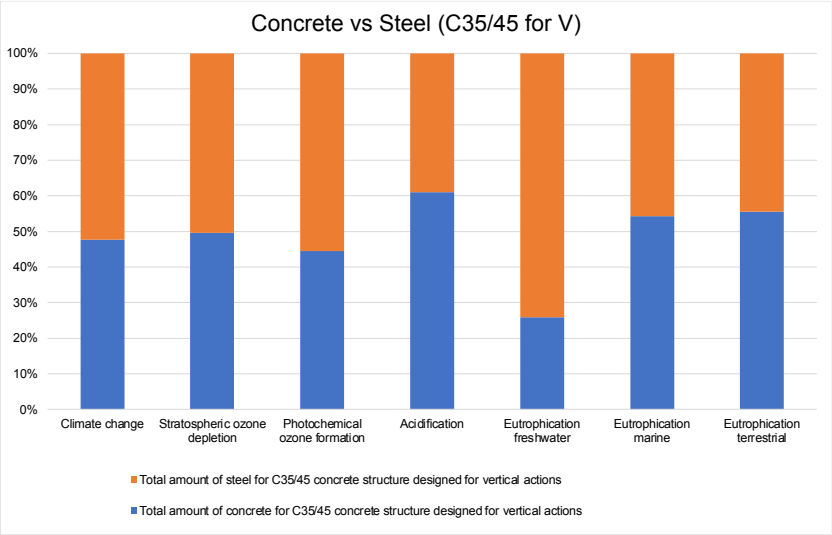


Figure 24 - Comparison of environmental impacts of steel and concrete according to functional unit for the concrete class C35/45 structure designed for vertical actions

5.2.2.2 STRUCTURES DESIGNED FOR SEISMIC DEMAND

The scenario where the structure is designed for seismic demand, the results were not as desired. Figure 25 illustrates the comparison of the structure dimensioned for two concrete classes, in yellow the lower concrete class with recycled aggregates and in orange the higher concrete class. From the graph it becomes obvious that the lower-class concrete structure, despite containing recycled material, has higher environmental impact values than concrete class C35/45.

This happens for two reasons. The first is that, in order to comply with the capacity design criteria (detailed in section 3.3.2 of this paper) it was necessary to increase the cross section. This led to the need to use more concrete in the lower grade structure. Once the cross section was increased and the concrete class offers lower structural strength, to ensure the safety of the structure, it was also necessary to increase the amount of reinforcement. This is the second reason why the impacts are higher. In this case, as can be seen from the graphs represented in figures 26 and 27, the contribution of steel and concrete is practically identical for both scenarios. However, the absolute quantity of concrete and steel in the structure with lower grade of concrete are higher (Table 4 and Table 5). Leading to the results of this same scenario being higher.

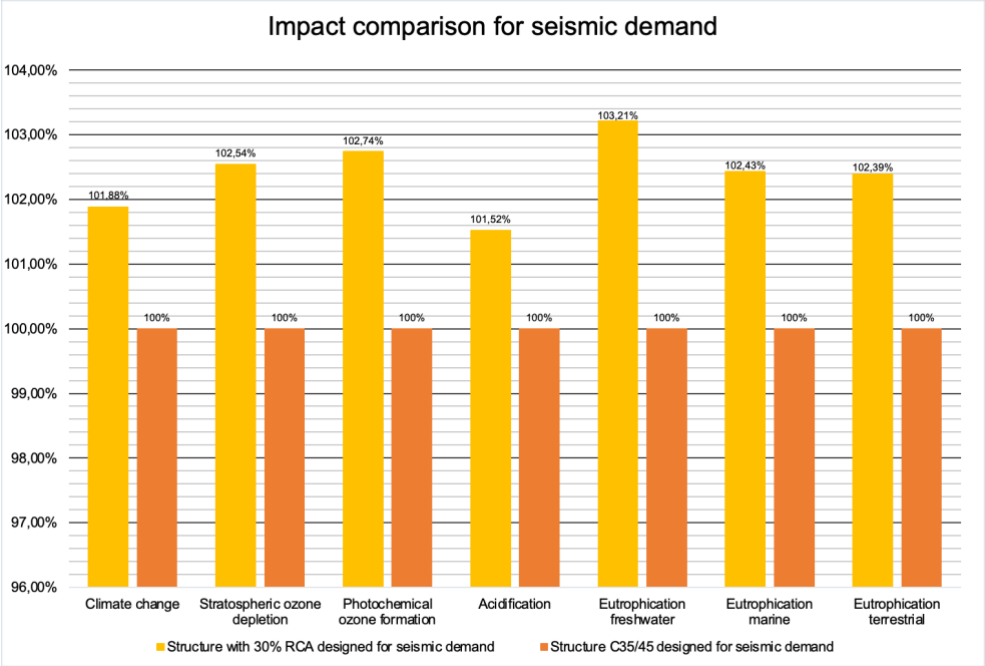


Figure 25 - Potential environmental impacts normalised to concrete class C35/45 for the scenario designed for seismic demand (Ecd)

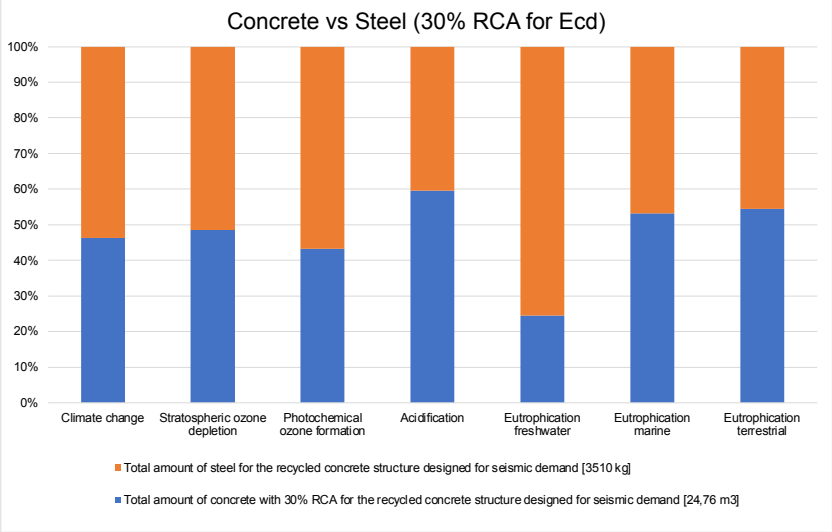


Figure 26 - Comparison of environmental impacts of steel and concrete according to functional unit for the recycled concrete structure designed for seismic demand

