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Parameterized environmental impacts of ready-mixed concrete in Spain

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Parameterized environmental impacts of ready-mixed concrete in Spain

This study includes the assessment of all possible combinations of ready-mix concrete encompassed in a reference construction database of building materials for Valencia (Spain). All concrete components are considered in the calculation: cement, water, aggregates, and admixtures. The life cycle assessment methodology was used to calculate the environmental impacts of each material, including the modules A1-A3, i.e., production of raw materials, transport, and manufacturing, and impact categories in accordance with EN 15804:2012+A2:2019. This study shows that cement is the concrete component with the greatest overall impact on the environment. Furthermore, the impact for the Global Warming Potential (stages A1-A3) can double depending on the type of cement; with CEM I and CEM II types having the highest impact. The regressions obtained for each impact category allow to predict the environmental impacts of every ready-mix concrete and also to analyze the relative importance of each concrete component in each impact category.

KEY WORDS: Life Cycle Assessment (LCA), concrete, cements, concrete dosage, environmental performance, parametric analysis.

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1. Introduction

In the existing literature, it is commonly known that concrete is the most consumed material as well as one of the major causes of environmental impacts in the construction sector [1,2]. In recent years, several studies have been focused on the sustainable improvement of the ready-mixed concrete production. Indeed, since 2014, there has been a notable growth in studies using the life cycle assessment (LCA) methodology to this aim [3].

A widely agreed result is that, among all concrete components, cement is the one that causes the greatest environmental impacts [2–6]. Additionally, cement has been also stated as the material with the greatest economic impact [5]. In recent literature, one of the main focus of research has been the environmental assessment and comparison of concretes including recycled aggregates or components such as fly ash, blast furnace slag or pozzolana [4–10] in order to find more sustainable and environmentally friendly concretes.

Given the large amount of concrete used globally each year, any environmental improvements achieved will significantly reduce the impacts of the construction sector. Although much research is currently being carried out in this area and interesting results are being obtained, some studies have warned that there are certain gaps in the studies that need to be addressed [1,3,4,11]. For example, a major issue is the lack of studies assessing environmental impacts holistically [1]. Concrete is known to be carbon intensive; however, LCA methodology allows impact data to be obtained for other important categories such as toxicity or depletion of non-renewable resources that should also be taken into account [3]. Another conflicting issue is the neglect of specific concrete phases or components because they have been considered insignificant on the basis of previous studies [1,4]. This has been a reason for some studies not to consider e.g. water consumption because of its low impact, or the use of admixtures because of their low content in the mix [1,12]. In addition, an alarming issue is the need for studies to be transparent about the criteria, data, functional unit and other basic methodological choices used to conduct LCA studies [3].

To these shortcomings defined in the previous paragraph, we must add the fact that the majority of published research studies show their results for a very small number of generic samples, which reduces the detail and rigor of the conclusions obtained. For example, several studies are found in which results for less than 10 concrete mixes are provided [8–10,13–20]. In other research, less than 15 concrete mixes are assessed [2,21,22]. A more ambitious study analyzed 28 concrete mix combinations, but all of them comprised the same cement type (CEM I) [6]. As exceptional cases, two studies using larger samples were found. First, a study in which more than 200 concrete mixes had been analyzed, obtained from 24 previous references, all of them using CEM I or CEM II in the mix [5]; and second, a study in which more than 600 recycled aggregate concrete mix designs collated from 61 individual studies had been assessed [23].

This research is the result of an analysis carried out for the Instituto Valenciano de la Edificación (IVE, i.e., Valencia Institute of Building, Spain) in which all possible combinations in the concrete composition within its reference database of building materials were assessed. The study, analyzing more than 1500 combinations of concrete dosage and composition, overcomes some of the previously defined problems. In the following section, the materials and method of the research are explained, including the scope of the study, the impact categories considered, the functional unit and other relevant methodological considerations in order to be transparent with the LCA methodology. All concrete components are considered in the calculation: cement, water, aggregates, and admixtures. Section 3 shows the life cycle inventory analysis detailing the data sources, the electricity mix model used for Spain, the cements inventory, transport of raw materials as well as the concrete manufacturing inventory. Results are shown in section 4 for all the impact categories according the standard EN 15804:2012+A2:2019, with special attention to the global warming potential and the abiotic resource depletion potential. Section 5 presents a parametric analysis of the results that allows to predict the environmental impacts of every ready-mix concrete and also to analyze the relative importance of each parameter in each impact category. Discussion is given in section 6 and finally, the most relevant conclusions are summarized at the end of the study.

2. Materials and method

This study includes the assessment of ready-mix concrete. The LCA methodology was used to calculate the environmental impacts of each material, considering their use in the Valencian Community (Spain). Additionally, LCA was performed in accordance with the guidelines provided by the new standard EN 15804:2012 +A2:2019.

2.1 Scope and system boundaries

Regarding the materials, the scope of this study includes all the parameters considered in the IVE 2020 construction database to define the ready-mix concrete (references PBPC.2$ to PBPC.8). Ready-mixed concretes containing recycled raw materials are not considered in any case.

The LCA was calculated according to the standards UNE-EN-ISO 14040 and UNE-EN-ISO 14044 of Environmental Management – LCA and the standard UNE-EN 15804:2012+A2:2020 of Sustainability in Construction (the Spanish equivalent of the European standard EN 15804:2012+A2:2019). The system boundary for this study follows a cradle-to-gate approach, including the modules A1-A3, i.e., production of raw materials, transport, and manufacturing (Figure 1). Additionally, the cut-off criteria for all activity stage flows considered within the system boundaries are also in accordance with EN 15804:2012+A2:2019.

On the other hand, this LCA excludes: (i) production and manufacture of concrete production equipment, concrete transport vehicles, earthmoving equipment, and laboratory equipment; (ii) staff-related activities (travels, furniture, office supplies); and (iii) non-productive activities such as selling activities. In the calculation of this LCA, double counting or omission of inputs or outputs through allocation has not been considered in any case.

The system defined in Figure 1 results, depending on the dosage used in the mix, in an infinite number of ready-mixed concretes. In this study, a total of 1505 possible concrete combinations have been included in the analysis. Environmental impact data were preferably obtained from Environmental Product Declarations (EPD) and LCA of Spanish products. In the absence of data from Spain or insufficient certainty, data from commercial databases and/or literature, as well as from the Ecoinvent 3.6 database using the SimaPro 9.1.1 tool [24] were used.

It should be noted that, although this research is focused on the materials of the reference construction database of the Valencian Community, the results could apply to the whole of Spain, since the sources of information used were mainly national in scope.

2.2 Impact categories

The impact categories were selected according with the standard EN 15804:2012+A2 of Sustainability in Construction. This Standard incorporates new units and developments in some impact categories with respect to the previous EN 15804:2012+A1 by adopting the EF method [25], except for biogenic carbon. The EF method updates the ILCD 2011 method [26]. The previous standard, EN 15804:2012+A1, was based on the CML-IA baseline method with the exception of acidification, which was based on the CML-IA non-baseline method [27]. The SimaPro v. 9.1.1.1 software incorporates, among its calculation methods, the EN 15804 +A2 Method V1.00 / EF 3.0, which allows the assessment of impacts in the impact categories and methods indicated in the new standard. As a transitory solution, an adjustment of the environmental impact values obtained from the EPDs that are based on the previous standard EN 15804:2012+A1 to the new standard was made.

The climate change category in the new EN 15804:2012+A2 standard is still based on the latest IPCC model [28]. In addition, the contents of fossil carbon, biogenic carbon and land use and land use change carbon (luluc) must be provided. In the case of cements and concretes, the content of biogenic carbon and luluc carbon is less than 5%, so it is possible to omit their declaration. In this study, it has been assumed that, for cements and concretes, the total climate change value is equal to the fossil carbon.

Acidification in EN 15804:2012+A1 was based on the CML-IA non-baseline method [27], which includes only emission but not dispersion, and the characterisation factor was expressed in kg SO_{2eq}. The new version of the standard has changed to the Cumulative Excess model [29,30], whose unit is the mole H^+_{eq}. The conversion factors were obtained directly from the calculation of the reference fluxes in the two methods indicated.

EPDs for cement and admixtures use the eutrophication model of the CML-IA baseline method [27] and the characterization factor units are kg $(PO_4)^{-3}_{eq}$. In the new standard, eutrophication is divided into three impact categories, one for each medium. Terrestrial eutrophication adopts the Cumulative Excess model [29,30] and the unit is mol N_{eq}. Marine water eutrophication adopts the RECIPE 2008 model [31] and the unit is kg N_{eq}. Freshwater eutrophication also adopts the RECIPE 2008; however, the unit in SimaPro with method EN 15804:2012+A2 is kg P_{eq}, while the unit in the standard EN 15804:2012+A1 was kg PO_{4eq}. The conversion factor 3.0665 kg PO_{4eq}/kg P_{eq} has been applied.

For the breakdown of the eutrophication from model CML-IA to models stated in the new standard the contribution of the inventory, specifically phosphates and nitrogen oxides, was analyzed. Phosphates emitted into freshwater contribute more than 99.8% to freshwater eutrophication. Nitrogen oxides contribute over 93-94% to marine eutrophication and to terrestrial eutrophication, respectively.

Water scarcity was not a compulsory impact category in the standard EN 15804:2012+A1. In the ILCD 2011 method [26], water depletion is characterized according to the mass of water used adjusted for scarcity [32]. In the method EF [25], the AWARE model is applied [33], which assesses impact in terms of restricted or deprived water quantity. The EPDs of cements and cement admixtures considered do not include this impact category. However, all these EPDs provide the value of the parameter ‘Net use of freshwater resources’, which enables completion of the impact value using as characterization factors of the AWARE model 77.7 m^3/m^3 for water consumption in Spain and 0.007 m^3 of private water per 1 · of road transport.

2.3 Description of the materials assessed

1505 different combinations of ready-mix concrete were assessed, according to the parameters in the construction database: compressive strength (in N/mm^2), consistency, maximum aggregate size (in mm), environment and exposure. Table 1 shows the number of combinations analyzed for each kind of cement.

Parameters defining the dosage of concrete are relevant when calculating the impact produced by different ready-mix concrete. The values considered in each case are detailed below:

2.3.1 Water/cement ratio

The Royal Decree 1247/2008 [34], hereinafter EHE-08, establishes the recommended minimum strengths based on durability requirements. Additionally, it also establishes the maximum water/cement ratio based on the exposure class, as well as the minimum cement content. These data have been taken as a reference for the calculation of the dosage of concrete mixes.

