Durability, life cycle cost and life cycle assessment of binary mixtures with fly ash, rice husk ash and concrete demolition waste

Durabilidade, custo do ciclo de vida e avaliação do ciclo de vida de misturas binárias com cinzas volantes, cinzas de casca de arroz e resíduos de demolição de concreto

Cristian Jonathan Franco de Lima
Francisco Roger Carneiro Ribeiro
Regina Célia Espinosa Modolo
Geraldo Cechella Isaia
Maurício Mancio

Abstract

This study analyses, by means of lifespan cost and lifespan assessment, the production of binary concrete admixtures compound by artificial pozzolan and concrete demolition waste. Ten formulations were developed, differentiating them in terms of mixtures, binder and aggregate content, in order to verify their potential use in concrete columns. The replacements were 25% of Portland cement for fly ash and rice husk ash, 15% and 30% of natural coarse aggregates for concrete demolition waste. The results revealed that the mixtures with pozzolan and demolition waste showed higher resistance to chloride penetration. The lowest concrete cost was achieved in the highest compressive strength (35 MPa) and the concrete admixture containing 15% replacement of the natural coarse aggregate by the recycled concrete aggregate and 25% substitution of cement by rice husk ash can be classified as the most environmentally sustainable one, especially in carbon dioxide emissions, among the mixtures studied.

Keywords: Durability. Lifespan Cost. Lifespan Assessment. Binary mixtures of concrete. Artificial pozzolan. Concrete demolition waste.

[1]**Cristian Jonathan Franco de Lima**
[1]Universidade do Vale do Rio dos Sinos
São Leopoldo - RS - Brasil

[2]**Francisco Roger Carneiro Ribeiro**
[2]Universidade Federal do Rio Grande do Sul
Porto Alegre - RS - Brasil

[3]**Regina Célia Espinosa Modolo**
[3]Universidade do Vale do Rio dos Sinos
São Leopoldo - RS - Brasil

[4]**Geraldo Cechella Isaia**
[4]Universidade Federal de Santa Maria
Santa Maria - RS - Brasil

[5]**Maurício Mancio**
[5]Universidade do Vale do Rio dos Sinos
São Leopoldo - RS - Brasil

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Resumo

Este estudo analisa, por meio do custo do ciclo de vida e da avaliação do ciclo de vida, a produção de misturas binárias de concreto constituídas por pozolanas artificiais e resíduos de demolição de concreto. Foram desenvolvidas dez formulações diferenciando-as quanto aos traços, conteúdo de ligantes e agregados, a fim de verificar o potencial emprego em pilares de concreto, tendo sido, portanto, adotado como sendo a unidade funcional do estudo. As devidas substituições foram de 25% de cimento Portland por cinza volante e cinza de casca de arroz, além de substituições de 15% e 30% de agregados graúdos naturais por resíduos de demolição de concreto. Os resultados evidenciam que as misturas com pozolanas e resíduos de demolição apresentaram uma maior resistência de penetração de cloretos, o menor custo de concreto foi alcançado na maior resistência característica de 35 MPa e que o concreto contendo 15% de substituição do agregado graúdo natural pelo agregado reciclado de concreto e substituição de 25% de cimento por cinza de casca de arroz pode ser classificado como o mais sustentável, principalmente em emissões de dióxido de carbono, dentre as misturas estudadas.

Palavras-chave*: Durabilidade. Custo do ciclo de vida. Avaliação do ciclo de vida. Misturas binárias de concreto. Pozolanas artificiais. Resíduos de demolição de concreto.*

Introduction

From the perspective of a sustainable future, conservation of non-renewable resources, high energy consumption, and the control of carbon dioxide (CO_2) emissions have been the major challenges for the construction industry. According to Chouhan *et al*. (2019), the mining of natural resources increased exponentially to meet the demands of cement production. Huang *et al*. (2018) affirm that the construction industry is responsible for 23% of global CO_2 emissions. Moreover, since 1950, the world cement production has grown to more than 4000 million tons per year, which contributes to about 8% of these anthropic carbon dioxide emissions (ANDREW, 2017).

At the same time, Isaia *et al*. (2017), Santos and Leite (2018) and Lima *et al*. (2020) report that the correct disposal of industrial solid waste has become an environmental concern for generating industries, considering that in many situations it is disposed of in landfills and/or lagoons, which can contaminate the soil, water, and air, such as fly ash (FA), rice husk ash (RHA) and concrete demolition waste (CDW).

The world production of fly ash from coal combustion for energy production is about 750 million tons per year (BLISSETT; ROWSON, 2012), while in Brazil approximately 3 million tons per year are generated in seven plants located in the South of the country alone (LEVANDOWSKI; KALKREUTH, 2009). The data for June from the Brazilian Institute of Geography and Statistics (INSTITUTO..., 2020) estimates that Brazilian rice production was 10.8 million tons. According to Mehta and Monteiro (2014), each ton of rice produced can result in 40 kilograms (kg) of ash. Therefore, in this case, it is presumed that about 432 thousand tons of rice husk ash were generated.

According to Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais (ABRELPE) (2019), Brazilian cities collected around 45 million tons of construction and demolition waste in 2018, which indicates a generation rate of approximately 213.50 kg/inhab.year, excluding waste generated by the construction companies. In the absence of reliable data, John and Agopyan (2000) propose to adopt a generation rate of 510 kg/inhab.year, which makes it possible to estimate an annual generation of 106 million tons in Brazil. Waskow *et al*. (2020) addition that in Brazil, these residues have as main constituents inert materials such as aggregates, ceramics, mortar, and concrete.

Within this context, the solid industrial waste mentioned above are the object of studies in the search for "ecologically correct" concrete, seeking to reduce environmental impacts through recycling, either by replacing Portland cement and/or replacing natural materials (GOLEWSKI, 2017; GURSEL; MARYMAN; OSTERTAG, 2016; HAYLES; SANCHEZ; NOEL, 2018; LIEW; SOJOBI; ZHANG, 2017). Given that the concrete is a significant challenge due to the high emissions in its production and the large volumes needed to meet modern society, with the increase in production associated with population growth and urbanization (SCRIVENER; JOHN; GARTNER, 2018; VISINTIN; XIE; BENNETT, 2020).

As supplementary cementitious materials (SCMs) have a recyclable status, increased use may offer a possible reduction in global carbon dioxide emissions (APRIANTI *et al*., 2017). However, the full sustainability of concrete also depends on its accessibility in the region and its physical, mechanical, and durability properties (GÖSWEIN *et al*., 2018; ARRIGONI *et al*., 2020).

In this situation, Life Cycle Cost Analysis (LCC) and Life Cycle Assessment (LCA) have become powerful tools to achieve reliable quantification of the environmental impacts and life cycle costs of a system and/or a product, where the results can confirm the benefits of inserting waste into concrete production (GENTIL *et al*., 2010; BUTERA; CHRISTENSEN; ASTRUP, 2015; HARILAL *et al*., 2019).

Therefore, this study aims to evaluate qualitatively and quantitatively binary mixtures produced with artificial pozzolan and concrete demolition waste, in order to be applied on a reinforced concrete pillar, by means of economic and environmental analyses of different types of concrete.