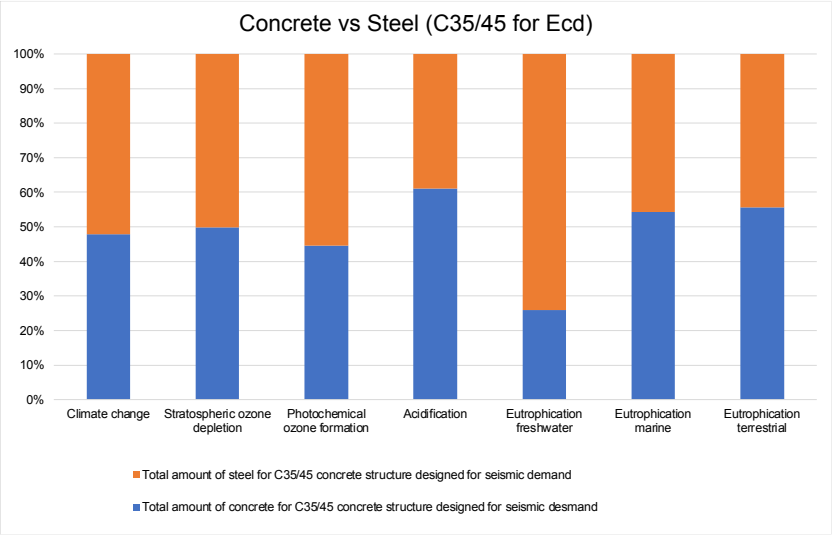


Figure 27 - Comparison of environmental impacts of steel and concrete according to functional unit for the concrete class C35/45 structure designed for seismic demand

5.3 IMPROVEMENT ANALYSIS

After carrying out this study it can be stated that some of the results obtained were not as positive as expected. The environmental impacts that are reduced by replacing virgin aggregates with recycled aggregates are not very significant when analysed in the final picture.

However, there are other impacts that were previously unaccounted for, but are avoided with this replacement and contribute to a more sustainable world. By resorting to the use of recycled aggregates, more waste is prevented from being dumped in landfills, the use of virgin aggregates is reduced, avoiding the destruction of more natural and energy resources as well.

5.3.1 ALTERNATIVE SCENARIO – 50% REPLACEMENT RATIO OF NATURAL AGGREGATES

The aim is to find a solution that can show better results than those previously presented. To this end, one of the scenarios envisaged would be to replace 50% of natural aggregates with RCA in the concrete mix of class C25/30. For this suggestion to be applied though, it would be necessary to ensure that the mechanical properties of the concrete would not be compromised. In (Meddah et al. 2020) it is stated that by increasing the replacement ratio up to 50% an increase in compressive strength is even visible. However, the remaining durability properties such as carbonation, sulphate, and chloride attack resistances decreased. If the necessary properties, so that strength is not affected, can be achieved, the final Impacts of the structure are as presented below.

The graph in Figure 28 compares the final EIs of the structure dimensioned for vertical loads and for the different concrete classes and different replacement ratios. The results have been normalized according to the higher-class concrete structure. The green bars represent the structure dimensioned for concrete class C25/30 with a 50% substitution ratio; the blue bars represent the structure dimensioned for the same concrete class, but with a 30% substitution ratio; the yellow bars represent the structure dimensioned for concrete class C35/45.

The graph in figure 29 makes the same comparison, but the structure was designed for seismic demand. The orange bars represent the structure dimensioned for concrete class C25/30 with a 50% substitution ratio; the dark blue bars represent the structure dimensioned for the same concrete class, but with a 30% substitution ratio; the dark green bars represent the structure dimensioned for concrete class C35/45.

With the increase of the replacement ratio, a reduction of impacts is seen in both scenarios. However, this reduction is not very accentuated, since, as previously stated, the aggregates do not have a large

contribution to the EIs of concrete. Note that, as also mentioned before, the results presented below refer to the complete structure with concrete and steel, having the steel emission factors quite accentuated.

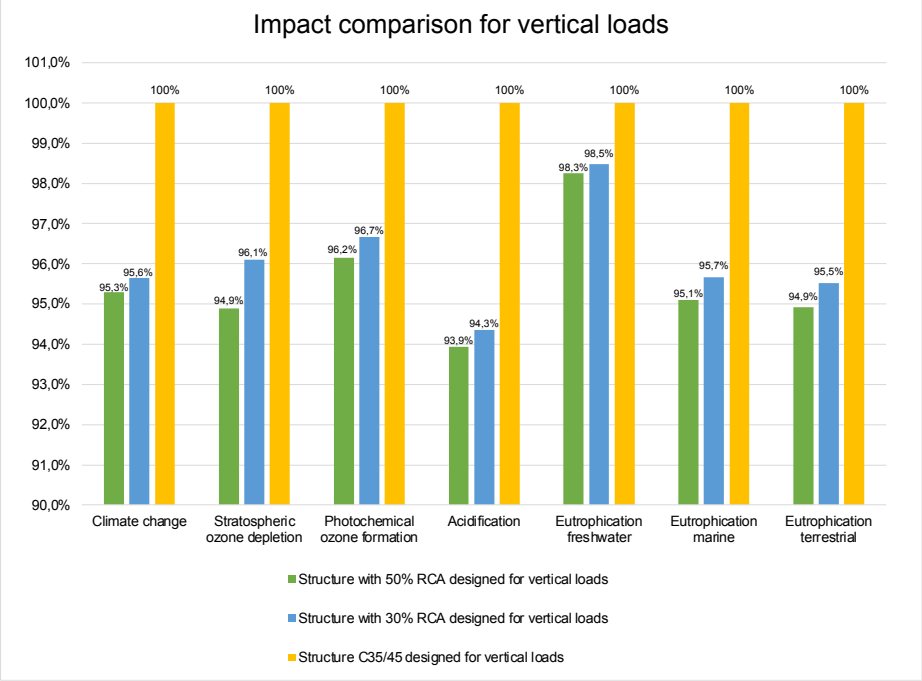


Figure 28 - Comparison of impacts between recycled concrete structure with 50%, 30% RCA and class C35/45 concrete dimensioned for vertical loads

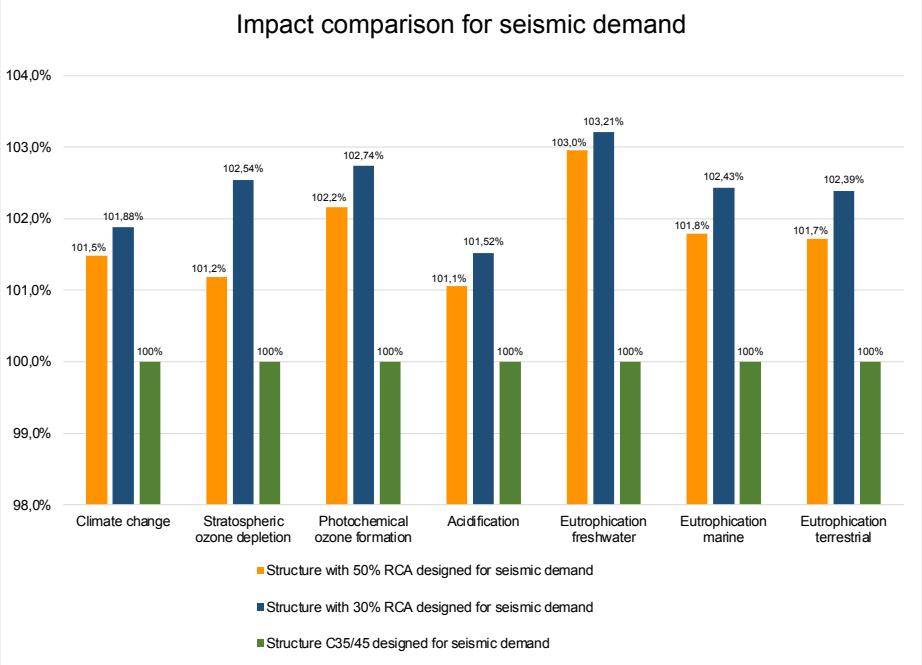


Figure 29 - Comparison of impacts between recycled concrete structure with 50% RCA, 30% RCA and class C35/45 concrete dimensioned for seismic demand

The solution proposed above does not produce as positive results as desired.