2.3.2 Quantity of water (l/m^3)

The quantity of water directly influences the concrete consistency, even though the maximum aggregate size must be also considered. On the other hand, in order to achieve the right consistency for each case, the use of additives such as plasticizers, superplasticizers and/or air-entraining agents is very common. It should be considered that incorporating this kind of products the amount of water required is significantly reduced without changing the content of cement. In this sense, it could be stated that innumerable possibilities of dosing concrete exist when considering additives.

In this study, a simplification of the multiple possibilities has been carried out by systematizing the dosage. According to data from the National Association of Manufacturers of Concrete and Mortar Additives of Spain (ANFAH) [35], plasticizers allow a reduction in water content of 8-10%, while with superplasticizers the reduction is even greater, between 12 and 20%. For their part, aerating agents also improve workability, so that when both additives are used, this reduction is even greater, without losing strength. The quantities of water used to calculate the environmental impacts are shown in Table 2.

Additionally, Figure 2b summarizes graphically the water content in the 1505 analyzed mixes. The IVE construction database coding system has been adopted. As shown in Table 1, each kind of concrete has an associated ‘PBPC’ code followed by a number. This number is followed by 4 letters that refer in this order to:

(1) concrete strength (varying from low to high),
(2) maximum aggregate size (a=40mm, b=20mm and c=12mm),
(3) consistency (a=plastic, b=soft, c=fluid and d=liquid) and
(4) exposure (a = s/, b = Qa, c = Qb, d = Qc, e = H, f = F, g = E).

2.3.3 Quantity of cement

Knowing the required quantity of water, the quantity of cement is directly obtained by applying the water/cement ratio. In Figure 2a, the cement content of the concretes analyzed is shown.

2.3.4 Concrete weight (kg/m^3)

According to data from EHE-08 [34], the average density of mass concrete is 2300 kg/m^3. However, this value may vary considerably depending on the maximum size of the aggregate used or in the case of using air-entraining admixtures.

2.3.5 Aggregates content

Based on the available data, the amount of aggregate is deducted from the total weight of the mix subtracting the amounts of water, cement, and admixtures. The graphical summary of the aggregates content in the mixtures analyzed is shown in Figure 2c.

2.3.6 Admixtures dosage

Regarding the admixtures added to the mixing water, it was considered relevant to use the most common ones for resistances of 30 N/mm^2 and higher. The most common ones are plasticizers and superplasticizers, depending on the consistency to be achieved. Additionally, air-entraining admixtures were considered in the case of Qa, Qb, Qc, H or F exposures. The dosage considered for fluidizing admixtures as a percentage of the weight of cement was: 0.5% for plastic consistency, 0.9% for soft consistency, 1.3% for fluid consistency and 1.8% for liquid consistency. The dosage considered for air-entraining admixtures as a percentage of the weight of cement was: 0.2% for Qa exposure, 0.5% for Qb exposure, 0.9% for Qc exposure and 0.5% for H and F exposure. Figure 3 summarizes graphically the admixtures content in the 1505 mixes analyzed.

2.4 Functional unit

As the results of this study were expected to be integrated into the IVE construction database, the same functional unit used by the database was adopted. The declared unit is 1 m^3 of each ready-mix concrete combination.

2.5 Limitations and methodological considerations

The possible mixtures for the manufacture of ready-mix concrete are practically infinite if all the parameters able to be combined are considered: cement, water, aggregates, and types of admixtures. In order to simplify the calculation and turn it feasible, the dosage has been systematized according to section 2.3.

Energy consumption in the concrete factory was considered the same for all concretes and the cement is assumed to be of national origin. Differences in impacts by aggregate particle size were not considered. In the case of admixtures, there was a lack of EPDs of Spanish products and environmental impacts from EPDs by the European Federation of Concrete Admixtures Associations Ltd. (EFCA) were obtained.

3. Life Cycle Inventory Analysis

3.1 Data sources

Data and materials used in this study are derived from several sources. Secondary data as well as EPDs data were used to collect material and energy flows (module 1) and input processes (modules 2 and 3). Table 3 describes qualitatively the data sources to collect the life cycle inventory for the subsequent life cycle impact assessment (LCA).

3.2 Electricity model in Spain

The environmental impacts caused by energy consumption in the ready-mix concrete manufacturing process were calculated using the Spanish electricity mix as a reference [36]. For the preparation of the Spanish electricity mix for 2019, primary energy and generated energy data from the Eurostat database [37], the pass-through coefficients for Europe provided by JEC WTT [38] and the Ecoinvent 3.6 database have been combined. Finally, the composition for 1 kWh generated by the Spanish mix in 2019 considered in the calculation is shown in Figure 4.

The standard EN 15804:2012+A2:2020 requires the use of renewable and non-renewable primary energy, as well as renewable and non-renewable secondary fuels, to be defined within the parameters describing resource use. To this aim, a distinction has been made between two kinds of energy (see Table 4), non-waste or conventional energy and waste-to-energy. Energies grouped under the waste-to-energy category are blast furnace gas, biogas, and municipal waste. All quantities generated have been obtained from Eurostat [28].

Regarding energy transmission and distribution losses, data for 2019 have been obtained from the Electricity Indicator Bulletins provided by the National Commission for Markets and Competition [39]. For the calculation, electricity flows have been modeled with SimaPro software considering a loss of 1.9% in high voltage lines and 7.1% in medium voltage lines.

3.3 Cements inventory

Environmental data for cements were obtained from the EPDs generated by the Spanish Institute of Cement and its Applications (Instituto Español del Cemento y sus Aplicaciones - IECA) [40]. The global warming data and total primary energy (sum of primary energy and secondary energy) from the IECA EPDs [40] have been compared with the values from the most relevant sources in the literature for Spain, Table 5. On the one hand, the complete inventory of cement production in Spain with data from 2010 is available [41,42] and, on the other hand, the data reported for Spain in the GNR CO2 project with data from 2018 are also available [43]. For these two studies the values refer to the average cement production and the same step factors have been applied to obtain the primary energy: 2.58 for electrical energy and 1.26 for thermal energy.

In both studies the thermal energy per ton of clinker is similar (3536-3600 MJ) and the percentage of clinker to cement is the same, 0.8, but there is an increase in electrical energy from 113 to 158 kWh/ton cement. The total energy values of the EPDs are higher for CEM I and CEM II cements and lower for CEM III. These variations are probably due to the different proportion of clinker in cement, but also to other energy consumptions not considered such as internal transports, raw material transports, differences in pitch factors, etc. The values provided by the EPDs have been considered valid to adapt the impacts according to EN 15804:2012+A2.

3.4 Transport of raw materials

In the transportation of raw materials for the manufacture of concrete, the environmental impacts corresponding to the cement and admixtures transport are included in the values of the impacts obtained from the EPDs of these products. For the specific transport of aggregates, environmental impact data were obtained per t·km from the Ecoinvent 3.6 database using SimaPro 9.1.1. For this calculation, the data of average distances from the provider to the concrete manufacturer's plant were obtained from the ANDECE's environmental self-declarations for precast concrete products [44]: 32.6 km for aggregates, 134.5 km for cements and 304.8 km for steels.

3.5 Concrete manufacturing

A literature review was carried out to elaborate the inventory of the concrete manufacturing stage and the results are summarized in Table 6.

The quality of Athena's inventory [45] stands out because of its timing and representativeness of production, even though it refers to a different country. Values for electricity and diesel in Spain are available from ANDECE through its EPDs for precast concrete [44]. Despite the fact that the manufacturing process is somewhat different from that of ready-mix concrete, consumption is between that of the USA and Canada [46]. In turn, the inventory available from Ecoinvent [47] is an earlier version of the Canadian inventory. Other authors also considered the Athena [48] and Ecoinvent [5] inventories. In summary, the inventory for the A3 stage was modeled on the basis of the Ecoinvent inventory uploaded with the Athena values [45] and adapted to the Spanish electricity, see Table 7.

4. Environmental impacts assessment RESULTS

Considering all the concrete mixes analyzed, Figure 5 shows a summary of the environmental impacts of concrete production by materials and by modules A1, A2 and A3. With the exception of the potential depletion of abiotic mineral resources, it can be stated that cement is generally the material with the greatest overall impact on the environment. During the production of raw materials (module A1), the impact of the cement is higher than 70% except in two cases. First, the GWP, for which the impact of the additives is even greater than the impact of the arid and the cement impact is less than 60%; and second, the ADP minerals and metals, for which the impact of the arid is logically higher than 90%. For this module, ‘others’ includes the use of water and additives.

Module A2 refers to the transport of raw materials. In that case, cement has the highest impact in all categories, while the impact caused by additives and water is negligible. In module A3, manufacturing, cement causes the greatest impact, although the manufacturing process at the plant (included in ‘others’) also has a very significant impact in some categories.

Figure 6 shows the results for the total Global Warming Potential (GWP) (stages A1-A3) for all calculated concrete mixtures and, as can be seen, the impact can be doubled depending on the type of cement and the dosage of the mix. The order in the graph goes from left to right by cement type, and within this, from lower to higher by concrete strength. The differences in impact among the various cement types are clearly reflected in the concrete mix impact results. In fact, the impact of concrete mixtures with cement type CEM I is the highest, followed by those with cement type CEM II, then those with cement type CEM IV, and the lowest impact is produced by those manufactured with cement type CEM III.

Within each type of cement, a fairly similar pattern appears, shown in more detail in Figure 7 for two cement types. For each value of concrete strength, it can be noted that the growing pattern is repeated. This is a consequence of the fact that the smaller the diameter of the aggregate, the higher the amount of water and cement in the mix, and therefore also the impact. Similarly, the more fluid the mix, the amount of water, cement, and plasticizers admixtures in the mix increases, and so does the impact. This trend is clearly identifiable in the concrete mixtures made with cement type CEM I and for a strength of 20 and 25 N/mm^2, where no aggressive exposure to concrete is considered.

For concretes with strength values from 30 N/mm^2 and above, within each consistency type (P, S, F or L), the mixtures vary according to exposure class from left to right: no exposure (s/), weak attack (Qa), medium attack (Qb), strong attack (Qc), ice without fluxing salts (H), ice with fluxing salts (F) and erosion (E). The strong chemical attack exposure (Qc) is only applicable to concrete with a strength of 35 N/mm^2 and above. Additionally, the consistency type Liquid is not applicable when the maximum aggregate diameter used is 40mm.

In mixtures with cement type CEM I and strength 30 N/mm^2, the s/ and H exposures cause less impact than the others do. This is because they have a higher water/cement ratio, i.e., less cement in the mixture, and less additives. This does not occur in the case of type CEM IIIa and resistance 30 N/mm cements since the water/cement ratio does not vary. From 35 N/mm^2 of resistance, the strong exposure class (Qc) is also considered, which stands out from the others for its greater impact, due to a lower water/cement ratio and a greater need for additives.