Materials and methods

This research used four types of Brazilian materials for the production of different concrete (CP V-ARI, CP IV-32, FA and RHA), a fine natural aggregate (sand), a coarse doleritic aggregate (gravel), a concrete demolition aggregate as waste and a water-reducing chemical admixture, and the strength levels intended were 25 and 35 MPa (fck). The physical and chemical characterizations of the above-mentioned materials, as well as the dosage processes of the mixtures can be found in Lima *et al*. (2020). Table 1 presents the definitive proportions reached by the Abrams curve and the average strength compression of the samples cured for 28 days.

Table 1 – **Definitive mixing ratios e Average compressive strength at 28 days**

Mixture Concrete	Mixing ratio						w/b ratio	Cement consumption (kg.m^{-3})	Admix-ture (%)	Fck (MPa)	Fcj,28 (MPa)
	Cement	RHA	FA	Sand	Gravel	CDW					
REF. CP V - ARI	1.00	-	-	2.28	3.28	-	0.54	329.37	-	35	40.17
CDW 15 + CP V - ARI	1.00	-	-	2.35	2.85	0.50	0.55	317.22	0.10	25	30.59
CDW 30 + CP V - ARI	1.00	-	-	1.55	1.78	0.77	0.42	412.01	0.10	25	30.25
CDW 15 + RHA 25 + CP V - ARI	0.75	0.25	-	2.67	3.20	0.57	0.62	280.97	0.12	35	40.64
CDW 30 + RHA 25 + CP V - ARI	0.75	0.25	-	2.12	2.25	0.97	0.53	324.47	0.15	35	40.25
CDW 15 + FA 25 + CP V - ARI	0.75	-	0.25	2.38	2.95	0.52	0.57	305.95	0.12	35	40.80
CDW 30 + FA 25 + CP V - ARI	0.75	-	0.25	1.77	2.00	0.86	0.47	366.50	0.15	35	39.89
REF. CP IV - 32	1.00	-	-	2.22	3.22	-	0.53	329.89	-	25	30.32
CDW 15 + CP IV - 32	1.00	-	-	2.04	2.58	0.46	0.50	343.80	0.10	25	30.44
CDW 30 + CP IV - 32	1.00	-	-	1.55	1.78	0.77	0.42	403.38	0.10	25	30.23

Objective and scope definition

The LCA of this work aimed to evaluate the environmental impact of the production of ten types of concrete binary mixtures, regarding the total impacts on human health, ecosystems and natural resources considering the scope from cradle-to-grave and the environmental aspects (climate change, consumption of natural resources, energy consumption, waste generation, and water consumption) energy consumption, waste generation, and water consumption) most relevant according to the scope of the modular life cycle analysis (LCA-m) methodology. In other words, a methodology built from the fundamental components of a life cycle, which form the minimum inventory scope (OLIVEIRA, 2015). The scope of this research is illustrated in Figure 1.

The functional study unit was defined as a reinforced concrete pillar. The design of the column was performed according to NBR 6118 (ABNT, 2014) from environmental aggressiveness class II (moderate) and 25 mm reinforcement cover. Based on these parameters, it was possible to estimate the loads acting on the column using the Eberick software (Table 2) and to dimension the column using the Oblique software 1.0 (Table 3).

Lifecycle inventory

The principles of ISO 14040 (INTERNATIONAL…, 2006) and ISO 14044 (INTERNATIONAL…, 2017), and the SimaPro 8.5.2. software were used for the evaluation of environmental impacts. The Price Composition Table for Budgets (TABELA…, 2008) was used for the calculation of the cost of living, where some data were applied based on the Silva (2014) and Lamberti (2015) studies, updated to March/2017. The percentage of social charges of 117.66% was adopted according to the National System of Cost Research and Civil Construction Indexes (BRASIL, 2017). The use of this composition and percentage of social charges aimed at continuing the studies of the research group GEPECON at the Federal University of Santa Maria – UFSM.

This study involves the construction, use/maintenance, demolition, and recycling phases of the reinforced concrete column in order to estimate the lifespan of the evaluated product. The maximum of 150 years was adopted according to NBR 15575-1 (ABNT, 2013), considering that achieving this objective is complex due to the dynamics of today's society. It was also assumed that this pillar is made of reinforced concrete, located on the ground floor of a building, sheltered from the weather, having only the phenomenon of chloride penetration as the main deterioration factor, receiving routine cleaning every three years to meet the aesthetics and established lifespan. Finally, it was also considered that the pillars that presented the estimated minimum of fewer than 50 years were coated with acrylic paint at intervals of eight years and the first painting was done after its execution.

Figure 1 - **Product system and boundaries of the complex**

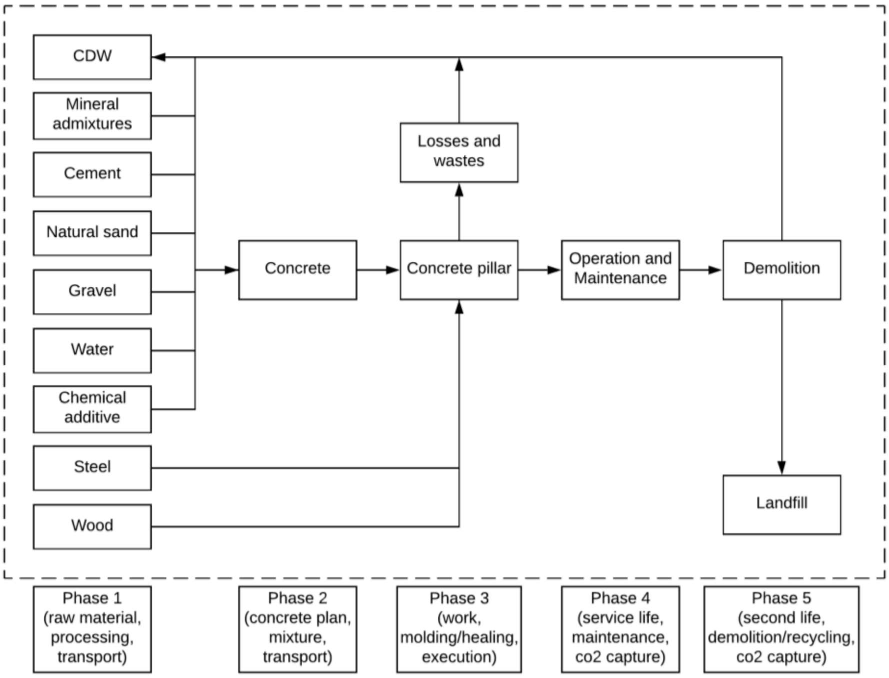


Table 2 – **Loads on the pillar and design definitions**

Parameter	Value
Design axial stress (Nd)	1200 KN
Specified Compressive strength of concrete (fck)	25 and 35 MPa
Bending moment in the y axis of the pillar section (Myd)	55 KN.m
Bending moment in the x-axis of the pillar section (Mxd)	78 KN.m
Cover to reinforcement	25 mm
Pillar height	2.75 m

Table 3 - **Material dimensions and consumption**

Characteristics	Pillar with fck = 25 MPa	Pillar with fck = 35 MPa
Cross-section (cm x cm)	25 x 50	25 x 45
Concrete volume (m^3)	0.344	0.309
Wood shapes area (m^2)	4.125	3.850
Stirrup spacing	Φ5 mm every 12 cm	
Weight of stirrups (kg)	4.43	3.99
Longitudinal reinforcement (un.)	10 Φ10mm	
Weight of longitudinal bars (kg)	16.97	
Total weight of steel (kg)	21.40	20.96

The methodology used to obtain the depths of chloride penetration in the different concrete mixtures followed those described by Wee, Suryavanshi and Tin (2000) and Otsuki, Nagataki and Nakashita (1992), opting for a curing time in a wet room of 7 days and without the use of paint.