5.3.2 SUSTAINABLE CEMENT PRODUCTION

As previously mentioned, cement is the component that most contributes to the environmental impacts of concrete. The suggested alternative can therefore be to replace this component, or part of it, by a more environmentally sustainable solution.

The search for sustainable alternatives to cement production is visible in the number of studies carried out. When it comes to improve the environment, all alternatives that emerge should be tested. The alternative sought by scientists now, is to reduce cement in cementitious mixtures by replacing it with supplementary cementitious materials (SCMs) (Kayla Hanson 2013). (Li et al. 2019) explores the prospect of using filler technology by adding SCMs such as granite powder to concrete mix thereby reducing the dumped waste and carbon footprint. The authors observed that the addition of granite powder as substitute for cement or cement paste could reduce cement content in the mixes and maintain strength. They state that the paste replacement method is a promising way to achieve high performance and eco-friendly results. In (Maddalena, Roberts, and Hamilton 2018) the study of different low carbon SCMs is done. They combine some materials such as metakaolin, silica fume, nano-silica, and calcium hydroxide to produce green cement for the construction sector. The result is a solution with high porosity and good thermal conductivity, allowing to reduce carbon emissions in domestic construction by 23 to 55%. (Puertas et al. 2008) describes the process of using new raw materials such as fired red ceramic wall tile; fired white ceramic wall tile or a combination of both by analysing their reactivity and burnability. The conclusion of the study was that this type of material can be used in cement mixtures, reducing once again the amount of cement in the mixture and consequently the environmental impacts generated by it.(Chu et al. 2019) studies the possibility of adding metakaolin and silica fume to a single concrete mix to improve its properties and decrease the amount of cement in the mix. To make this evaluation, the authors test several mixtures of fresh and hardened concrete. The results of the co-addition are positive. It is concluded that a lower paste volume can lead to the use of backfilling technology to produce more sustainable cementitious mixtures.

All the studies mentioned above prove that it is possible to reduce the impacts caused by cement by choosing to use SCMs. These materials make it possible to reduce the amount of cement used in mixtures without significantly altering their properties. The most widely used SCM in cement mixes is fly ash (The Euclid Chemical Company). It is a by-product of thermal power plants for energy production and depending on the type of coal used, fly ash can be siliceous, calcareous, or fluidized bed combustion (Giergiczny 2019).

This process of making cement more sustainable through the use of SCM is really the way forward to achieve greener concrete.

6 CONCLUSIONS

In this dissertation an assessment of the sustainability of two types of concrete was carried out as a function of a reinforced concrete frame structure. The study was based on concrete of class C25/30 with 30% recycled concrete aggregates taken from the article (Meddah et al. 2020) and standardised concrete of class C35/45. The design of the structure was made considering two types of actions, vertical and seismic. This study allowed understanding the initial phase of the structure's life cycle. The impacts of the production of both concrete classes were analysed, with the transport, construction and demolition phase remaining to be analysed.

An analysis of three types of concrete was also carried out (C25/30; C25/30 with 30% RCA and C35/45), which led to the conclusion that lower class concrete has lower environmental impacts and that the replacement of 30% of aggregates reduces EIs visibly. Analysis of the aggregates' EIs in an individual way, showed the reason for this reduction.

In order to carry out this study, the methodology of Life Cycle Analysis was used. The environmental impact categories were chosen and the indicators that would be subsequently evaluated were defined, based on existing standards. The data used were mostly taken from Ecoinvent v3.8, others were obtained using EPDs. The calculations were done using Simapro software v3.9.0.3. Based on this data it was possible to reach the final results that were presented and through its analysis understand if the proposed solution would really be more sustainable or not.

It has been shown that for the scenario where the structure is solely subject to vertical actions, the proposed solution (class C25/30 concrete with 30% RCA) provides more sustainable results, i.e., lower environmental impacts than the higher concrete class (C35/45). For the case where the structure is subject to seismic actions the results were not so positive. The structure proved to be less sustainable for the proposed solution, i.e., higher environmental impacts than the higher concrete class.

The search for sustainable solutions should be a point to consider when drawing up a construction project. The creation of “cradle-to-cradle” life cycles should be a targeted objective.

6.1 GOALS ACHIEVED

The main objective of this dissertation was to identify aspects that would allow to increase the sustainability of structural concrete. The choice was made to replace virgin aggregates by recycled concrete aggregates in the concrete mix and this way attempting on achieving a sustainable solution. The goal was to analyse a phase of the structure's life cycle (production of reinforced concrete) through environmental indicators.

The proposed objective was met, leaving room for improvement and adjustments.

6.2 CONSTRAINTS AND FUTURE WORK

To carry out this work it was necessary to collect data on the total quantities necessary for the production of the structure and of emission factors to evaluate the environmental indicators. The data concerning the quantities used in the construction were obtained through rigorous modelling and, although they cannot be considered primary, the values represent a good approximation of a real structure. The data for the emission factors were taken from the databases Ecoinvent V3.8 and considered reliable, the calculations were done using SimaPro v9.3.0.3. Some required values were not available in the LCI databases used and were therefore taken from the literature.

As future work it is undoubtedly necessary to study alternative substitutions of concrete components. Suggestions would be to substitute a part of the cement or to substitute a higher percentage of the virgin aggregates. It would be interesting to try to obtain a solution that could offer a satisfactory level of sustainability without compromising the strength of structural concrete.

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Annex

A1

STRUCTURAL DESIGN FOR CONCRETE CLASS C25/30 - DESIGN FOR VERTICAL LOADS

TABLE A1.1 - BEAM FLEXURAL REINFORCEMENT *V*

Beam	bxh [mxm]	M_{Ed} (-) kN.m	M_{Ed} (+) kN.m	Upper Reinforcement	lower Reinforcement
$B_{1,A-B}$	0,30x0,40	195,05	100,51	6 ϕ 20	4 ϕ 16
$B_{1,B-C}$	0,30x0,40	195,05	100,51	6 ϕ 20	4 ϕ 16
$B_{2,A-B}$	0,30x0,40	189,79	100,37	5 ϕ 20	4 ϕ 16
$B_{2,B-C}$	0,30x0,40	189,79	100,37	5 ϕ 20	4 ϕ 16
$B_{3,A-B}$	0,30x0,40	191,36	103,06	5 ϕ 20	4 ϕ 16
$B_{3,B-C}$	0,30x0,40	191,36	103,06	5 ϕ 20	4 ϕ 16
$B_{4,A-B}$	0,30x0,40	194,99	106,95	6 ϕ 20	4 ϕ 16
$B_{4,B-C}$	0,30x0,40	194,99	106,95	6 ϕ 20	4 ϕ 16
$B_{5,A-B}$	0,30x0,40	146,19	84,32	6 ϕ 20	3 ϕ 16
$B_{5,B-C}$	0,30x0,40	146,19	84,32	6 ϕ 20	3 ϕ 16