The results for other impact categories such as ozone depletion, acidification, terrestrial, marine water and freshwater eutrophication, photochemical ozone creation and water depletion potential follow a similar pattern with the exception of the Abiotic resource Depletion Potential for non-fossil resources, which results are summarized in Figure 8. In this category, the impact variation caused by the different concrete mixtures is not so remarkable, with the lowest value being $1.18 \cdot 10^{-3}$ and the highest $1.27 \cdot 10^{-3}$. The environmental impact caused by plasticizer additives is the most relevant, while differences in impact among cement types are less noticeable. In fact, a higher impact in concrete mixtures made with cement type CEM IIIc can be seen, due to the higher amount of admixtures present in these concretes.

In addition, in this category, within each type of cement a fairly similar pattern can be observed. Two types of these cements are displayed in more detail in Figure 9. The results show a greater impact for mixtures with larger diameter aggregates. In addition, the amount of admixtures and concrete in the mixtures also influences the increase in impact.

The range of the impact values is stated in Table 8, which shows the results of the basic environmental impact parameters (excluding those specific to the potential impact on fossil, biogenic and land use climate change), for ready-mixed concrete with maximum and minimum GWP values, grouped by cement type.

5. Parametric analysis

A deeper significance of the concrete parameters on the environmental impacts was analyzed with multiple linear regression models. Linear regression analysis, i.e., a statistical technique used to study the relationship between variables, can be used to explore and quantify the relationship between a variable called dependent (Y) and one or more variables called independent (X). The statistical analysis was performed using SPSS v27 software.

Several of the concrete parameters, as they appear in the IVE database, are qualitative or categorical variables. This is the case for the environment-cement, specific exposure, and consistency variables. It is not possible to assign values to the levels of a categorical (or qualitative) variable. This does not imply that variables of this type cannot be used, however some transformations to detect the different levels contained in the qualitative variables are required. This solution is possible if the primitive categorical variable is transformed into dummy variables.

A dummy variable is a binary, nominal, dichotomous, categorical variable that can only take the values 0 or 1, indicating the absence/presence of the measured attribute. Here, the letter 'D' at the beginning of the variable name identifies dummy variables. Each categorical variable must be transformed through dummy variables, as many as possible alternatives minus one unit. The categorical variable consistency is therefore transformed in three dummy variables DSOFT, DFLUID and DLIQUID, represented by the triads: 1,0,0; 0,1,0 and 0,0,1 respectively, and plastic consistency is represented by the triad 0,0,0. The categorical variable environment-cement is transformed in other three dummy variables DCEM1, DCEM2 and DCEM3 without considering differences for the subcategories a, b or c. The categorical variable exposure with 7 levels presented more complexity. A univariate analysis of variance for exposure and the dependent variable GWP was performed. Figure 10a) shows how the exposure variable is grouped in three levels (observed-predicted, predicted-Std. residual and observed-Std. residual). Therefore, the seven initial categories were grouped in three levels and two dummy variables were created based on the results shown in Figure 10b): QHSEX grouping exposures H and s/ and QcEX for the exposure Qc. The rest of exposures (Qa, Qb, F, E) are represented by the dummy's duo 0,0.

Independence of the dependent variables and linearity between dependent variables and independent ones were assessed for all possible combinations. Initially, the strength and direction of association between two ranked variables was measured with the non-parametric Spearman's rank-order correlation. Considering GWP as independent variable, all the correlations with the dependent variables were significant at the 0.05 level, except for resistance and the dummy variable DSOFT. However, the other dummy variables transforming consistency were significantly correlated. Resistance also presented significant correlations with the dummy variables DCEM1, DCEM3, DSHEXP and DQcEXP. The potential linearity of resistance with the independent variable was investigated with partial correlations, controlling the effect of the rest of dependent variables. This partial correlation was statistically significant at 0.001. Therefore, no variable was discarded in this first assessment, previous to the multiple linear regression.

The multiple linear regression model is defined by the following equation:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon \qquad \textbf{(1)}$$

According to this model, the dependent variable (Y) is interpreted as a linear combination of a set of K independent variables (X_k), each of them being accompanied by a coefficient (β_k)

indicating the relative weight of that variable in the equation. The equation also features a constant (β_0) and a random component (the residuals, ε) gathering what the independent variables are not able to explain. The minimum-quadratic regression equation is constructed by estimating the values of the β coefficients of the regression model. These estimates are obtained by minimizing the squared differences between the observed (Y) and predicted ($\hat{Y}$) values:

$$\hat{Y} = B_0 + B_1X_1 + B_2X_2 + \cdots + B_kX_k \qquad \textbf{(2)}$$

where B_K are the unstandardized coefficients.

The independent variables are selected with a stepwise method. In stepwise regression, only those variables that contribute significantly to the model fit are incorporated into the regression model. The individual contribution of a variable to the model fit is established by contrasting, from the partial correlation coefficient, the hypothesis of independence between that variable and the dependent variable. Specifically, the significance criterion is the probability of the F statistic. A variable becomes part of the regression model if the critical level associated with its partial correlation coefficient, when testing the hypothesis of independence, is less than 0.05 (entry probability). And it remains outside the regression model if this critical level is greater than 0.10 (exit probability). Once the significance criterion has been passed, a variable only becomes part of the model if its tolerance level is greater than the established level (0.01).

The multiple linear regressions obtained for each impact category are found in

Table 9. The first rows (of each impact category) contain the unstandardized coefficient of equation **(2)**. They are interesting to predict the environmental impacts of every ready-mix concrete. The second rows contain the standardized coefficient of equation **(1)**. They are interesting to analyze the relative importance of each parameter in each impact category. All variables are significant at 0.001 and the adjusted R^2 is very high (0.85-0.95), except for the impact category of abiotic depletion (0.52). An explanation for the relative low adjustment of

this impact category is the transformation of the categorical variable exposition focused on the pattern of global warming. Note GWP and ADP have different pattern as shown in Figure 6 and Figure 8, respectively.

Figure 11 highlights the relative importance of the categorical variables in the dependent variable as a function of the independent (and numerical) variable arid size, when assuming a constant compression strength of 35 N/mm^2. This figure is obtained with the coefficients B from

Table 9 for the GWP. For each line of the figure, only one dummy variable is activated (value 1) and the rest are null (value 0). For this impact category, cements 1 and 2 clearly produce the highest impacts, followed by consistency and exposition. At the same time, the selection of the type of cement (continuous line) is responsible for the highest variabilities. On the opposite side, the variability in consistency (dashed lines) produces the lowest variabilities.

This model is based on a series of assumptions: linearity, independence, normality, homoscedasticity and non-collinearity. Linearity and non-collinearity were assessed previously with the bivariate correlations and the partial correlations. In addition, new regression models were tested controlling the effect of the variable resistance and the dummy variables relative to cement and exposition. In all cases, the adjustment, the statistic F, and the normality of the residues worsen. The statistics tolerance, that indicates the percent of variance in the predictor that cannot be accounted for by the other predictors, was always higher than 0.1 (specifically, the lowest value is 0.44 for the variable DCEM3). Moreover, the condition index is always lower than 30. It can be concluded that the non-collinearity is satisfied.

The remaining assumptions independence, homoscedasticity, and normality, are closely associated with the behavior of the residuals. The variables are timeless, but there could be other causes of correlation of the residuals. Figure 12 shows the plot of the standardized residues against each of the original predictor variables. The categorical variables are not transformed and boxplots are used. The residuals are randomly scattered without showing any systematic patterns, although some small deviations from zero are observed for the median of the standardized residuals affecting to the dummy variables DCEM1, DCEM3 and DQSHEXP.

The top and middle graphs in Figure 13 show the histograms and the graphics P-P normal for the impact categories GWP and ADP. The P-P plot compares the observed cumulative distribution function of the standardized residual to the expected normal distribution. Comparing the normal curve with the empirical distribution in the histogram and evaluating the deviation of the points represented in the second graph with respect to the diagonal, it can be concluded that there are no large deviations from the normal curve. The bottom graph of Figure 13 shows that the trend is centered around zero but also that the variance remains around zero. It can be stated that the linearity and the heteroscedasticity assumptions are satisfied.

6. Discussion

LCA methodology has been widely used to assess the environmental impact of concrete mixtures [4,6,8–10,19,49,50] ; however, this is the first study that analyzes more than 1500 ready-mixed concrete combinations, including 7 different types of cement and obtaining a large number of detailed and parameterized results. This differs substantially from other studies conducted so far, which have generally focused on specific impact categories, on comparisons between concretes with recycled content, or on a very small number of concrete combinations and cement types. For example, in recent years, several studies have focused on comparing environmental impacts of concrete with natural and recycled or ecological aggregates [5–9,11,19]. These types of comparisons are not the subject of this study since this differentiation is not contemplated in the IVE construction database. However, it should be noted that the inventory data of the cement EPDs from which the data have been obtained are 100% representative of Spanish cement production. This includes, therefore, a certain proportion of blast furnace slag, silica fume, natural pozzolans, fly ash and limestone in the composition of cements [40,41]. In contrast to U.S. cement products, about 70% of cements consumed in Europe are blended cements (cement with fly ash, slag or natural pozzolans) [1].

The problem of not considering the environmental impacts of additives in the studies has been denounced in the literature [1]. Previously, the environmental impact of these components had been considered irrelevant because of their low presence in the mixture [12]. Although the results of our study do not associate additives with a total impact of great relevance, it was shown that their impact is significant in the phase of production of raw materials (module A1) for the global warming potential category.

Studies comparing ready-mixed concretes with different types of cement in their composition are rarely found in the literature [5,51,52]; however, this study includes significant results for 7 different types of cement depending on the aggressiveness of the environment in which it will be used (see Table 1). Overall, the results showed a greater impact for concrete mixes with cement type CEM I, followed by CEM II, and lesser impact for concretes with cement types CEM III and CEM IV (Figure 11). This outcome is partly related to the amount of clinker used in each type of cement; however, we cannot consider this to be the only influencing factor, since the amount of clinker used in CEM II and CEM IV is similar whereas the difference in impact values is significant. The EPDs provided by the Spanish Cement Institute for each type of cement do not break down the impact of clinker and the other components of each cement, thus the impacts of clinker would have been studied, but they do indicate that the average energy consumption is 3.56 MJ/kg clinker, considering conventional and alternative fuels. This value is consistent with the values provided for Spain in the GRN Project Reporting CO_2 [43], which also differentiates by type of kiln. The thermal energy consumption in 2018 was 3.56 and 3.66 MJ/kg clinker in kiln with preheater and precalciner and in kiln with preheater and without precalciner, with a production split of 56.8% and 43.2%, respectively. From this comparison, it can be deduced that the energy difference for clinker production between the two types of kilns is less than 3%.