The AutoCAD software was used to scale the image and outline the area penetrated by chlorides in the scanned photographs of the test specimens. The analyzed region was divided by parallel lines drawn along the penetration depth and spaced 1mm from each other. Through a routine called DIMENSION, the length of each of these lines was measured, thus generating a file in Excel format. The values obtained were transferred to a spreadsheet for statistical treatment. As a result, the mean distance of chloride penetration was obtained, in which the discrepant values with a coefficient of variation higher than 20% were excluded.

In the life cycle inventory the material input and output flows (mass flow) and the energy for each of the process units of the system related to the product were established. The calculation was carried out in the following way: elementary flows were classified as "input" or "output"; data were uniformed by quantity.year; the total of materials, fuels and energy involved in the whole unit process was calculated; the total of each of the inputs was divided by the total of the main material produced in kilograms and the input and output flows of each process unit were obtained.

In this study, data from the inventory formulated by Silva (2014) were considered, namely the phases of obtaining the raw material and execution of the pillar, and involved the phases of use/maintenance, demolition and recycling of the functional unit based on data collected by Lamberti (2015). For the phases of obtaining raw material and execution of the functional unit (pillar), data on aggregates and cement CP IV-32 and CP V- ARI were obtained directly from the supplying plants. Data on water, wood and additive were taken from the SimaPro program database and steel information was collected from the Steel Sustainability Report (INSTITUTO…, 2013).

In addition, it was found necessary to perform the calculations of elementary fluxes of diesel oil, electric power and the explosive that were used in the quarry. Therefore, the fuel inventory was carried out by converting the energy emitted from the burning to the quantity (grams) of each of the burning elements, such as: carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO(x)) and particulate material (MP). Mud explosives were used to obtain the gravel, and the emissions were quantified by stoichiometric calculations. However, for the quantification of electrical energy data, carbon dioxide emissions were determined through the average of emissions during the period from October 2012 to September 2013, provided by the Ministry of Science and Technology (MINISTÉRIO…, 2013).

The RHA and FA were used as partial substitutes for Portland cement and the CDW as a substitute for the natural coarse aggregate, considering the ash data from the Simapro 8.5.2.2 software database and the CDW data related to waste recycling.

In relation to the values of acrylic paint used in the painting of the pillars, they were obtained through the database of the software SimaPro 8.5.2.2. Also, during the period of use of the structure, occurred the fixing of CO_2 of the environment in the concrete pillar, this being a positive point and considered in order to contribute to the assessment of sustainability. The quantification of CO_2 absorbed was studied by some authors (LAGERBLAD, 2006; PADE; GUIMARAES, 2007; COLLINS, 2010) and the model used is presented in Equation 1.

$$CO_2 = X.C.CaO.R.A.M \qquad \text{Eq. 1}$$

Where:

X = carbonated depth in meters;

C = amount (kg/m) of clinker in the binder;

CaO = proportion of calcium oxide, adopting 0.65 according to Collins (2010);

R = proportion of totally carbonated CaO transformed into $CaCO_3$ of 0.75 according to Lagerblad (2006);

A = area of exposed concrete (m); and

M = adimensional chemical molar fraction of CO_2/CaO of 0.79 according to Collins (2010).

According to Kazmierczak and Helene (1995), acrylic painting causes a reduction of approximately 2.5 times in the carbonation coefficient in concrete structures and although this work is about the penetration of chlorides, it was necessary to use this same value to make the probable estimate of chloride penetration of mixtures.

The clinker contents in CP IV-32 and CP V-ARI cements were 63.14% and 92.72%, respectively, according to Itambé (2010) technical handout, while the cement and clinker contents per cubic meter in the concrete produced are in Table 4.

Table 4 – **Amount of cement and clinker per cubic meter**

Mixture Concrete	kg of cement. m^{-3}	kg of clinker. m^{-3}
REF. CP V - ARI	329.37	305.39
CDW 15 + CP V - ARI	317.22	294.13
CDW 30 + CP V - ARI	412.01	382.02
CDW 15 + RHA 25 + CP V - ARI	280.97	260.52
CDW 30 + RHA 25 + CP V - ARI	324.47	300.85
CDW 15 + FA 25 + CP V - ARI	305.95	283.68
CDW 30 + FA 25 + CP V - ARI	366.50	339.82
REF. CP IV - 32	329.89	208.29
CDW 15 + CP IV - 32	343.80	217.08
CDW 30 + CP IV - 32	403.38	254.69

In the deconstruction and recycling phase, Lamberti (2015) considered the demolition by means of a breaker hammer using diesel oil for its operation. The loading of the generated debris and the diesel consumed in its transportation were obtained through data taken from the TCPO (TABELA…, 2008), for the realization of the inventory. After the rubble arrived at its destination in the GR2 company located in the city of Santa Maria - RS, the consumption of diesel oil by the machines was considered for the steel separation and the crushing of the rubble. In the study of Lima (2018), appendix C, are the input data entered in the software SimaPro and details of the inventory can be found in Silva (2014) and Lamberti (2015).

The life-cycle impact assessment phase of this study was conducted in a quantitative and qualitative manner. The Eco-indicator 99 method was used to consider different cultural perspectives and to deal with the methodological uncertainties of the model, since opinions on the seriousness and risk of different environmental effects are diverse. Therefore, the final result of these quantifications was represented in the unit of one thousandth of the average annual environmental load of a European citizen (Pt). Next, a unit comparison was made, based on the division of the data obtained by the lifespan in years and the compressive strength at 28 days of age ($f_{cj,28}$), and to finalize the indexes for the results of the different pillar alternatives were established.

However, in order to carry out the full environmental impact analysis it was necessary to calculate the impact of the carbon dioxide equivalent (CO_{2eq}) emissions of each of the proposed pillar alternatives, considering that each pillar releases and absorbs CO_2 in a different way. For these calculations, the inventory generated by the SimaPro software was used, as well as the equivalence factors adapted from Table 2.14 of the Fourth Assessment Report (INTERGOVERNMENT…, 2007).

To complete the analyses, the results were integrated in order to choose the best environmental/economic alternative, through the geometric average of the environmental and economic indexes $(I_a.I_e)^{0.5}$.