TABLE A1.2 - BEAM SHEAR REINFORCEMENT *V*

Beam	bxh [mxm]	V_{Ed} kN	n_{legs}	s cm	d_{bw} mm	Reinforcement
$B_{1,A-B}$	0,30x0,40	190,38	2	15,0	8	ϕ 8 // 15
$B_{1,B-C}$	0,30x0,40	190,38	2	15,0	8	ϕ 8 // 15
$B_{2,A-B}$	0,30x0,40	188,57	2	15,0	8	ϕ 8 // 15
$B_{2,B-C}$	0,30x0,40	188,57	2	15,0	8	ϕ 8 // 15
$B_{3,A-B}$	0,30x0,40	190,00	2	15,0	8	ϕ 8 // 15
$B_{3,B-C}$	0,30x0,40	190,00	2	15,0	8	ϕ 8 // 15
$B_{4,A-B}$	0,30x0,40	192,38	2	15,0	8	ϕ 8 // 15
$B_{4,B-C}$	0,30x0,40	192,38	2	15,0	8	ϕ 8 // 15
$B_{5,A-B}$	0,30x0,40	141,80	2	20,0	8	ϕ 8 // 20
$B_{5,B-C}$	0,30x0,40	141,80	2	20,0	8	ϕ 8 // 20

TABLE A1.3 - COLUMN FLEXURAL REINFORCEMENT *V*

Column	bxh [mxm]	Position	N_{Ed} [kN]	M_{Ed} [kN·m]	ν	Reinforcement
$C_{1,A}$	0,40x0,40	Bottom	890,18	38,31	0,334	4 ϕ 16 + 8 ϕ 12
		Top	871,28	77,85	0,327	
$C_{2,A}$	0,35x0,35	Bottom	694,23	77,22	0,340	4 ϕ 12 + 8 ϕ 12
		Top	681,83	76,79	0,334	
$C_{3,A}$	0,35x0,35	Bottom	502,97	83,83	0,246	4 ϕ 12 + 8 ϕ 12
		Top	490,57	92,26	0,240	
$C_{4,A}$	0,30x0,30	Bottom	313,14	61,38	0,209	4 ϕ 16 + 8 ϕ 12
		Top	304,03	67,32	0,203	
$C_{5,A}$	0,30x0,30	Bottom	128,99	75,67	0,086	4 ϕ 16 + 12 ϕ 12
		Top	119,87	80,41	0,080	
$C_{1,B}$	0,40x0,40	Bottom	1849,29	0	0,693	4 ϕ 16 + 8 ϕ 12
		Top	1868,19	0	0,701	
$C_{2,B}$	0,35x0,35	Bottom	1456,13	0	0,713	4 ϕ 12 + 8 ϕ 12
		Top	1468,54	0	0,719	
$C_{3,B}$	0,35x0,35	Bottom	1066,58	0	0,522	4 ϕ 12 + 8 ϕ 12
		Top	1078,99	0	0,528	
$C_{4,B}$	0,30x0,30	Bottom	677,47	0	0,452	4 ϕ 12 + 4 ϕ 12
		Top	686,59	0	0,458	
$C_{5,B}$	0,30x0,30	Bottom	283,6	0	0,189	4 ϕ 12 + 4 ϕ 12
		Top	292,71	0	0,195	
$C_{1,C}$	0,40x0,40	Bottom	890,18	38,31	0,334	4 ϕ 16 + 8 ϕ 12
		Top	871,28	77,85	0,327	
$C_{2,C}$	0,35x0,35	Bottom	694,23	77,22	0,340	4 ϕ 12 + 8 ϕ 12
		Top	681,83	76,79	0,334	
$C_{3,C}$	0,35x0,35	Bottom	502,97	83,83	0,246	4 ϕ 12 + 8 ϕ 12
		Top	490,57	92,26	0,240	
$C_{4,C}$	0,30x0,30	Bottom	313,14	61,38	0,209	4 ϕ 16 + 8 ϕ 12
		Top	304,03	67,32	0,203	
$C_{5,C}$	0,30x0,30	Bottom	128,99	75,67	0,086	4 ϕ 16 + 12 ϕ 12
		Top	119,87	80,41	0,080	

TABLE A1.4 - COLUMN SHEAR REINFORCEMENT *V*

Column	bxh [mxm]	V_{Ed} kN	n_{legs}	s cm	d_{bw} mm	Reinforcement
$C_{1,A}$	0,40x0,40	33,19	2	25	8	ϕ 8 // 25
$C_{2,A}$	0,35x0,35	51,34	2	20	8	ϕ 8 // 20
$C_{3,A}$	0,35x0,35	58,70	2	20	8	ϕ 8 // 20
$C_{4,A}$	0,30x0,30	42,90	2	15	8	ϕ 8 // 15
$C_{5,A}$	0,30x0,30	52,03	2	15	8	ϕ 8 // 15
$C_{1,B}$	0,40x0,40	0,00	2	20	8	ϕ 8 // 20
$C_{2,B}$	0,35x0,35	0,00	2	20	8	ϕ 8 // 20
$C_{3,B}$	0,35x0,35	0,00	2	20	8	ϕ 8 // 20
$C_{4,B}$	0,30x0,30	0,00	2	20	8	ϕ 8 // 20
$C_{5,B}$	0,30x0,30	0,00	2	20	8	ϕ 8 // 20
$C_{1,C}$	0,40x0,40	33,19	2	20	8	ϕ 8 // 20
$C_{2,C}$	0,35x0,35	51,34	2	20	8	ϕ 8 // 20
$C_{3,C}$	0,35x0,35	58,70	2	20	8	ϕ 8 // 20
$C_{4,C}$	0,30x0,30	42,90	2	20	8	ϕ 8 // 20
$C_{5,C}$	0,30x0,30	52,03	2	20	8	ϕ 8 // 20

A2

STRUCTURAL DESIGN FOR CONCRETE CLASS C25/30 - DESIGN FOR SEISMIC DEMAND

TABLE A2.1 - BEAM FLEXURAL REINFORCEMENT E_{CD}

Beam	bxh [mxm]	M_{Ed} (-) kN.m	M_{Ed} (+) kN.m	Upper Reinforcement	Lower Reinforcement
$B_{1,A-B}$	0,40x0,60	388,13	199,02	6 ϕ 20	5 ϕ 16
$B_{1,B-C}$	0,40x0,60	395,57	149,06	6 ϕ 20	5 ϕ 16
$B_{2,A-B}$	0,40x0,60	377,78	187,08	6 ϕ 20	5 ϕ 16
$B_{2,B-C}$	0,40x0,60	396,14	151,65	6 ϕ 20	5 ϕ 16
$B_{3,A-B}$	0,40x0,60	328,43	155,63	8 ϕ 16	5 ϕ 16
$B_{3,B-C}$	0,40x0,60	347,58	120,57	8 ϕ 16	5 ϕ 16
$B_{4,A-B}$	0,40x0,50	234,37	103,81	7 ϕ 16	4 ϕ 16
$B_{4,B-C}$	0,40x0,50	238,87	103,81	7 ϕ 16	4 ϕ 16
$B_{5,A-B}$	0,40x0,50	148,32	82,97	5 ϕ 16	5 ϕ 12
$B_{5,B-C}$	0,40x0,50	142,34	82,97	5 ϕ 16	5 ϕ 12