Environmental impacts in this study are in the same range that literature values, although the large variability of the impacts for the same compressive strength should be noted. For example, Figure 14 shows global warming potential impacts of ready-mixed concrete in a selection of the literature [5,13,22,45,46,53] and this study for different strengths. In the comparison are included different cements (CEMI , CEM II) [5], fly ash [13,45,46,53], recycled materials [5,13] and carbonation during use phase [53]. The 1505 ready-mixed concrete combinations of this study are represented with a box and whisker plot and the literature values with a thick line from minimum to maximum GWP. In this study, the median impacts do not increase as the compressive stress increases, as most of the studies in the literature claim [13,22,49,53]. The inclusion of different types of cements and admixtures, as explained above, are the reason for the impacts not being linearly related to strength [5,52].

The detail of the results offered in this study, considering all the variables involved in the definition of the concrete mix, is an important contribution for future research, because it will allow to consider the influence of parameters such as strength, consistency, maximum aggregate size, water/cement ratio or exposure. Despite the interest in the literature to evaluate the use of recycled aggregates and the substitution of cement components, some studies are also found highlighting the importance of concrete mix design on the environmental impact of the complete life cycle of concrete [52,53], taking into account not only the CO_2 absorption of concrete during its useful life, but also parameters such as porosity or the thickness of the reinforcement coating.

This study shows for the first time a detailed parametric analysis of the variables involved in concrete mix dosage. The regressions obtained for each impact category (

Table 9) allow to predict the environmental impacts of every ready-mix concrete and also to analyze the relative importance of each parameter in each impact category.

This research has some limitations. Some of them derive from the EPDs used. Although it was requested, the quality of the data was not contrasted, and the same environmental impacts were considered for the production stage of all cement types, since the EPD is the same for all of them.

Other limitations are related to the parametric analysis. For all impact categories, the same simplification of categorical variables is applied, defined on the previous GWP assessment. Further simplifications, specifically for abiotic depletion, would improve the results, although they would also increase complexity. In the same sense of improving results at the cost of greater complexity lays the limitation of the number of levels in the categorical variables (e.g., exposure and cement environment).

Quantifying environmental impacts offers many advantages [45,54], among which the following can be highlighted:

- It explores the reduction of environmental impacts, aiming for more efficient solutions from an environmental point of view.
- Improves the environmental performance of buildings, reducing their environmental impacts during construction and the lifespan of the building.
- Encourages the demand for more environmentally friendly products and services.
- It avoids misleading with false green marketing or greenwashing about the non-existent environmental benefits of a material or building [55].
- Highlights and discloses the economic benefits of sustainability to stakeholders and customers.
- It introduces environmental factors into the market, beyond functional, economic, or esthetic criteria.
- Allows for recognition in current or future regulations in green public procurement and/or innovative procurement [56].

- It establishes a market reference by being ahead of current environmental legislation and being a differentiating factor at the same time.
- Supports certified environmental product declarations, environmental product self-declarations, carbon footprints and life cycle analysis of buildings.
- Improves competitiveness in construction sites that are certified under environmental assessment systems such as LEED [57], BREEAM [58] o Green Globes [59], which provide credits for the use of products with certified EPD, environmental self-declarations and life cycle assessments.
- Provides average or baseline values from which to accredit impact reduction improve competitiveness, recognition, and leadership through distinctions such as LEED (U.S. Green Building Council, n.d.) or Architecture 2030 (Architecture 2030, 2018).

7. Conclusions

This study shows for the first time a detailed parametric analysis of the variables involved in concrete mix dosage. The study is based on the analyses of more than 1500 combinations of concrete dosage and composition (cement, water, aggregates, and admixtures) included in a reference construction database of building materials for Valencia (Spain).

The life cycle assessment methodology was used to calculate the environmental impacts of each material, including the modules A1-A3, i.e., production of raw materials, transport and manufacturing, and the impact categories in accordance with EN 158E04:2012+A2:2019.

Results showed a greater impact for concrete mixes with cement type CEM I, followed by CEM II, and lesser impact for concretes with cement types CEM III and CEM IV. Behind the impact influence of cement types CEM I and CEM II comes first the consistency (liquid and fluid, in this order) and then the exposure (strong attack, Qc). Simultaneously, larger aggregate size reduces the environmental impacts.

The regressions obtained for each impact category allow to predict the environmental impacts of every ready-mix concrete and also to analyze the relative importance of each parameter in each impact category.

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TABLES

Table 1. Codes, description, and number of combinations analyzed in this study, as they appear in the IVE construction database.

IVE Code	Description	No. of combinations
PBPC.2$	Concrete Non-aggressive environment I	240
PBPC.3$	Concrete Normal environment IIa	231
PBPC.4$	Concrete Normal environment IIb	220
PBPC.5$	Concrete Marine environment IIIa	220
PBPC.6$	Concrete Marine environment IIIb	220
PBPC.7$	Concrete Marine environment IIIc	154
PBPC.8$	Concrete Chloride environment IV	220

Table 2. Amount of mixing water for concrete composition (in l/m^3).

	Water (in l/m^3) for maximum aggregate sizes (in mm)								
	Concrete without additives			Concrete with plasticizers and superplasticizers			Concrete with plasticizers and air-entraining admixtures		
Consistency	**12**	**20**	**40**	**12**	**20**	**40**	**12**	**20**	**40**
Plastic	200	185	160	184	170	149	176	163	142
Soft	215	200	175	194	180	159	189	176	156
Fluid	225	205	180	198	182	162	193	178	158
Liquid	230	210	185	196	181	161	191	176	157

Table 3. Data sources for raw materials (A1) and transport (A2).

Supply of raw materials (A1)				
Material	**Source of data for LCI**	**Geographical area**	**Year**	**Quality of data assessment**
Cements (tn)	Instituto Español del Cemento y sus Aplicaciones (IECA)	Spain	2020	**Technology:** Very good. **Currency:** Good. Valid until 17/09/2021. **Geographical area:** Very good. **Full:** Medium. Several impact categories were adapted to EN 15804:2012+A2:2019. **Reliability:** Very Good.
Additives (kg)	European Federation of Concrete Admixtures	Belgium, France, Spain, Germany, Italy, Netherlands, Norway, Sweden,	2015	**Technology:** Very good. **Currency:** Very good. Valid until 13/09/2020. **Geographical area:** Good. **Full:** Medium. Several impact categories were

Supply of raw materials (A1)

Material	Source of data for LCI	Geographical area	Year	Quality of data assessment
	Associations, Ltd (EFCA)	Switzerland, Turkey and UK		adapted to EN 15804:2012+A2:2019. **Reliability:** Good. Inventory data has been obtained directly from manufacturers for a specific product.
Aggregates (kg)	Ecoinvent process: '*Gravel, round gravel and sand quarry operation | Cut-off, U'* Ecoinvent 3.6	Switzerland, adaptation to Spain.	2019	**Technology:** Very good. Sand (35%) and gravel (65%) production. **Currency:** Very good. **Geographical area:** Medium. Similar conditions. **Full:** Very good. **Reliability:** Very Good. Data verified by Ecoinvent.
Water (kg)	Ecoinvent process: '*Tap water production, conventional treatment | Cut-off, U'* Ecoinvent 3.6	Europe without Switzerland	2019	**Technology:** Very good. **Currency:** Very good. **Geographical area:** Good. **Full:** Very good. **Reliability:** Very Good. Data verified by Ecoinvent.

Transport (A2)

Process	Source of data for LCI	Geographical area	Year	Quality of data assessment
Aggregates transportation (t·km)	Ecoinvent process: 'Transport, freight, lorry 16-32 metric ton, EURO4 RER' Ecoinvent 3.6	Europe	2019	**Technology:** Good. **Currency:** Very good. **Geographical area:** Good. **Full:** Very Good. **Reliability:** Very Good. Data verified by Ecoinvent.

Table 4. Primary energy mix in Spain, 2019. Amounts for 1 MJ generation.

	MJ	%
Total	2.374	100.0
Non-renewable, fossil	1.018	42.9
Non-renewable, nuclear	0.799	33.7
Non-renewable, biomass	0.000	0.0
Renewable, biomass	0.100	4.2
Renewable, wind, solar, geothermal	0.349	14.7
Renewable, water	0.107	4.5

Table 5. Comparison of global warming and total primary energy for cement production in Spain.

		IECA EPD	**IECA EPD**	**IECA EPD**	[41,42]	[43]
	Unit	CEM I	CEM II	CEM III	Medium	Medium
Global warming	kg $CO_{2\ eq}$/t	884	752	417	799	677
Total Primary Energy	MJ/t	7224	6173	3891	4595	5352
Thermal Energy	MJ/t clinker	3560	3560	3560	3536	3600
Electrical Energy	kWh/t	ND	ND	ND	113	158
Seasonality		2014	2014	2014	2010	2018
Annual Production (ton)					$2.28\ 10^7$	$1.59\ 10^7$

Table 6. Inventories for the concrete manufacturing process (A3). Raw materials and transport are not included.

	U	[45]	[46]	[7]	[44]	[47]
Electricity	kWh	4.21	8.87	0.71	6.34	4.114
Natural gas	m^3	0.44	1.99			0.19134
Fuel oil	l	0.0378	0.114			
Diesel	l	1.59	1.539		2.60	0.4232
Petrol	l		0.034			
Liquid propane	l	0.0378	0.023			
Other fuels	l		0.001			
Water emitted	l	114	88.36			40
Hazardous waste	kg	0.014	0.89			
Non-hazardous waste	kg	4.12	11.07			24.5
Location		USA	Canada		Spain	Canada
Timing		2019	2015		2016	2014
Annual Production (m3)		23257054	8713846		35% Spain	4700000
Number of plants		489	191			
Others					Precast tiles	

Table 7. A3 stage inventory. Manufacturing of ready-mix concrete.