Analysis and discussion of results

Immersion Chloride Penetration (EPCl)

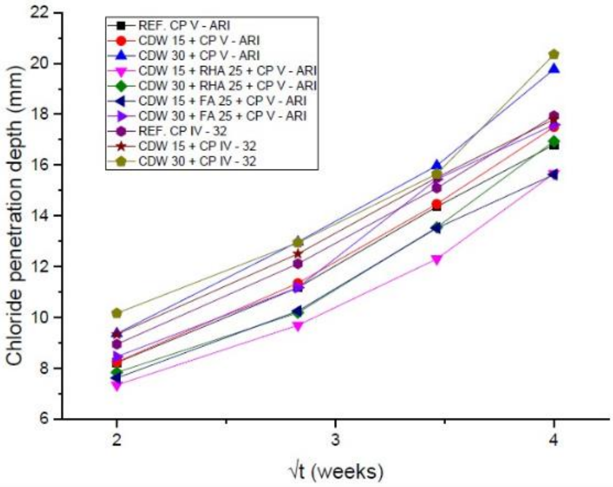
Figure 2 illustrates the average chloride penetration depths of all mixtures produced for later evaluation.

Based on the results in Figure 2 it was possible to obtain, through the trend lines, the equation of type $f(x) = a.x + b$, where the angular coefficient of the straight line, calculated by linear regression ($\sqrt{t}$ in weeks versus chloride penetration depth in mm) where "a" is the penetration coefficient (Kcl) and the value "b", result of the freedom of the function, represents the point where the straight lines cross the ordinate axis.

In addition and in accordance with the specifications established in the design of the reinforced concrete column, it was possible to estimate the lifespan of each of the studied pillar options according to Table 5, where a penetration front advance of x = 20 mm (25 mm of the covering layer, reduced by 5 mm of the penetration front) was adopted. For the calculation of the probable estimated service life, the use of paint on the abutments was taken into consideration, with an estimated life below the minimum required (50 years) according to NBR 15575-1 (ABNT, 2013) and considering a maximum of 150 years.

Table 5 shows that all mixtures required painting to achieve the minimum. Kou and Poon (2006) reported that with the reduction of the water/binder ratio, mixtures obtain a significant increase in resistance to chloride penetration, since there is a lower volume of pores with a less permeable matrix. However, with the insertion of recycled aggregates this chloride penetration resistance decreases and can thus be compensated with the use of 25 to 35% pozzolanic material.

Figure 2 – **Average chloride penetration depths**



√t (weeks)	Concrete mixtures									
	REF. CP V-ARI	CDW 15 + CP V-ARI	CDW 30 + CP V-ARI	CDW 15 + RHA 25 + CP V-ARI	CDW 30 + RHA 25 + CP V-ARI	CDW 15 + FA 25 + CP V-ARI	CDW 30 + FA 25 + CP V-ARI	REF. CP IV-32	CDW 15 + REF. CP IV-32	CDW 30 + REF. CP IV-32
2	8.23	8.25	9.37	7.35	7.84	7.62	8.46	8.95	9.34	10.17
2.83	11.18	11.35	12.98	9.70	10.19	10.26	11.18	12.12	12.51	12.95
3.46	14.36	14.47	15.98	12.31	13.55	13.52	15.44	15.10	15.51	15.65
4.00	16.80	17.50	19.77	15.67	16.94	15.63	17.59	17.94	17.80	20.35

Table 5 - **Chloride equations and penetration coefficients**

Mixture Concrete	f (x) = a.x + b	Coefficient (mm x week$^{-0,5}$)		Theoretical estimated time (years)	Kcl probable with painting (mm)	Probable estimated time (years)
		Kcl	R²	t = (x/Kcl)²	Kcl' = (Kcl/2,5)	t' = [x/(Kcl'/2,5)]²
REF. CP V - ARI	4.3257x - 0.6511	4.33	0.9943	21.33	1.73	133.34
CDW 15 + CP V - ARI	4.6085x - 1.2701	4.61	0.9910	18.82	1.84	117.64
CDW 30 + CP V - ARI	5.1004x - 1.1491	5.10	0.9872	15.38	2.04	96.12
CDW 15 + RHA 25 + CP V - ARI	4.0818x - 1.2865	4.08	0.9679	24.03	1.63	150.18
CDW 30 + RHA 25 + CP V - ARI	4.5389x - 1.8185	4.54	0.9680	19.41	1.82	121.29
CDW 15 + FA 25 + CP V - ARI	4.086x - 0.7993	4.09	0.9908	23.91	1.64	149.45
CDW 30 + FA 25 + CP V - ARI	4.734x - 1.3806	4.73	0.9802	17.88	1.89	111.74
REF. CP IV - 32	4.4801x - 0.2406	4.48	0.9944	19.93	1.79	124.56
CDW 15 + CP IV - 32	4.2627x + 0.6901	4.26	0.9981	22.04	1.70	137.76
CDW 30 + CP IV - 32	4.9013x - 0.2824	4.90	0.9473	16.66	1.96	104.12

The pillar alternatives with the lowest theoretical estimated times were the mixtures that contained the highest contents of large recycled aggregates: CDW30+CPV-ARI and CDW30+CPIV-32, which denotes a negative influence of these aggregates on the durability of concrete. This fact can be explained by the higher specific surface, absorption and porosity of the recycled aggregates (LEITE, 2001).

However, CDW15+RHA25+CPV-ARI and CDW15+FA25+CPV-ARI mixtures containing simultaneously coarse recycled aggregates and artificial pozzolans had the best theoretical estimated times, even above the reference mixture. This fact can be explained by the densification and improvement of the microstructure by the presence of the pozzolan, regardless of the water/binder relations and curing time, thus compensating the presence of concrete demolition waste (LI; XIAO; ZHOU, 2009).

Life Cycle Cost (LCC)

Table 6 presents the calculated costs for each concrete produced in different stages of its cycle, Based on the Price Composition Table for Budgets (TABELA…, 2008) as March/2017 the reference month. It should be noted that all the pillars were painted to reach the established minimum and none of them went through any washing process.

Table 6 shows that the acrylic paint service charged the final cost of all the pillars, overcoming the other services. Even the CDW15+RHA25+CPV-ARI mixture and the CDW30+CPV-ARI mixture had the highest and lowest final cost, respectively. In general, painting accounted on average for 81.62% of the total value, a value considerably above the studies of Reis (2008), in which painting can be responsible for around 12% of the initial value of a work and when considering the maintenance of this service over 100 years, this cost can represent around 60% of the initial value.