TABLE A2.2 - BEAM SHEAR REINFORCEMENT E_{CD}

Beam	bxh [mxm]	VEd,CD kN	n_{legs}	s cm	d_{bw} mm	Reinforcement
$B_{1,A-B}$	0,40x0,60	238,116	2	10,0	8	ϕ 8 // 10
$B_{1,B-C}$	0,40x0,60	230,236	2	10,0	8	ϕ 8 // 10
$B_{2,A-B}$	0,40x0,60	234,776	2	10,0	8	ϕ 8 // 10
$B_{2,B-C}$	0,40x0,60	231,475	2	10,0	8	ϕ 8 // 10
$B_{3,A-B}$	0,40x0,60	225,365	2	10,0	8	ϕ 8 // 10
$B_{3,B-C}$	0,40x0,60	222,246	2	10,0	8	ϕ 8 // 10
$B_{4,A-B}$	0,40x0,50	188,688	2	10,0	8	ϕ 8 // 10
$B_{4,B-C}$	0,40x0,50	186,538	2	10,0	8	ϕ 8 // 10
$B_{5,A-B}$	0,40x0,50	146,157	2	7,5	8	ϕ 8 // 7,5
$B_{5,B-C}$	0,40x0,50	138,087	2	7,5	8	ϕ 8 // 7,5

TABLE A2.3 - COLUMN FLEXURAL REINFORCEMENT E_{CD}

Column	bxh [mxm]	Position	NEd kN	MEd kN·m	ν	Reinforcement
$C_{1,A}$	0,55x0,55	Bottom	448,51	311,78	0,0890	4 ϕ 25 + 8 ϕ 20
		Top	422,55	83,25	0,0838	
$C_{2,A}$	0,50x0,50	Bottom	369,62	111,02	0,0887	4 ϕ 20 + 12 ϕ 16
		Top	351,23	115,01	0,0843	
$C_{3,A}$	0,50x0,50	Bottom	297,58	66,66	0,0714	4 ϕ 20 + 12 ϕ 16
		Top	279,19	84,48	0,0670	
$C_{4,A}$	0,45x0,45	Bottom	211,52	51,91	0,0627	4 ϕ 20 + 12 ϕ 16
		Top	196,62	56,29	0,0583	
$C_{5,A}$	0,45x0,45	Bottom	102,73	5,38	0,0304	4 ϕ 16 + 8 ϕ 16
		Top	87,83	29,21	0,0260	
$C_{1,B}$	0,55x0,55	Bottom	1348,23	387,89	0,2674	4 ϕ 25 + 8 ϕ 20
		Top	1322,27	240,84	0,2623	
$C_{2,B}$	0,50x0,50	Bottom	1048,77	285,6	0,2517	4 ϕ 25 + 8 ϕ 20
		Top	1030,38	284,57	0,2473	
$C_{3,B}$	0,50x0,50	Bottom	766,76	235,91	0,1840	4 ϕ 25 + 8 ϕ 20
		Top	748,37	258,54	0,1796	
$C_{4,B}$	0,45x0,45	Bottom	487,49	167,39	0,1444	4 ϕ 25 + 8 ϕ 20
		Top	472,59	166,21	0,1400	
$C_{5,B}$	0,45x0,45	Bottom	221,14	75,43	0,0655	4 ϕ 20 + 8 ϕ 20
		Top	206,24	109,3	0,0611	
$C_{1,C}$	0,55x0,55	Bottom	1083,3	358,89	0,2149	4 ϕ 25 + 8 ϕ 20
		Top	1057,34	179,84	0,2097	
$C_{2,C}$	0,50x0,50	Bottom	822,24	217,62	0,1631	4 ϕ 20 + 12 ϕ 16
		Top	803,84	220,37	0,1594	
$C_{3,C}$	0,50x0,50	Bottom	570,72	178,87	0,1370	4 ϕ 20 + 12 ϕ 16
		Top	552,33	205,4	0,1326	
$C_{4,C}$	0,45x0,45	Bottom	335,56	146,09	0,0994	4 ϕ 20 + 12 ϕ 16
		Top	320,66	156,5	0,0950	
$C_{5,C}$	0,45x0,45	Bottom	143,06	87,64	0,0424	4 ϕ 16 + 8 ϕ 16
		Top	128,16	133,36	0,0380	

TABLE A2.4 - COLUMN SHEAR REINFORCEMENT E_{CD}

Column	bxh [mxm]	$V_{Ed,CD}$ kN	n_{legs}	s cm	d_{bw} mm	Reinforcement
$C_{1,A}$	0,55x0,55	191,21	4	15	8	ϕ 8 // 15
$C_{2,A}$	0,50x0,50	92,82	4	15	8	ϕ 8 // 15
$C_{3,A}$	0,50x0,50	108,18	4	15	8	ϕ 8 // 15
$C_{4,A}$	0,45x0,45	84,03	4	15	8	ϕ 8 // 15
$C_{5,A}$	0,45x0,45	65,76	4	10	8	ϕ 8 // 10
$C_{1,B}$	0,55x0,55	290,51	4	15	8	ϕ 8 // 15
$C_{2,B}$	0,50x0,50	268,81	4	15	8	ϕ 8 // 15
$C_{3,B}$	0,50x0,50	287,21	4	15	8	ϕ 8 // 15
$C_{4,B}$	0,45x0,45	209,98	4	15	8	ϕ 8 // 15
$C_{5,B}$	0,45x0,45	159,48	4	10	8	ϕ 8 // 10
$C_{1,C}$	0,55x0,55	259,01	4	15	8	ϕ 8 // 15
$C_{2,C}$	0,50x0,50	176,94	4	15	8	ϕ 8 // 15
$C_{3,C}$	0,50x0,50	137,93	4	15	8	ϕ 8 // 15
$C_{4,C}$	0,45x0,45	132,52	4	15	8	ϕ 8 // 15
$C_{5,C}$	0,45x0,45	97,92	4	10	8	ϕ 8 // 10