Flow	**Quantity**	**Unit**	**Source**
Inputs			
Concrete mixing factory {GLO}| market for | Cut-off, U	4.57E-07	p	Ecoinvent
Lubricating oil {RoW}| market for lubricating oil | Cut-off, U	0.0119	kg	Ecoinvent
Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U	0.0238	kg	Ecoinvent
Synthetic rubber {GLO}| market for | Cut-off, U	0.00713	kg	Ecoinvent

Flow	Quantity	Unit	Source
Diesel, burned in building machine {GLO}| market for | Cut-off, U	58.76	MJ	Athena. Includes combustion emissions
Electricity, medium voltage, production ES, at grid/ES U IVE	4.21	kWh	Athena. Electricity modeled for Spain
Heat, district or industrial, natural gas {RER}| market group for | Cut-off, U	24.44	MJ	Athena. Includes combustion emissions
Tap water {Europe without Switzerland}| tap water production, conventional treatment | Cut-off, U	114	kg	Athena
Air emissions			
Water/m^3	0.0171	m^3	Athena. 15% of water emissions
Air emissions			
Chlorides, unspecified	3.09E-09	kg	Ecoinvent
Copper	1.55E-08	kg	Ecoinvent
Iron	1.55E-08	kg	Ecoinvent
Oils, unspecified	2.32E-07	kg	Ecoinvent
Suspended solids, unspecified	4.64E-07	kg	Ecoinvent
Waste			
Waste concrete {RoW}| market for waste concrete | Cut-off, U	4.12	kg	Athena
Wastewater from concrete production {RoW}| market for wastewater from concrete production | Cut-off, U	0.0969	m^3	Athena. 85% of water emissions
Waste cement, hydrated {RoW}| treatment of, residual material landfill | Cut-off, U	0.014	kg	Athena

Table 8. Results of the basic environmental impact parameters for ready-mixed concrete with maximum and minimum GWP values. Values per m^3 of concrete.

TOTAL (A1 - A3)

Nº	IVE code	GWP	ODP	AP	EP - f	EP - m	EP - t	POCP	ADP	ADP - f	WDP
		kg CO_2 eq	kg CFC 11 eq	mol H^+ eq	kg PO_4 eq	kg N eq	mol N eq	kg NMVOC eq	kg Sb eq	MJ	m^3 global eq
PBPC.2 …		Structural concrete, non-aggressive environment CEM I									
160 **237**	dcdd ecdd	$4.94\cdot10^{2}$	$4.90\cdot10^{-5}$	1.48	$1.57\cdot10^{-1}$	$3.50\cdot10^{-1}$	3.85	2.24	$1.24\cdot10^{-3}$	$3.81\cdot10^{3}$	$7.21\cdot10^{3}$
1 **10**	aaaa baaa	$2.53\cdot10^{2}$	$2.75\cdot10^{-5}$	$8.31\cdot10^{-1}$	$8.00\cdot10^{-2}$	$2.05\cdot10^{-1}$	2.25	1.19	$1.22\cdot10^{-3}$	$1.98\cdot10^{3}$	$3.76\cdot10^{3}$
PBPC.3 …		Structural concrete, normal environment CEM IIa									
391 **468**	ccdd dcdd	$4.28\cdot10^{2}$	$4.29\cdot10^{-5}$	1.32	$1.33\cdot10^{-1}$	$3.32\cdot10^{-1}$	3.65	2.10	$1.24\cdot10^{-3}$	$3.39\cdot10^{3}$	$7.17\cdot10^{3}$
241	aaaa	$2.39\cdot10^{2}$	$2.63\cdot10^{-5}$	$8.03\cdot10^{-1}$	$7.39\cdot10^{-2}$	$2.08\cdot10^{-1}$	2.29	1.21	$1.23\cdot10^{-3}$	$1.90\cdot10^{3}$	$4.08\cdot10^{3}$

PBPC.4 …		Structural concrete, normal environment CEM IIb									
688 **611**	ccdd bcdd	$4.28\cdot10^{2}$	$4.29\cdot10^{-5}$	1.32	$1.33\cdot10^{-1}$	$3.32\cdot10^{-1}$	3.65	2.10	$1.24\cdot10^{-3}$	$3.39\cdot10^{3}$	$7.17\cdot10^{3}$
615 **538** **472**	caaa baaa aaaa	$2.63\cdot10^{2}$	$2.84\cdot10^{-5}$	$8.68\cdot10^{-1}$	$8.12\cdot10^{-2}$	$2.24\cdot10^{-1}$	2.47	1.32	$1.25\cdot10^{-3}$	$2.09\cdot10^{3}$	$4.46\cdot10^{3}$
PBPC.5 …		Structural concrete, marine environment CEM IIIa									
908 **831**	ccdd bcdd	$2.61\cdot10^{2}$	$2.73\cdot10^{-5}$	$9.38\cdot10^{-1}$	$8.42\cdot10^{-2}$	$2.49\cdot10^{-1}$	2.74	1.62	$1.24\cdot10^{-3}$	$2.38\cdot10^{3}$	$7.16\cdot10^{3}$
692 **697** **758** **764** **835** **841**	aaaa aaag baaa baag caaa caag	$1.69\cdot10^{2}$	$1.98\cdot10^{-5}$	$6.64\cdot10^{-1}$	$5.46\cdot10^{-2}$	$1.81\cdot10^{-1}$	1.99	1.08	$1.26\cdot10^{-3}$	$1.54\cdot10^{3}$	$4.70\cdot10^{3}$
PBPC.6 …		Structural concrete, marine environment CEM IIIb									
1128 **1051**	ccdd bcdd	$2.61\cdot10^{2}$	$2.73\cdot10^{-5}$	$9.38\cdot10^{-1}$	$8.42\cdot10^{-2}$	$2.49\cdot10^{-1}$	2.74	1.62	$1.24\cdot10^{-3}$	$2.38\cdot10^{3}$	$7.16\cdot10^{3}$
912 **917** **978** **984** **1055** **1061**	aaaa aaag baaa baag caaa caag	$1.72\cdot10^{2}$	$2.01\cdot10^{-5}$	$6.73\cdot10^{-1}$	$5.55\cdot10^{-2}$	$1.83\cdot10^{-1}$	2.02	1.09	$1.26\cdot10^{-3}$	$1.56\cdot10^{3}$	$4.79\cdot10^{3}$
PBPC.7 …		Structural concrete, marine environment CEM IIIc									
1282 **1205**	bcdd acdd	$2.61\cdot10^{2}$	$2.73\cdot10^{-5}$	$9.38\cdot10^{-1}$	$8.42\cdot10^{-2}$	$2.49\cdot10^{-1}$	2.74	1.62	$1.24\cdot10^{-3}$	$2.38\cdot10^{3}$	$7.16\cdot10^{3}$
1132 **1138** **1209** **1215**	aaaa aaag baaa baag	$1.85\cdot10^{2}$	$2.14\cdot10^{-5}$	$7.15\cdot10^{-1}$	$5.99\cdot10^{-2}$	$1.93\cdot10^{-1}$	2.13	1.17	$1.27\cdot10^{-3}$	$1.66\cdot10^{3}$	$5.19\cdot10^{3}$
PBPC.8 …		Structural concrete, chloride environment CEM IV									
1502	ccdd	$3.45\cdot10^{2}$	$3.52\cdot10^{-5}$	1.12	$1.10\cdot10^{-1}$	$2.84\cdot10^{-1}$	3.12	1.83	$1.24\cdot10^{-3}$	$2.89\cdot10^{3}$	$7.33\cdot10^{3}$
1286 **1291** **1352** **1358** **1429** **1435**	aaaa aaag baaa baag caaa caag	$2.23\cdot10^{2}$	$2.47\cdot10^{-5}$	$7.81\cdot10^{-1}$	$7.07\cdot10^{-2}$	$2.02\cdot10^{-1}$	2.22	1.21	$1.25\cdot10^{-3}$	$1.86\cdot10^{+3}$	$4.79\cdot10^{+3}$

Table 9. Unstandardized B coefficients and standardized β coefficients of the regressions for 1 m^3 of ready-mix concrete in each one of the impact categories assessed. Parameters included: type of cement, consistency, exposition, arid size and resistance.

		B_0	DCEM1	DCEM2	DCEM3	DSOFT	DFLUID	DLIQ	DSHEX	DQcEX	Arid (mm)	Resist (N/mm^2)	Adj R^2
GWP	B	262.4	105.9	63.4	-58.8	20.0	31.6	42.6	-19.4	23.2	-1.8	1.0	0.952
	β		0.536	0.401	-0.398	0.123	0.195	0.227	-0.124	0.097	-0.275	0.056	
ODP	B	$2.83\ 10^{-5}$	$9.8\ 10^{-6}$	$5.93\ 10^{-6}$	$-5.39\ 10^{-6}$	$1.67\ 10^{-6}$	$2.50\ 10^{-6}$	$3.16\ 10^{-}$	$-1.81\ 10^{-}$	$2.07\ 10^{-}$	$-1.67\ 10^{-7}$	$8.41\ 10^{-8}$	0.951
	β		0.543	0.409	-0.397	0.112	0.168	0.183	-0.126	0.095	-0.282	0.054	
AP	B	0.931	0.254	0.150	-0.120	0.055	0.085	0.112	-0.053	0.066	-0.005	0.003	0.938
	β		0.543	0.400	-0.344	0.144	0.222	0.253	-0.145	0.117	-0.328	0.066	
EP - f	B	0.096	0.034	0.018	-0.017	0.006	0.010	0.013	-0.006	0.007	$-5.61\ 10^{-4}$	$3.02\ 10^{-4}$	0.949
	β		0.564	0.366	-0.388	0.126	0.197	0.226	-0.129	0.098	-0.287	0.059	
EP - m	B	0.230	0.046	0.037	-0.021	0.014	0.022	0.030	-0.012	0.015	-0.001	$6.24\ 10^{-4}$	0.927
	β		0.471	0.476	-0.280	0.173	0.274	0.321	-0.159	0.126	-0.366	0.075	
EP - t	B	2.529	0.504	0.407	-0.224	0.152	0.241	0.328	-0.134	0.162	-0.013	0.007	0.926
	β		0.471	0.477	-0.280	0.173	0.275	0.322	-0.159	0.126	-0.364	0.075	
POCP	B	1.426	0.275	0.207	-0.116	0.097	0.152	0.200	-0.089	0.128	-0.009	0.004	0.908
	β		0.439	0.415	-0.249	0.190	0.295	0.336	-0.180	0.170	-0.440	0.083	
ADP	B	$1.19\ 10^{-3}$	$-3.27\ 10^{-6}$	$-1.12\ 10^{-6}$	$9.19\ 10^{-6}$	$7.35\ 10^{-6}$	$1.33\ 10^{-5}$	$2.19\ 10^{-}$	$-5.73\ 10^{-}$	-6.33 10	$7.63\ 10^{-7}$	$4.23\ 10^{-7}$	0.523
	β		-0.072	-0.031	0.269	0.196	0.356	0.505	-0.159	-0.115	0.513	0.108	
ADP - f	B	2120.3	652.3	387.3	-334.0	170.5	280.8	398.0	-143.4	193.1	-12.9	7.6	0.938
	β		0.514	0.382	-0.351	0.164	0.269	0.330	-0.143	0.126	-0.311	0.070	
WDP	B	7411.8	-232.9	-146.0	111.4	359.3	536.1	671.4	-293.6	424.9	-34.9	15.2	0.845
	β		-0.138	-0.108	0.088	0.259	0.387	0.419	-0.221	0.209	-0.635	0.105	