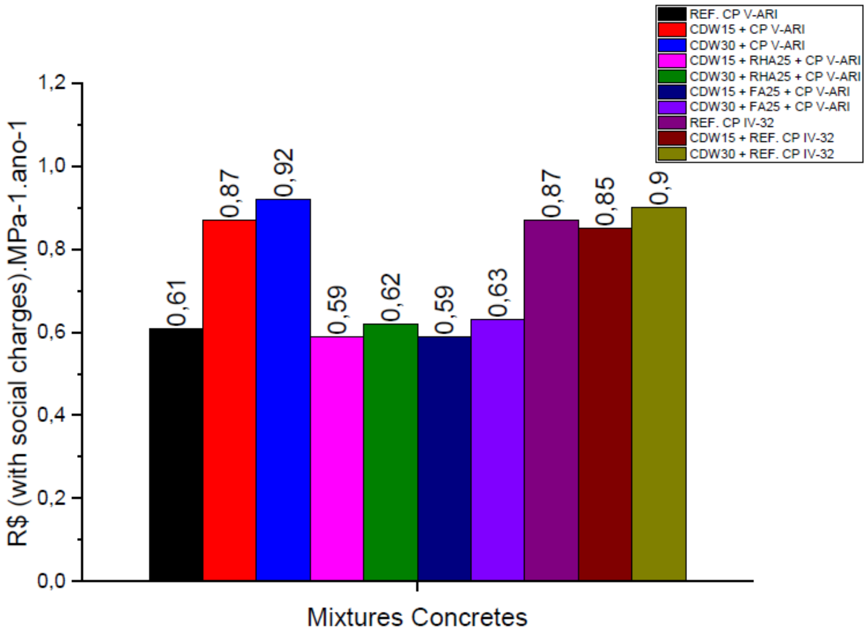
Figure 3 illustrates the unit costs of each type of pillar, where the total cost (R$) was divided by the average axial compressive strength at 28 days and its lifespan.

According with the results in Figure 3, the mixture with the highest unit cost was CDW30+CPV-ARI, which had the highest chloride penetration coefficient (Kcl = 5.10) and the lowest theoretical estimated time (15.38 years), which leads to a lower durability of the part and a higher cost of MPa per year for subsequent repairs. However, the lowest cost mixtures were CDW15+RHA25+CPV-ARI and CDW15+FA25+CPV-ARI, which also indicates that a lower cost product can be obtained environmentally by replacing natural aggregates and Portland cement.

Table 6 - **Composition of costs with social charges of the pillars**

Mixture Concrete	Costs with social charges (R$.pillar^{-1})						
	Construction	Painting	Wash	Descons-truction	Transpor-tation	Manage-ment of the CDW	Total
REF. CP V - ARI	505.00	2,688.72	0.00	45.47	13.16	1.02	3,253.37
CDW 15 + CP V - ARI	523.41	2,543.74	0.00	50.52	13.16	1.13	3,131.96
CDW 30 + CP V - ARI	543.64	2,076.64	0.00	50.52	13.16	1.13	2,685.10
CDW 15 + RHA 25 + CP V - ARI	495.07	3,024.66	0.00	45.47	13.16	1.02	3,579.38
CDW 30 + RHA 25 + CP V - ARI	503.18	2,445.74	0.00	45.47	13.16	1.02	3,008.57
CDW 15 + FA 25 + CP V - ARI	500.26	3,013.57	0.00	45.47	13.16	1.02	3,573.48
CDW 30 + FA 25 + CP V - ARI	511.91	2,253.17	0.00	45.47	13.16	1.02	2,824.73
REF. CP IV - 32	514.37	2,691.08	0.00	50.52	13.16	1.13	3,270.27
CDW 15 + CP IV - 32	516.78	2,976.26	0.00	50.52	13.16	1.13	3,557.86
CDW 30 + CP IV - 32	526.83	2,249.48	0.00	50.52	13.16	1.13	2,841.13

Figure 3 - **Unit cost of different mixtures concrete**



It can also be noted that the average unit cost was grouped by the strength class of concrete, with 0.88 R$.MPa^{-1}.year^{-1} for concrete with fck = 25 years and 0.61 R$.MPa^{-1}.year^{-1} for concrete with fck = 35 years, demonstrating the economic feasibility of binary concrete.

Life Cycle Assessment (LCA)

Figure 4 illustrates the results of the total impacts, from cradle-to-grave, on human health, ecosystems and natural resources, as well as the total of these impacts for each concrete.

Figure 4 presents that the alternatives dimensioned with a fck of 35 MPa have slightly the lowest total environmental impacts compared to the alternatives dimensioned with a fck of 25 MPa, which have an average of 32.99 Pt and 33.23 Pt, respectively. Therefore, the greatest impacts were caused by the CDW30+CPV-ARI and CDW30+CPIV-32 pillars, both using 30% CDW, resulting in 34.42 Pt and 33.32 Pt, respectively. These two pillars were produced with a lower water use, water/binder ratio of 0.42 for both, consequently with a higher cement consumption per cubic meter of concrete, which indicates a significant influence of the amount of cement used in the mixtures.

In addition, the pillars are found to cause greater impacts on human health, followed by natural resources and finally the quality of ecosystems, in that order. It can be observed that the overall average among the ten compositions was 33.11 Pt, a standard deviation of 0.4689 and a coefficient of variation of only 1.42%, which means similarity of the mixtures and difficulty in defining the best pillar, thus depending on the availability of the various materials used in the mixture at the concrete production site. Therefore, Table 7 was prepared for a more complete analysis of the results.

The smallest impact per unit occurred with the CDW15+RHA25+CPV-ARI pillar, resulting in 53.35 Pt.MPa^{-1}.year^{-1}.10^{4}, or 13.62% lower impact than the REF mixture. CP V-ARI, as a result of the mixtures dosed to 35 MPa. In the mixtures dosed for 25 MPa, the composition CDW15+CPIV-32 obtained a better performance, resulting in 78.24 Pt.MPa^{-1}.year^{-1}.10^{4}, i.e. 13.63% less impact than the composition REF - CP IV-32.

Additionally, it is noted that although the CDW15+RHA25+CPV-ARI mixture was constituted by a lower cement consumption, it still obtained the best results in terms of the theoretical and estimated probable lifespan, with 24.03 years and 150 years, respectively. This fact may have occurred due to the presence of 25% of RHA replacing CP V-ARI cement, providing greater durability. In contrast, the CDW30+CPV-ARI mixture presented the worst results with 117.79 Pt.MPa^{-1}.year^{-1}.10^{4}, that is, causing 90.73% more impact than the REF pillar. CP V-ARI. This fact can be explained by the higher consumption of cement per cubic meter, as well as the lower theoretical and estimated probable results.