A3

STRUCTURAL DESIGN FOR CONCRETE CLASS C35/45 - DESIGN FOR VERTICAL LOADS

TABLE A3.1 - BEAM FLEXURAL REINFORCEMENT *V*

Beam	bx*h* [mxm]	M_{Ed} (-) kN.m	M_{Ed} (+) kN.m	Upper Reinforcement	Lower Reinforcement
$B_{1,A-B}$	0,30x0,40	195.05	100.51	5 ϕ 20	4 ϕ 16
$B_{1,B-C}$	0,30x0,40	195.05	100.51	5 ϕ 20	4 ϕ 16
$B_{2,A-B}$	0,30x0,40	189.79	100.37	5 ϕ 20	4 ϕ 16
$B_{2,B-C}$	0,30x0,40	189.79	100.37	5 ϕ 20	4 ϕ 16
$B_{3,A-B}$	0,30x0,40	191.36	103.06	5 ϕ 20	4 ϕ 16
$B_{3,B-C}$	0,30x0,40	191.36	103.06	5 ϕ 20	4 ϕ 16
$B_{4,A-B}$	0,30x0,40	194.99	106.95	5 ϕ 20	4 ϕ 16
$B_{4,B-C}$	0,30x0,40	194.99	106.95	5 ϕ 20	4 ϕ 16
$B_{5,A-B}$	0,30x0,40	146.19	84.32	4 ϕ 20	3 ϕ 16
$B_{5,B-C}$	0,30x0,40	146.19	84.32	4 ϕ 20	3 ϕ 16

TABLE A3.2 - BEAM SHEAR REINFORCEMENT *V*

Beam	bxh [mxm]	V_{Ed} kN	n_{legs}	s cm	d_{bw} mm	Reinforcement
$B_{1,A-B}$	0,30x0,40	190,38	2	15	8	ϕ 8 // 15
$B_{1,B-C}$	0,30x0,40	190,38	2	15	8	ϕ 8 // 15
$B_{2,A-B}$	0,30x0,40	188,57	2	15	8	ϕ 8 // 15
$B_{2,B-C}$	0,30x0,40	188,57	2	15	8	ϕ 8 // 15
$B_{3,A-B}$	0,30x0,40	190	2	15	8	ϕ 8 // 15
$B_{3,B-C}$	0,30x0,40	190	2	15	8	ϕ 8 // 15
$B_{4,A-B}$	0,30x0,40	192,38	2	15	8	ϕ 8 // 15
$B_{4,B-C}$	0,30x0,40	192,38	2	15	8	ϕ 8 // 15
$B_{5,A-B}$	0,30x0,40	141,8	2	20	8	ϕ 8 // 20
$B_{5,B-C}$	0,30x0,40	141,8	2	20	8	ϕ 8 // 20

TABLE A3.3 – COLUMN FLEXURAL REINFORCEMENT *V*

Column	bxh [mxm]	Position	Ned	Med	ρ_{pov_total} %	Reinforcement
$C_{1,A}$	0,40x0,40	Bottom	890,18	38,31	1,07%	4 ϕ 16 + 8 ϕ 12
		Top	871,28	77,85		
$C_{2,A}$	0,35x0,35	Bottom	694,23	77,22	1,11%	4 ϕ 12 + 8 ϕ 12
		Top	681,83	76,79		
$C_{3,A}$	0,35x0,35	Bottom	502,97	83,83	1,11%	4 ϕ 12 + 8 ϕ 12
		Top	490,57	92,26		
$C_{4,A}$	0,30x0,30	Bottom	313,14	61,38	1,90%	4 ϕ 16 + 8 ϕ 12
		Top	304,03	67,32		
$C_{5,A}$	0,30x0,30	Bottom	128,99	75,67	2,40%	4 ϕ 16 + 12 ϕ 12
		Top	119,87	80,41		
$C_{1,B}$	0,40x0,40	Bottom	1849,29	0	1,07%	4 ϕ 16 + 8 ϕ 12
		Top	1868,19	0		
$C_{2,B}$	0,35x0,35	Bottom	1456,13	0	1,11%	4 ϕ 12 + 8 ϕ 12
		Top	1468,54	0		
$C_{3,B}$	0,35x0,35	Bottom	1066,58	0	1,11%	4 ϕ 12 + 8 ϕ 12
		Top	1078,99	0		
$C_{4,B}$	0,30x0,30	Bottom	677,47	0	1,01%	4 ϕ 12 + 4 ϕ 12
		Top	686,59	0		
$C_{5,B}$	0,30x0,30	Bottom	283,6	0	1,01%	4 ϕ 12 + 4 ϕ 12
		Top	292,71	0		
$C_{1,C}$	0,40x0,40	Bottom	890,18	38,31	1,07%	4 ϕ 16 + 8 ϕ 12
		Top	871,28	77,85		
$C_{2,C}$	0,35x0,35	Bottom	694,23	77,22	1,11%	4 ϕ 12 + 8 ϕ 12
		Top	681,83	76,79		
$C_{3,C}$	0,35x0,35	Bottom	502,97	83,83	1,11%	4 ϕ 12 + 8 ϕ 12
		Top	490,57	92,26		
$C_{4,C}$	0,30x0,30	Bottom	313,14	61,38	1,90%	4 ϕ 16 + 8 ϕ 12
		Top	304,03	67,32		
$C_{5,C}$	0,30x0,30	Bottom	128,99	75,67	2,40%	4 ϕ 16 + 12 ϕ 12
		Top	119,87	80,41		

TABLE A3.4 - COLUMN SHEAR REINFORCEMENT *V*

Column	bxh [mxm]	V_{Ed} kN	n_{legs}	s cm	d_{bw} mm	Reinforcement
$C_{1,A}$	0,40x0,40	33,19	2	25	8	ϕ 8 // 25
$C_{2,A}$	0,35x0,35	51,34	2	20	8	ϕ 8 // 20
$C_{3,A}$	0,35x0,35	58,7	2	20	8	ϕ 8 // 20
$C_{4,A}$	0,30x0,30	42,9	2	15	8	ϕ 8 // 15
$C_{5,A}$	0,30x0,30	52,03	2	15	8	ϕ 8 // 15
$C_{1,B}$	0,40x0,40	0	2	25	8	ϕ 8 // 25
$C_{2,B}$	0,35x0,35	0	2	20	8	ϕ 8 // 20
$C_{3,B}$	0,35x0,35	0	2	20	8	ϕ 8 // 20
$C_{4,B}$	0,30x0,30	0	2	15	8	ϕ 8 // 15
$C_{5,B}$	0,30x0,30	0	2	15	8	ϕ 8 // 15
$C_{1,C}$	0,40x0,40	33,19	2	25	8	ϕ 8 // 25
$C_{2,C}$	0,35x0,35	51,34	2	20	8	ϕ 8 // 20
$C_{3,C}$	0,35x0,35	58,7	2	20	8	ϕ 8 // 20
$C_{4,C}$	0,30x0,30	42,9	2	15	8	ϕ 8 // 15
$C_{5,C}$	0,30x0,30	52,03	2	15	8	ϕ 8 // 15