FIGURES

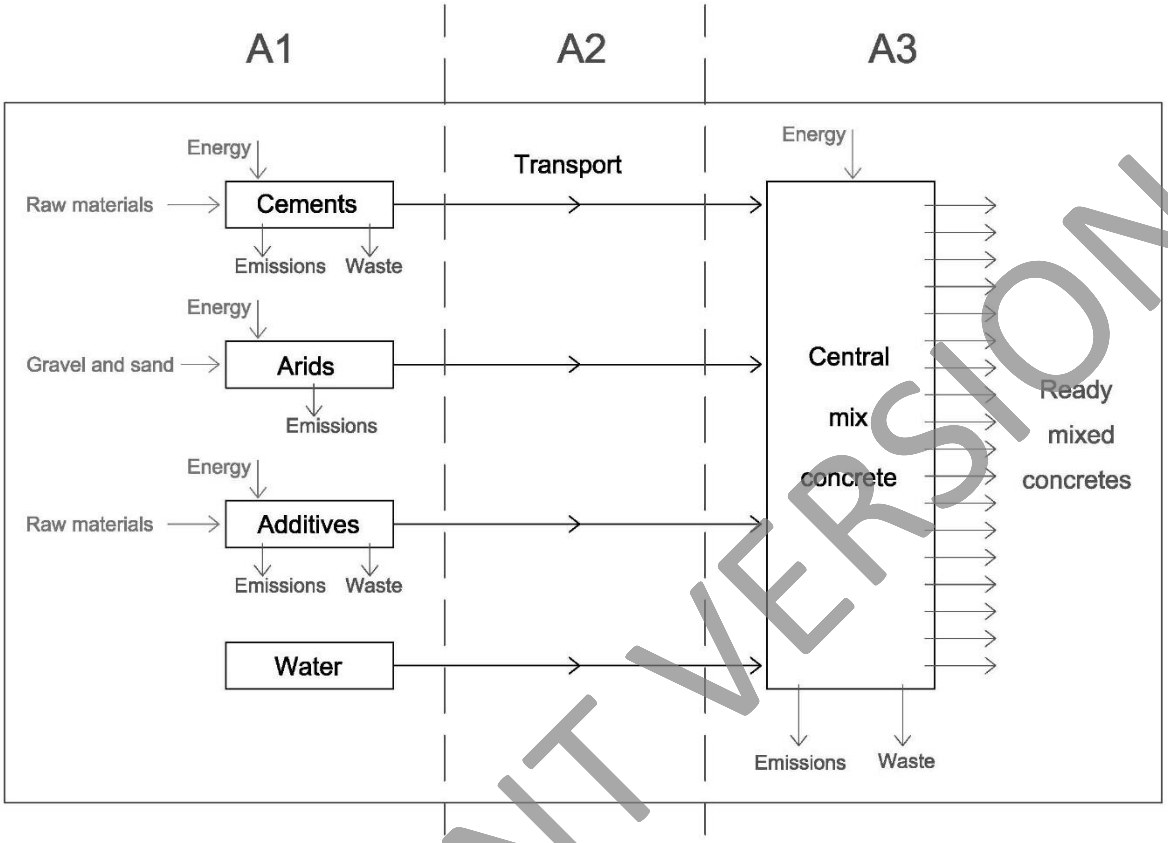
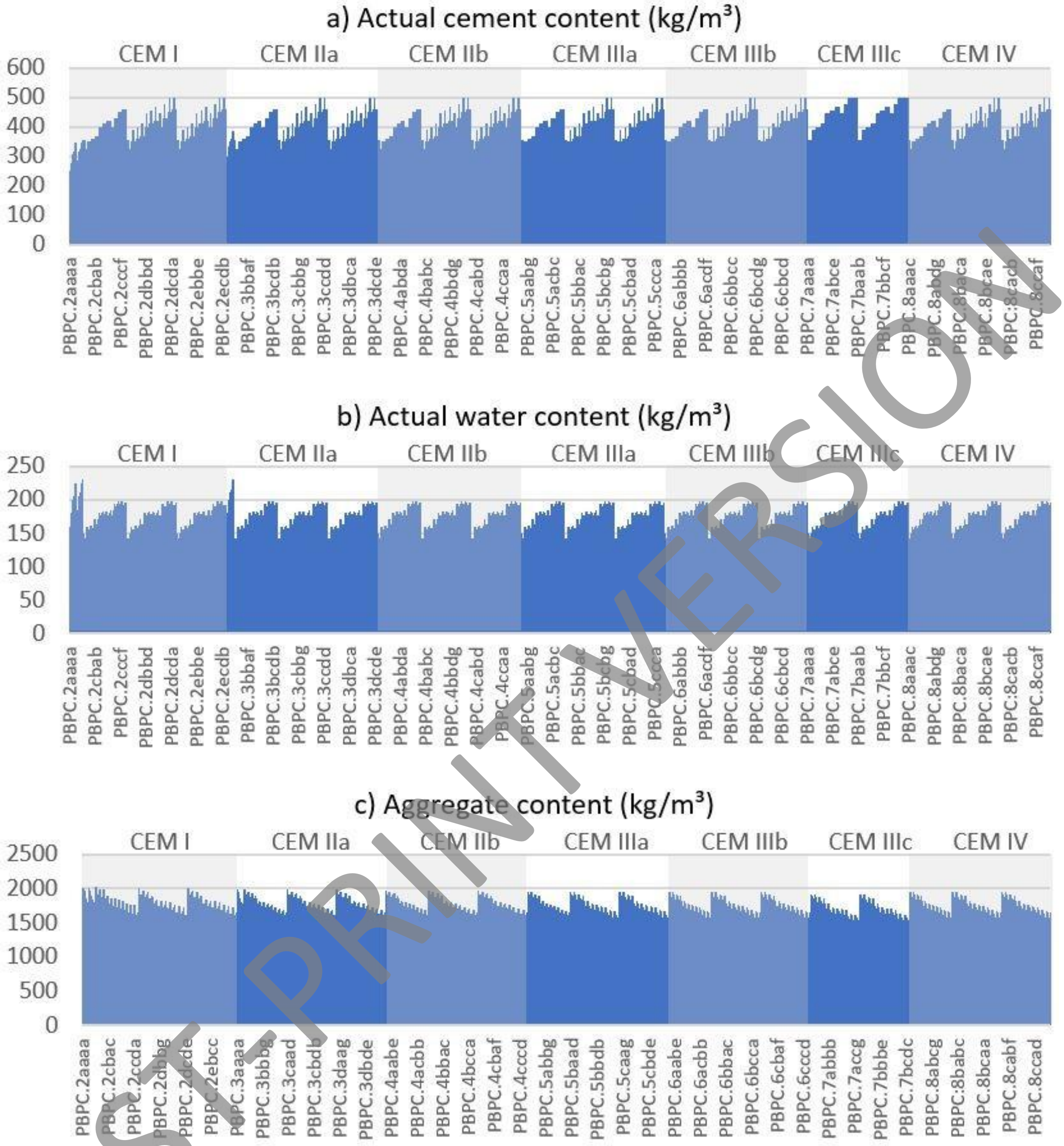


Figure 1. System boundaries



a) Actual cement content (kg/m³)

b) Actual water content (kg/m³)

c) Aggregate content (kg/m³)

Figure 2. Content of a) cement, b) water and c) aggregates in the 1505 concrete mixtures.

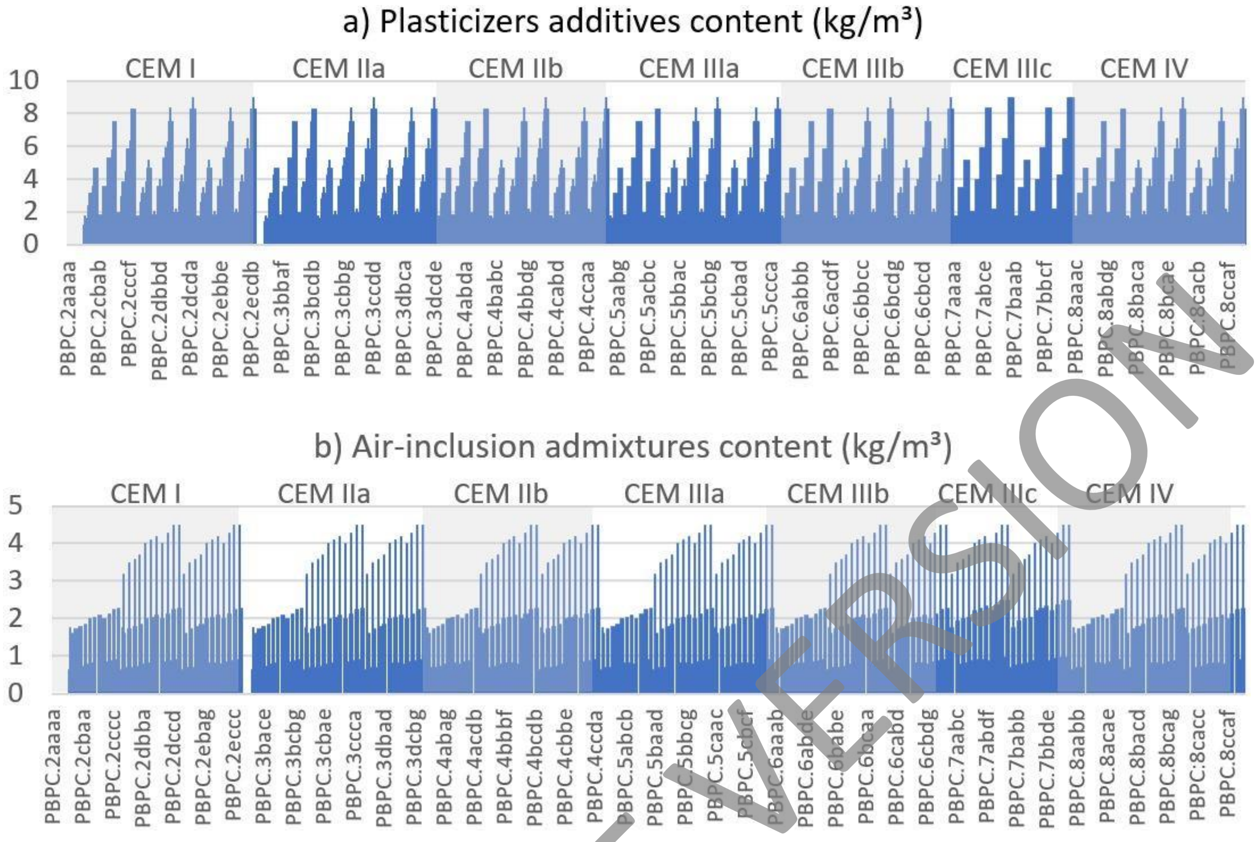


Figure 3. Content of a) Plasticizers additives and b) air-entraining admixtures in the 1505 concrete mixtures.