Figure 4 - **Total impacts on human health, ecosystems and natural resources**

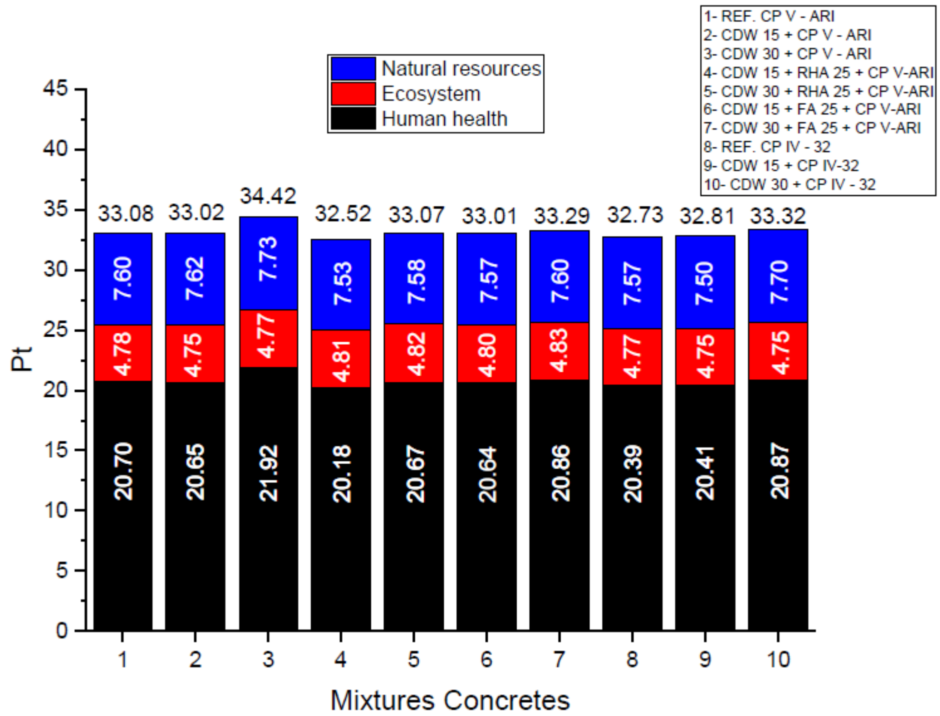


Table 7 - **Total impacts, unit impacts, costs and indexes**

Fck	Pillar	Total Impacts (Pt.pillar^{-1})	Unitary Impacts (Pt.MPa^{-1}. year^{-1}.10^4)	Indexes of Unitary Impacts	Total Cost (R\$. pillar^{-1})	Unitary Cost (R\$. MPa^{-1}. year^{-1})	Index of the Cost Unitary
25 MPa	CDW 15 + CP V - ARI	33.02	91.76	148.57	3.131.96	0.87	142.62
	CDW 30 + CP V - ARI	34.25	117.79	190.73	2.685.10	0.92	150.82
	REF. CP IV - 32	32.73	86.66	140.32	3.270.27	0.87	142.62
	CDW 15 + CP IV - 32	32.81	78.24	126.69	3.557.86	0.85	139.34
	CDW 30 + CP IV - 32	33.32	105.86	171.41	2.841.13	0.90	147.54
	DP* (%)	0.62	15.75	-	345.97	0.03	-
35 MPa	REF. CP V - ARI	33.08	61.76	100.00	3.253.37	0.61	100.00
	CDW 15 + RHA 25 + CP V - ARI	32.52	53.35	86.38	3.579.38	0.59	96.72
	CDW 30 + RHA 25 + CP V - ARI	33.07	67.74	109.68	3.008.57	0.62	101.64
	CDW 15 + FA 25 + CP V - ARI	33.01	54.14	87.66	3.573.48	0.59	96.72
	CDW 30 + FA 25 + CP V - ARI	33.29	74.69	120.93	2.824.73	0.63	103.28
	DP* (%)	0.29	9.08	-	336.25	0.02	-

Note: *DP = Standard Deviation.

In general, it can be noticed that the best results were obtained by the pillars where concrete mixtures were used with partial substitution of cement by rice husk ash and fly ash, as well as with the partial substitution of natural coarse aggregate by 15% of recycled coarse aggregate. It is still clear that concrete dosed for greater strength tends to cause less impact, i.e., in this survey the average impact for fck = 25 MPa was 96.06 Pt.MPa^{-1}.year^{-1}.10^4 and for fck = 35 MPa was 62.34 Pt.MPa^{-1}.year^{-1}.10^4, or 40.12% fewer impacts. The fact can be explained by the substitution of cement by pozzolan, lower consumption of cement by m , lower CO_2 emissions and higher resistance to provide concrete parts with smaller dimensions.

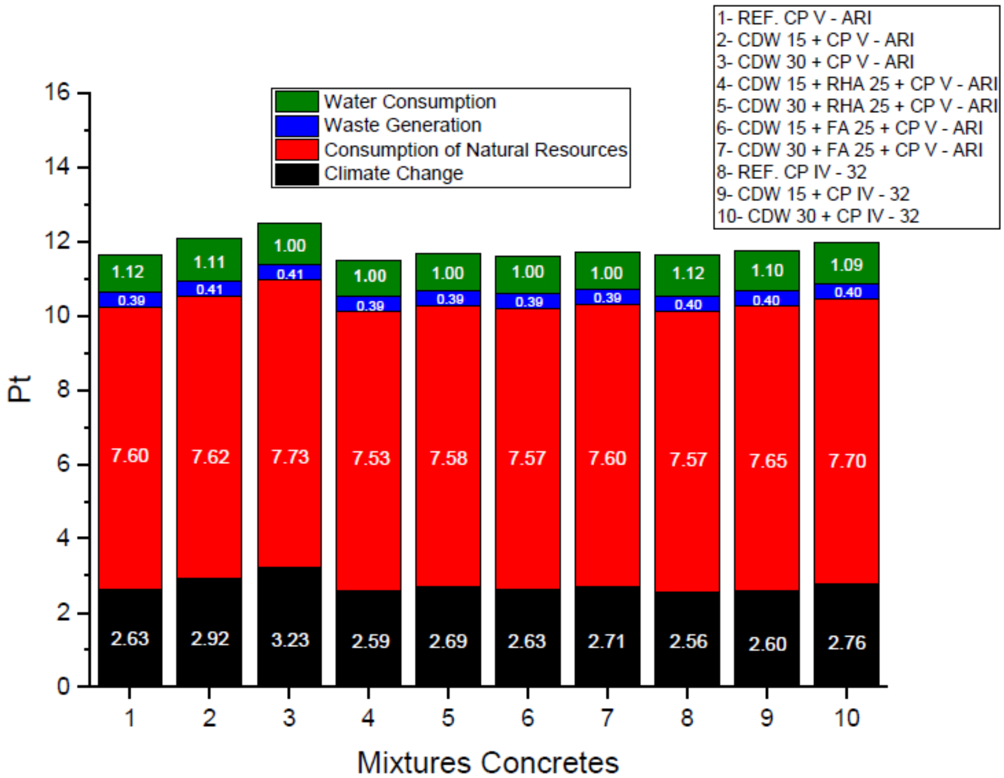
Figure 5 presents the most relevant environmental aspects according to the methodology of the modular life cycle analysis (LCA-m): climate changes, consumption of natural resources, energy consumption, waste generation and water consumption.

In pillars dimensioned with fck = 25 MPa, the average impact under climate change was 2.81 Pt and in pillars with fck= 35 MPa, the average impact was 2.65 Pt, which means 5.69% lower impact by distinguishing the strength class of concrete. When CP IV-32 cement was used, the average impact was 2.64 Pt, with CP V-ARI cement the average was 2.93 Pt and in the compositions with pozzolan the average obtained was 2.66 Pt. In the case of the percentage of substitution of the natural aggregate by the recycled aggregate, the reference mixtures obtained an average impact of 2.59 Pt, mixtures with 15% substitution an average of 2.68 Pt and mixtures with 30% substitution an average of 2.85 Pt. It should therefore be noted that the replacement of the natural aggregate by the recycled aggregate does not bring benefits, probably because these replacements cause a decrease in the strength and durability of concrete, consequently leading to an increase in cement consumption to achieve the required strengths.