A4

STRUCTURAL DESIGN FOR CONCRETE CLASS C35/45 - DESIGN FOR SEISMIC DEMAND

TABLE A4.1 - BEAM FLEXURAL REINFORCEMENT E_{CD}

Beam	bxh [mxm]	M_{Ed} (-) kN.m	M_{Ed} (+) kN.m	Upper Reinforcement	Lower Reinforcement
$B_{1,A-B}$	0,40x0,50	356,82	167,9	7 ϕ 20	5 ϕ 16
$B_{1,B-C}$	0,40x0,50	358,42	133,63	7 ϕ 20	5 ϕ 16
$B_{2,A-B}$	0,40x0,50	368,16	168,27	7 ϕ 20	5 ϕ 16
$B_{2,B-C}$	0,40x0,50	378,7	147,28	7 ϕ 20	5 ϕ 16
$B_{3,A-B}$	0,40x0,50	326,74	142,02	7 ϕ 20	5 ϕ 16
$B_{3,B-C}$	0,40x0,50	338,06	120,13	7 ϕ 20	5 ϕ 16
$B_{4,A-B}$	0,35x0,45	228,05	106,95	5 ϕ 20	4 ϕ 16
$B_{4,B-C}$	0,35x0,45	230,74	106,95	5 ϕ 20	4 ϕ 16
$B_{5,A-B}$	0,35x0,45	146,76	84,32	5 ϕ 16	5 ϕ 12
$B_{5,B-C}$	0,35x0,45	147,76	84,32	5 ϕ 16	5 ϕ 12

TABLE A4.2 - BEAM SHEAR REINFORCEMENT E_{CD}

Beam	bxh [mxm]	n_{legs}	s cm	d_{bw} mm	Reinforcement
$B_{1,A-B}$	0,40x0,50	2	12,5	8	ϕ 8 // 12,5
$B_{1,B-C}$	0,40x0,50	2	12,5	8	ϕ 8 // 12,5
$B_{2,A-B}$	0,40x0,50	2	12,5	8	ϕ 8 // 12,5
$B_{2,B-C}$	0,40x0,50	2	12,5	8	ϕ 8 // 12,5
$B_{3,A-B}$	0,40x0,50	2	12,5	8	ϕ 8 // 12,5
$B_{3,B-C}$	0,40x0,50	2	12,5	8	ϕ 8 // 12,5
$B_{4,A-B}$	0,35x0,45	2	12,5	8	ϕ 8 // 12,5
$B_{4,B-C}$	0,35x0,45	2	12,5	8	ϕ 8 // 12,5
$B_{5,A-B}$	0,35x0,45	2	7,5	8	ϕ 8 // 7,5
$B_{5,B-C}$	0,35x0,45	2	7,5	8	ϕ 8 // 7,5

TABLE A4.3 - COLUMN FLEXURAL REINFORCEMENT E_{CD}

Column	bxh [mxm]	Position	N_{Ed} kN	M_{Ed} kN.m	ν	Reinforcement
$C_{1,A}$	0,55x0,55	Bottom	341,02	346,8	0,0483	4 ϕ 25 + 8 ϕ 20
		Top	314,56	31,71	0,0446	
$C_{2,A}$	0,50x0,50	Bottom	280,67	114,67	0,0481	4 ϕ 20 + 8 ϕ 16
		Top	261,92	101,37	0,0449	
$C_{3,A}$	0,50x0,50	Bottom	231,72	55,74	0,0397	4 ϕ 20 + 8 ϕ 16
		Top	212,97	82,92	0,0365	
$C_{4,A}$	0,45x0,45	Bottom	169,43	35,63	0,0359	4 ϕ 20 + 8 ϕ 16
		Top	154,25	58,32	0,0326	
$C_{5,A}$	0,45x0,45	Bottom	79,79	45,75	0,0169	4 ϕ 16 + 8 ϕ 16
		Top	64,6	8,98	0,0137	
$C_{1,B}$	0,55x0,55	Bottom	1221,7	421,36	0,1731	4 ϕ 25 + 8 ϕ 20
		Top	1195,23	184,89	0,1693	
$C_{2,B}$	0,50x0,50	Bottom	954,66	286,34	0,1637	4 ϕ 25 + 8 ϕ 20
		Top	935,91	271,53	0,1604	
$C_{3,B}$	0,50x0,50	Bottom	698,36	230,85	0,1197	4 ϕ 25 + 8 ϕ 20
		Top	679,61	265,17	0,1165	
$C_{4,B}$	0,45x0,45	Bottom	441,99	156,11	0,0935	4 ϕ 25 + 8 ϕ 20
		Top	426,8	169,1	0,0903	
$C_{5,B}$	0,45x0,45	Bottom	196,37	61	0,0416	4 ϕ 20 + 8 ϕ 20
		Top	181,19	112,51	0,0383	
$C_{1,C}$	0,55x0,55	Bottom	941,81	396,61	0,1334	4 ϕ 25 + 8 ϕ 20
		Top	915,34	133,43	0,1297	
$C_{2,C}$	0,50x0,50	Bottom	718,79	224,98	0,1232	4 ϕ 20 + 8 ϕ 16
		Top	700,04	208,99	0,1200	
$C_{3,C}$	0,50x0,50	Bottom	496,8	169,72	0,0852	4 ϕ 20 + 8 ϕ 16
		Top	478,05	206,46	0,0820	
$C_{4,C}$	0,45x0,45	Bottom	288,2	131,61	0,0610	4 ϕ 20 + 8 ϕ 16
		Top	273,01	158,85	0,0578	
$C_{5,C}$	0,45x0,45	Bottom	119,65	71,89	0,0253	4 ϕ 16 + 8 ϕ 16
		Top	104,47	135,67	0,0221	

TABLE A4.4 - COLUMN SHEAR REINFORCEMENT E_{CD}

Column	bxh [mxm]	n_{legs}	s	d_{bw}	Reinforcement
			cm	mm	
$C_{1,A}$	0,55x0,55	4	15	8	ϕ 8 // 15
$C_{2,A}$	0,50x0,50	4	15	8	ϕ 8 // 15
$C_{3,A}$	0,50x0,50	4	15	8	ϕ 8 // 15
$C_{4,A}$	0,45x0,45	4	15	8	ϕ 8 // 15
$C_{5,A}$	0,45x0,45	4	10	8	ϕ 8 // 10
$C_{1,B}$	0,55x0,55	4	25	8	ϕ 8 // 15
$C_{2,B}$	0,50x0,50	4	15	8	ϕ 8 // 15
$C_{3,B}$	0,50x0,50	4	15	8	ϕ 8 // 15
$C_{4,B}$	0,45x0,45	4	15	8	ϕ 8 // 15
$C_{5,B}$	0,45x0,45	4	10	8	ϕ 8 // 10
$C_{1,C}$	0,55x0,55	4	15	8	ϕ 8 // 15
$C_{2,C}$	0,50x0,50	4	15	8	ϕ 8 // 15
$C_{3,C}$	0,50x0,50	4	15	8	ϕ 8 // 15
$C_{4,C}$	0,45x0,45	4	15	8	ϕ 8 // 15
$C_{5,C}$	0,45x0,45	4	10	8	ϕ 8 // 10