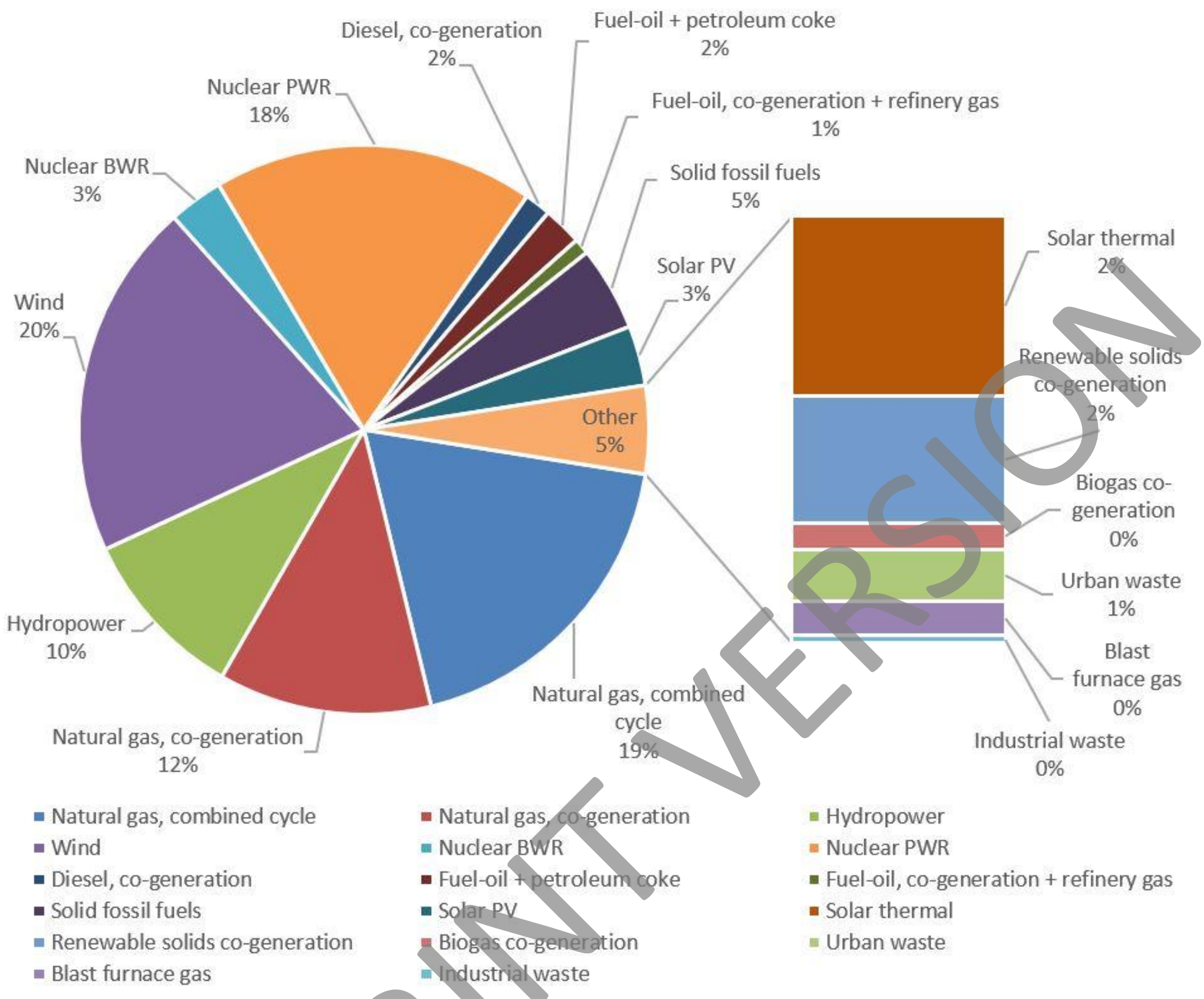


Figure 4. Composition for 1 kWh generated of the Spanish electricity mix for 2019.

Figure 5. Environmental impacts of concrete production by material. ‘Others’ includes water and additives in A1, transport of additives in A2 and the manufacturing process at the plant in A3.

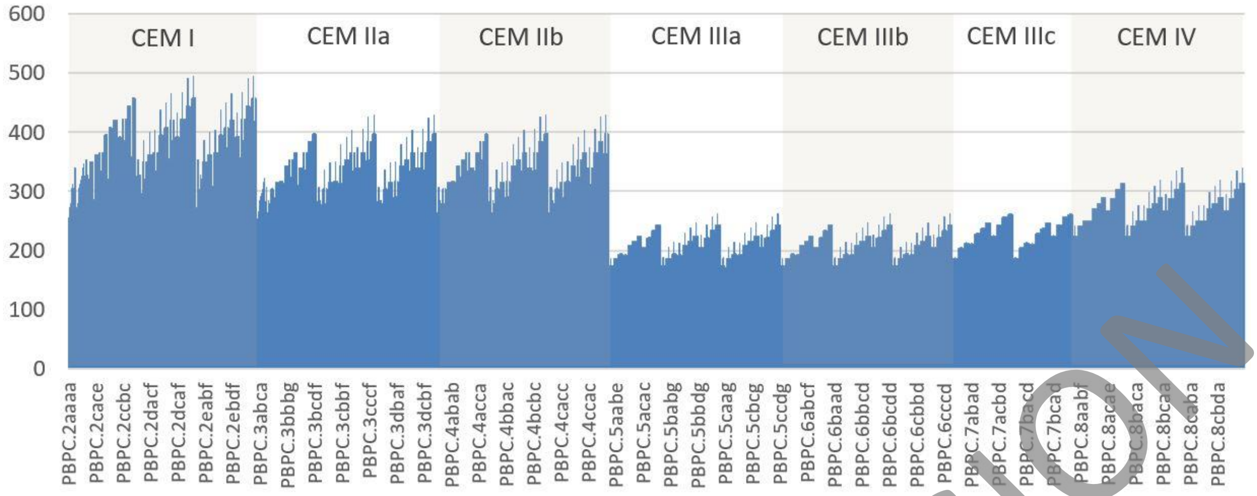


Figure 6. Total Global Warming Potential (kg CO_2 eq) for all calculated concrete mixes (stages A1-A3).

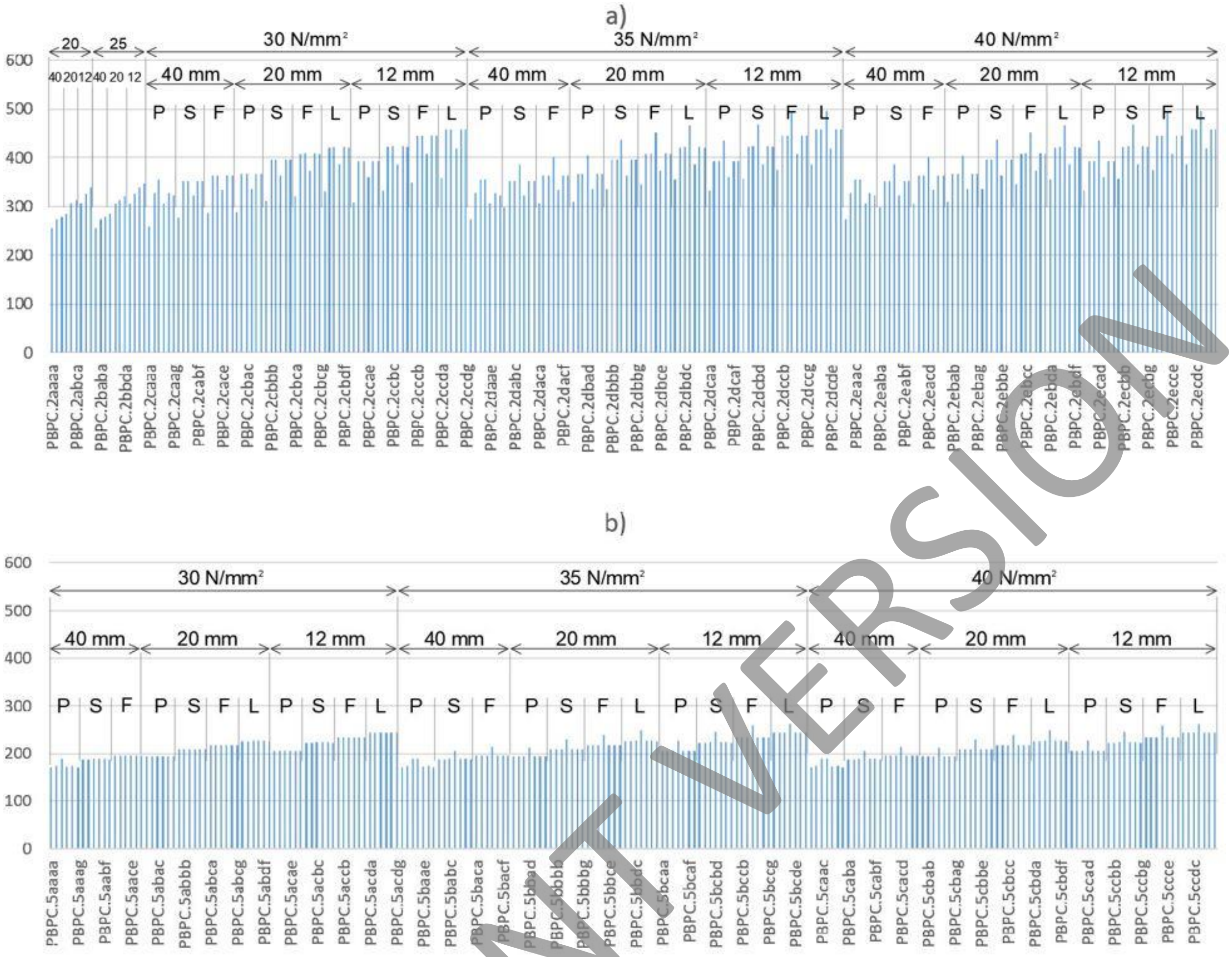


Figure 7. Global Warming Potential (kg CO_2 eq) for: a) concrete mixes with CEM I (non-aggressive environment); and b) concrete mixes with CEM IIIa (marine environment).