In terms of consumption of natural resources, it should be noted that the fck = 25 MPa pillars have an average impact of 7.65 Pt, while the fck = 35 MPa pillars have an average impact of 7.58 Pt, relatively similar results. Regarding the type of cement, it can be seen that when CPIV-32 cement was used, the average impact was 7.64 Pt and with CPV-ARI cement, not considering the mixtures with pozzolans, it was 7.65 Pt. In the case of the percentage of substitution of the natural aggregate by the recycled aggregate, the reference mixtures had an average impact of 7.58 Pt, mixtures with 15% substitution have an average of 7.59 Pt and mixtures with 30% substitution an average of 7.65 Pt. For the use of pozzolan, the pillars using the compositions with RHA and FA obtained an average impact of 7.57 Pt.

Regarding the waste generation, it can be seen that the impact results of the different pillars were close when compared within their respective fck groups (25 MPa and 35 MPa). The pillars with fck = 25 MPa resulted in an average of 0.40 Pt and the pillars with fck = 35 MPa reached an average of 0.39 Pt, i.e., only 2.50% less impact. When comparing all mixtures, it can be seen that there are no significant differences in the impacts of this category.

Figure 5 - **Environmental aspects according to LCA-m**



In relation to water consumption, it is noted that there is little influence on the total impacts caused by each of the alternative pillars, where the pillars sized with a smaller fck have more impact in this regard than the pillars sized with a higher fck, with the average impact for fck = 25 MPa of 0.00111 Pt, while for fck = 35 MPa was 0.00100, i.e. the highest strength obtained 9.91% less impact. It was found that the water consumption per cubic meter for fck = 25 MPa was on average 172.73 $kg.m^{-3}$, while for fck = 35 MPa it was on average 174.14 $kg.m^{-3}$. Nevertheless, the pillars dimensioned for 25 MPa have larger dimensions than those dimensioned for 35 MPa, that is, 0.25x0.50x2.75m (0.344 m) and 0.25x0.45x2.75m (0.309 m), respectively. Therefore, the higher fck pillar tends to use less water and therefore explains the impacts presented. Figure 6 illustrates the electric energy consumption of the concrete produced.

Table 6 indicates that the greatest impact resulted from the CDW30+CPV-ARI pillar, reaching 0.053 Pt, followed by the CDW30+CPIV-32 pillar, which reached 0.051 Pt. The pillar with the lowest impact was the CDW15+RHA25+CPV-ARI, followed by the CDW15+FA25+CPV-ARI pillar reaching 0.032 Pt and 0.035 Pt, respectively.

In general, it can be verified that the pillars with fck = 35 MPa had a lower impact than the pillars with fck = 25 MPa, promoting the use of pozzolans to reduce the impacts in this category, at the same time that the use of CDW in the composition of the mixtures became harmful. It is worth considering that one Pt is equivalent to one thousandth of the average annual environmental load of a European citizen, so the energy consumption of the entire life cycle of a reinforced concrete pillar, which includes the energy consumption of the concrete mixer (construction phase) and the jet washer (use phase), were low.

Finally, carbon dioxide equivalent ($CO_{2eq.}$) was calculated as a carbon footprint according to Figure 7.

Figure 7 reveals that the pillar with the highest $CO_{2eq.}$ footprint was the CDW30+CPV-ARI with 535.61 $kg.pillar^{-1}$, followed by the CDW30+CPIV-32 pillar which resulted in 463.89 $kg.pillar^{-1}$. This result is mainly due to the higher cement consumption of the concrete mixtures used in these columns, 412.01 $kg.m^{-3}$ and 403.38 $kg.m^{-3}$, respectively, and to the lower water/commodity ratio, both with 0.42. Meanwhile, CDW15+RHA25+CP V-ARI and CDW15+FA25+CP V-ARI mixtures have improved $CO_{2eq.}$ intensities, which corroborates advances in mixture design and material selection in order to achieve a reduction in carbon dioxide intensity without compromising the mechanical requirements of concrete mixtures (GURSEL; MARYMAN; OSTERTAG, 2016).

As in the total impacts, the unit impacts were calculated for the individual aspects and are presented in Table 8.