A5

INVENTORY RESULTS

TABLE A5.1– CONCRETE CLASS C35/45 COMPONENTS FOR 1 m^3; 12,71 m^3 AND 22,30 m^3

C35/45 components				
Materials/fuels	**1 m^3**	**12,71 m^3**	**22,30 m^3**	**units**
Acetic acid w/o water, in 98% solution state	0,350000	4,448499	7,804998	kg
Alkylbenzene sulfonate, linear, petrochemical	0,180000	2,287799	4,013998	kg
Cement, Portland	315,306130	4007,540912	7031,326699	kg
Chemical, organic	1,150000	14,616495	25,644991	kg
Concrete mixing factory	0,000000	0,000006	0,000010	p
Ethylene oxide	1,399999	17,793987	31,219978	kg
Gravel, round	960,066750	12202,4484	21409,488525	kg
Lubricating oil	0,011900	0,151249	0,265370	kg
Sand	823,636210	10468,4162	18367,087483	kg
Steel, low-alloyed, hot rolled	0,023800	0,302497	0,530738	kg
Synthetic rubber	0,007130	0,090622	0,158999	kg
Tap water	202,941110	2579,381508	4525,586753	kg
Electricity/heat				
Diesel, burned in building machine	15,642710	198,818844	348,832433	MJ
Electricity, medium voltage	4,113999	52,288923	91,742171	kWh
Heat, district or industrial, natural gas	10,632266	135,136101	237,099532	MJ
Emissions to air				
Water/m^3	0,006141	0,078053	0,136947	m^3
Emissions to water				
Chlorides, unspecified	3,09E-09	3,93E-08	6,89E-08	kg
Copper	1,55E-08	1,97E-07	3,46E-07	kg
Iron	1,55E-08	1,97E-07	3,46E-07	kg
Oils, unspecified	2,32E-07	2,95E-06	5,17E-06	kg
Suspended solids, unspecified	4,64E-07	5,90E-06	1,03E-05	kg
Waste to treatment				
Waste concrete	24,499992	311,394898	546,349822	kg
Wastewater from concrete production	0,034800	0,442307	0,776038	m^3

TABLE A5.2 – CONCRETE CLASS C25/30 WITH RECYCLED AGGREGATES COMPONENTS FOR 1 m^3; 12,71 m^3 AND 24,76 m^3

C25/30 components with recycled concrete aggregates				
Materials/fuels	**1 m3**	**12,71 m^3**	**24,76 m^3**	**units**
Cement, Portland	281,8117225	3581,826993	6977,658249	kg
Chemical, organic	0,909999731	11,56609658	22,53159334	kg
Concrete mixing factory	4,57E-07	5,80847E-06	1,13153E-05	p
Gravel, round	714,125046	9076,529335	17681,73614	kg
Recycled concrete aggregates	306,0535911	3889,941143	7577,886916	kg
Lubricating oil	0,011899996	0,151248949	0,294643901	kg
Sand	964,6243549	12260,37555	23884,09903	kg
Steel, low-alloyed, hot rolled	0,023799993	0,302497911	0,589287827	kg
Synthetic rubber	0,007129998	0,090622275	0,17653875	kg
Tap water	206,9411153	2630,221575	5123,862015	kg
Electricity/heat				
Diesel, burned in building machine	15,64271058	198,8188515	387,313514	MJ
Electricity, medium voltage	4,113998784	52,28892454	101,8626099	kWh
Heat, district, or industrial, natural gas	10,63226686	135,1361118	263,2549275	MJ
Emissions to air				
Water/m3	0,006141175	0,078054334	0,152055493	m^3
Emissions to water				
Chlorides, unspecified	3,09E-09	3,93E-08	7,65E-08	kg
Copper	1,55E-08	1,97E-07	3,84E-07	kg
Iron	1,55E-08	1,97E-07	3,84E-07	kg
Oils, unspecified	2,32E-07	2,95E-06	5,74E-06	kg
Suspended solids, unspecified	4,64E-07	5,90E-06	1,15E-05	kg
Waste to treatment				
Waste concrete	24,499992	311,3948983	606,6198019	kg
Wastewater from concrete production	0,03479999	0,442307873	0,861647752	m^3

A6

ENVIRONMENTAL IMPACTS RESULTS

ENVIRONMENTAL IMPACTS OF STEEL AND CONCRETE FOR CLASS C25/30 WITH 30% RCA DESIGNED FOR VERTICAL LOADS

Impact categories	Concrete	Steel	Total	Units
Climate change	3,46E+03	4,37E+03	7,83E+03	kg CO2 eq
Stratospheric ozone depletion	1,72E-04	1,98E-04	3,70E-04	kg CFC11 eq
Photochemical ozone formation	1,25E+01	1,77E+01	3,02E+01	kg NMVOC eq
Acidification	2,36E+01	1,73E+01	4,09E+01	mol H+ eq
Eutrophication freshwater	5,15E-01	1,71E+00	2,22E+00	kg P eq
Eutrophication marine	4,21E+00	4,02E+00	8,23E+00	kg N eq
Eutrophication terrestrial	4,61E+01	4,16E+01	8,77E+01	mol N eq

ENVIRONMENTAL IMPACTS OF STEEL AND CONCRETE FOR CLASS C25/30 WITH 30% RCA DESIGNED FOR SEISMIC DEMAND

Impact categories	Concrete	Steel	Total	Units
Climate change	6,75E+03	7,86E+03	1,46E+04	kg CO2 eq
Stratospheric ozone depletion	3,36E-04	3,56E-04	6,92E-04	kg CFC11 eq
Photochemical ozone formation	2,43E+01	3,19E+01	5,62E+01	kg NMVOC eq
Acidification	4,61E+01	3,12E+01	7,72E+01	mol H+ eq
Eutrophication freshwater	1,00E+00	3,08E+00	4,08E+00	kg P eq
Eutrophication marine	8,19E+00	7,24E+00	1,54E+01	kg N eq
Eutrophication terrestrial	8,98E+01	7,49E+01	1,65E+02	mol N eq

ENVIRONMENTAL IMPACTS OF STEEL AND CONCRETE FOR CLASS C35/45 DESIGNED FOR VERTICAL LOADS

Impact categories	Concrete	Steel	Total	Units
Climate change	3,91E+03	4,28E+03	8,19E+03	kg CO2 eq
Stratospheric ozone depletion	1,91E-04	1,94E-04	3,85E-04	kg CFC11 eq
Photochemical ozone formation	1,39E+01	1,74E+01	3,12E+01	kg NMVOC eq
Acidification	2,64E+01	1,70E+01	4,34E+01	mol H+ eq
Eutrophication freshwater	5,84E-01	1,67E+00	2,26E+00	kg P eq
Eutrophication marine	4,66E+00	3,94E+00	8,60E+00	kg N eq
Eutrophication terrestrial	5,11E+01	4,08E+01	9,18E+01	mol N eq

ENVIRONMENTAL IMPACTS OF STEEL AND CONCRETE FOR CLASS C35/45 DESIGNED FOR SEISMIC DESIGN

Impact categories	Concrete	Steel	Total	Units
Climate change	6,86E+03	7,48E+03	1,43E+04	kg CO2 eq
Stratospheric ozone depletion	3,36E-04	3,39E-04	6,75E-04	kg CFC11 eq
Photochemical ozone formation	2,43E+01	3,03E+01	5,47E+01	kg NMVOC eq
Acidification	4,64E+01	2,96E+01	7,60E+01	mol H+ eq
Eutrophication freshwater	1,02E+00	2,93E+00	3,95E+00	kg P eq
Eutrophication marine	8,18E+00	6,89E+00	1,51E+01	kg N eq
Eutrophication terrestrial	8,96E+01	7,13E+01	1,61E+02	mol N eq