Figure 6 - **Electrical consumption of binary mixtures**

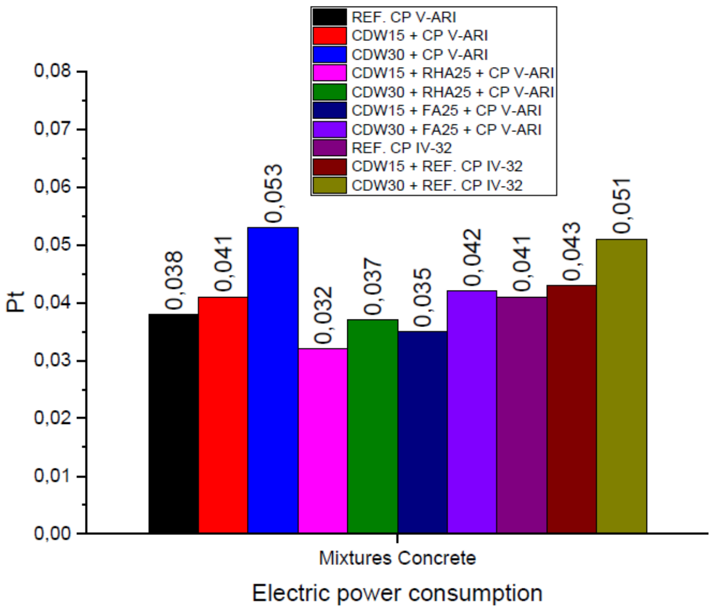


Figure 7 - **Carbon dioxide equivalent**

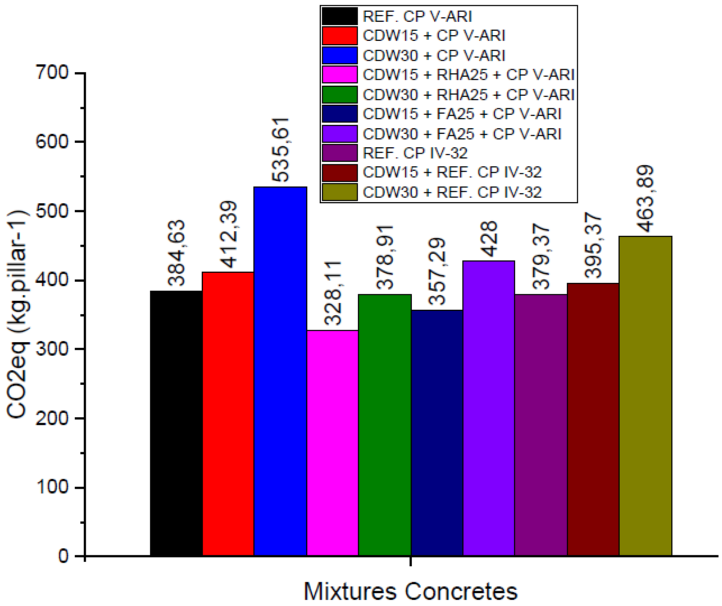


Table 8 - **Unit impacts of individual aspects and indexes**

Individual impacts ($Pt.MPa^{-1}.year^{-1}.10^4$)	Mixture Concretes									
	REF. CP V-ARI	CDW 15 + CP V-ARI	CDW 30 + CP V-ARI	CDW 15 + RHA 25 + CP V-ARI	CDW 30 + RHA 25 + CP V-ARI	CDW 15 + FA 25 + CP V-ARI	CDW 30 + FA 25 + CPV-ARI	REF. CP IV-32	CDW 15 + CP IV-32	CDW 30 + CP IV-32
Climate change	4.91	8.11	11.11	4.25	5.51	4.31	6.08	6.78	6.20	8.77
Index	100.00	165.26	226.24	86.53	112.22	87.84	123.82	138.05	126.27	178.58
Natural resources	14.19	21.17	26.59	12.35	15.53	12.41	17.05	20.04	18.24	24.46
Index	100.00	149.23	187.37	87.06	109.43	87.50	120.17	141.27	128.57	172.41
Consumpti-on of energy	0.07	0.11	0.18	0.05	0.08	0.06	0.09	0.11	0.10	0.16
Index	100.00	159.47	256.34	74.85	107.97	81.57	133.52	154.96	145.30	226.90
Waste generation	0.73	1.13	1.40	0.63	0.79	0.64	0.87	1.07	0.96	1.28
Index	100.00	154.57	191.77	87.19	108.59	87.39	119.24	146.92	132.32	175.85
Consumpti-on of water	0.00190	0.00311	0.00382	0.00164	0.00205	0.00164	0.00224	0.00297	0.00262	0.00346
Index	100.00	163.44	200.47	86.14	107.57	86.12	117.81	155.73	137.75	181.85
Carbon footprint	718.09	1145.97	1842.08	538.24	776.15	585.96	960.22	1004.51	942.84	1473.81
Index	100.00	159.59	256.52	74.95	108.08	81.60	133.72	139.89	131.30	205.24

Table 8 shows that in all the items analyzed, the worst performances were of the pillars with characteristic strength of 25 MPa. In the natural resources item, the individual impact with the highest value was from the CDW30+CPV-ARI pillar with a unit value of 26.59 $Pt.MPa^{-1}.year^{-1}.10^4$, while the lowest impact value was from the CDW15+CPIV-32 pillar with 18.24 $Pt.MPa^{-1}.year^{-1}.10^4$. For columns with a characteristic strength of 35 MPa, the individual impact with the highest value was the CDW30+FA25+CPV-ARI column with a unit value of 17.05 $Pt.MPa^{-1}.year^{-1}.10^4$, while the lowest impact value was the CDW15+RHA25+CP-ARI column with 12.35 $Pt.MPa^{-1}.year^{-1}.10^4$.

In terms of carbon CO_{2eq} footprint, it is found that the increase in the characteristic resistance level from 25 to 35 MPa decreases on average by 44.16% the unit emission of greenhouse gases, due to the higher estimates of mixtures for fck = 35 MPa. The lowest values are found in the CDW15+RHA25+CPV-ARI pillars (538.24 $CO_{2eq}.MPa^{-1}.year^{-1}.10^4$) and CDW15+FA25+CPV-ARI (585.96 $CO_{2eq}.MPa^{-1}.year^{-1}.10^4$), both dimensioned with characteristic strength of 35 MPa. It can be concluded that in the pillars where the use of a higher characteristic strength has been chosen, are the most environmentally adequate choices.

Conclusions

Through this research, it was concluded that the concomitant analysis of LCC with LCA is an effective methodology for a better quantitative environmental assessment of the costs and impacts of different concrete compositions. Despite the complexity of application and the absence of regional data that hinders the dissemination of the use of these methods.

It was verified that CDW15+RHA25+CPV-ARI and CDW15+FA25+CPV-ARI concrete obtained the best results regarding durability, specifically chloride penetration, while CDW30+CP IV-32 concrete had the worst result.

By analyzing the Life Cycle Cost (LCC), it is perceptible that the pillars were grouped by strength class (25 MPa and 35 MPa) which obtained an average unit cost of 0.88 R$.MPa^{-1}.year^{-1} and 0.61 R$.MPa^{-1}.year^{-1}, respectively, indicating that greater strengths are also favorable in terms of costs over the service life of the structures. Thus, the use of CP V-ARI cement combined with pozzolan became beneficial, while CP IV-32 cement with the use of CDW became harmful.

In relation to Life Cycle Analysis (LCA) for all analyzed impact classes, in general, the alternative pillars sized with fck = 35 MPa obtained slightly better results than the others. Once the CDW was inserted in the mixtures, it became harmful as it caused a higher consumption of cement per cubic meter of concrete, directly influencing the environmental impacts. On the other hand, the use of pozzolans provided a lower consumption of cement, improvements in the mechanical performance and durability of concrete. Moreover, when analyzing the unit impacts of individual aspects, the most influenced were natural resources and climate change, while the aspects of waste generation, water consumption, and energy obtained less significant results.

Finally, by integrating the results of LCC and ACL, it is concluded that the best alternative analyzed was the pillar dosed with a fck = 35 MPa, consisting of CDW15+RHA25+CP V-ARI, presenting itself as the most viable alternative from a sustainable and economic point of view.

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Cristian Jonathan Franco de Lima
Programa de Pós-Graduação em Engenharia Civil, Escola Politécnica | Universidade do Vale do Rio dos Sinos | Bairro Cristo Rei, Bloco C | São Leopoldo – RS – Brasil | CEP 93022-750 | Tel.: (51) 3591-1714 | E-mail: cristian.jfl@outlook.com

Francisco Roger Carneiro Ribeiro
Programa de Pós-Graduação em Engenharia Civil | Universidade Federal do Rio Grande do Sul | Av. Osvaldo Aranha, 99, 7º Andar, Sala 706 | Porto Alegre - RS – Brasil | CEP 90035-190 | Tel.: (51) 3308-4848 | E-mail: roger.ribeiro_@hotmail.com

Regina Célia Espinosa Modolo
Programa de Pós-Graduação em Engenharia Civil | Universidade do Vale do Rio dos Sinos | E-mail: reginaem@unisinos.br

Geraldo Cechella Isaia
Programa de Pós-Graduação em Engenharia Civil | Universidade Federal de Santa Maria | Av. Roraima, 1000, Camobi, Centro de Tecnologia, Prédio INPE, Sala 2061 | Santa Maria – RS – Brasil | CEP 97105-900 | Tel.: (55) 3220-8837 | E-mail: geraldoisaia@gmail.com

Maurício Mancio
Programa de Pós-Graduação em Engenharia Civil | Universidade do Vale do Rio dos Sinos | E-mail: mancio@unisinos.br

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Av. Osvaldo Aranha, 99 - 3º andar, Centro
Porto Alegre – RS - Brasil
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www.seer.ufrgs.br/ambienteconstruido
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E-mail: ambienteconstruido@ufrgs.br