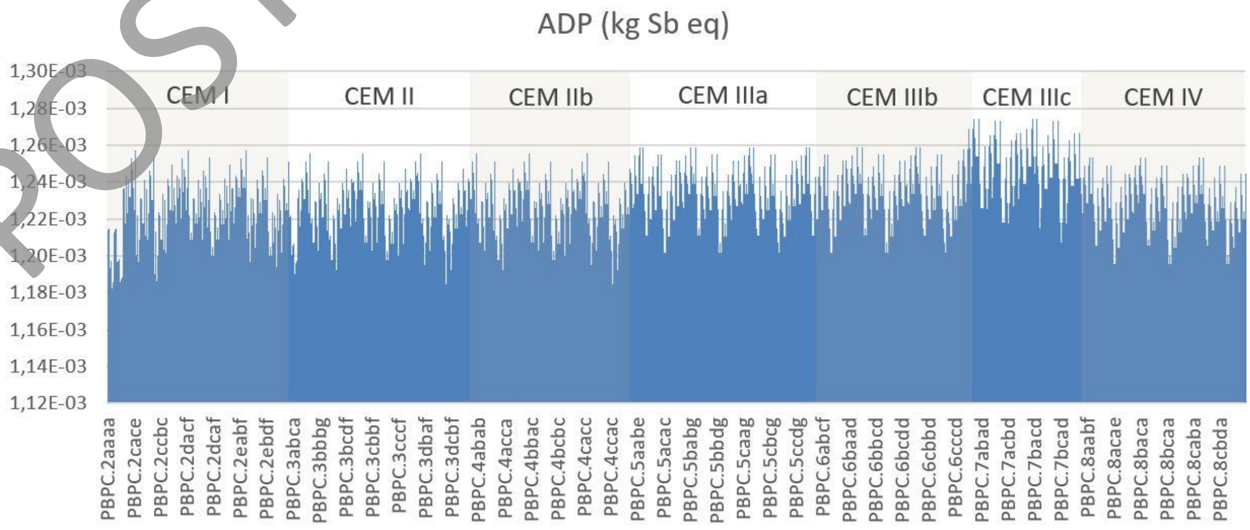


Figure 8. Abiotic resource Depletion Potential (kg Sb eq) for all calculated concrete mixes (stages A1-A3).

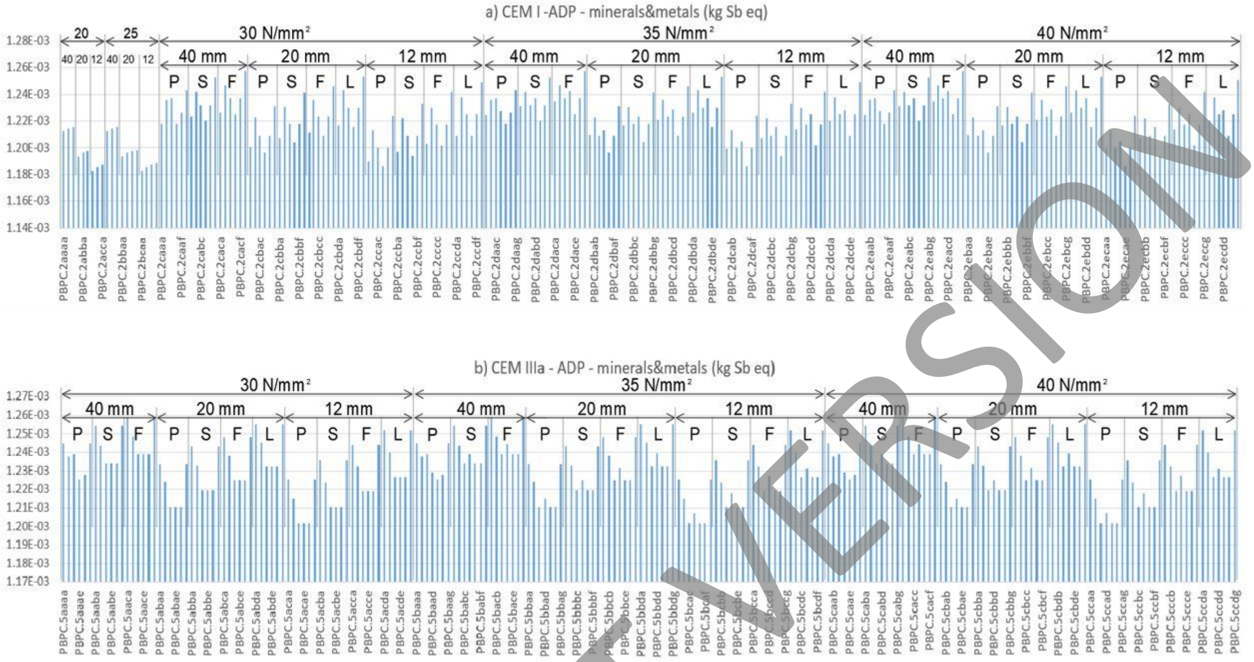


Figure 9. Abiotic resource Depletion Potential (kg Sb eq) for: a) concrete mixes with CEM I (non-aggressive environment); and b) concrete mixes with CEM IIIa (marine environment).

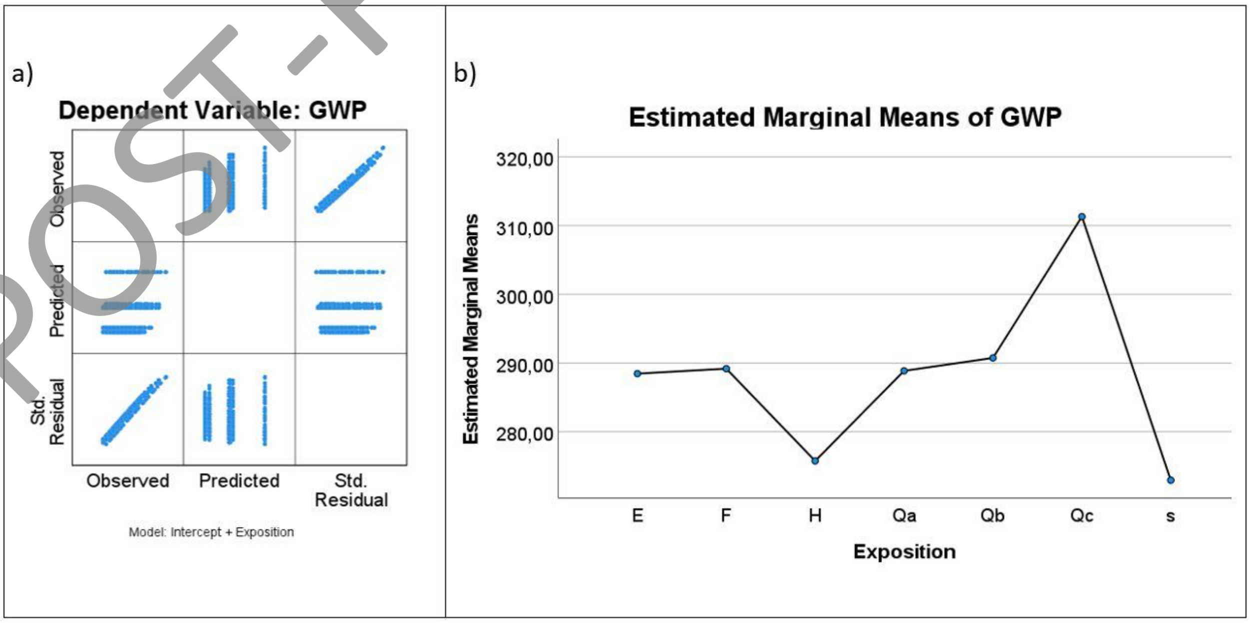


Figure 10. Plots of the univariate analysis of variance for the variable exposure on GWP.

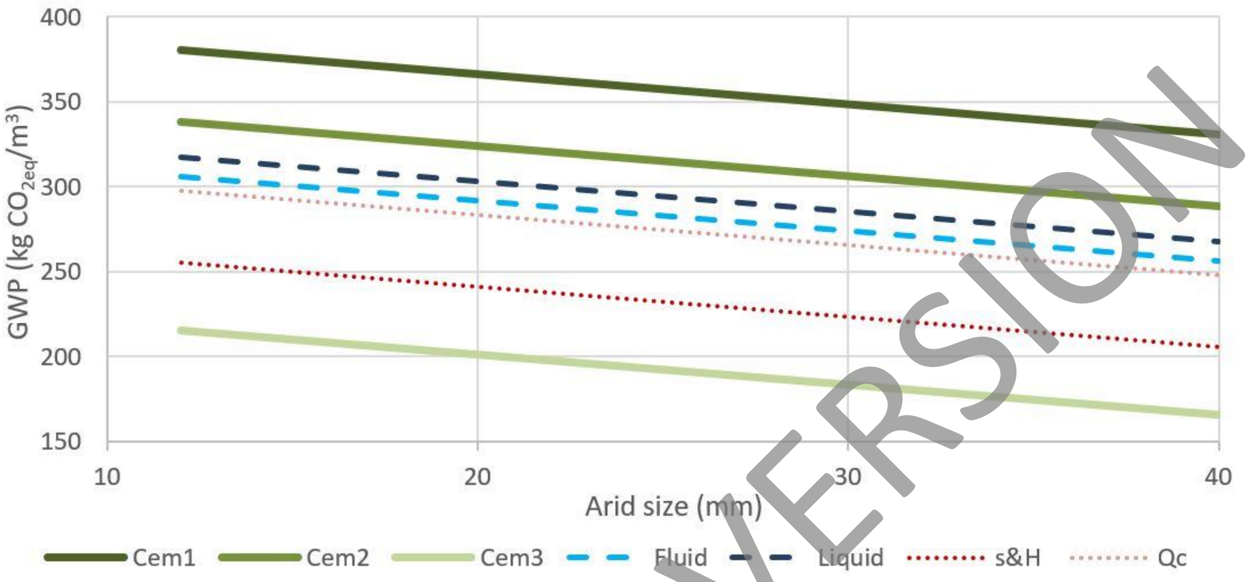


Figure 11. Relation of the dependent variable with each dummy variable assuming the rest of categorical variables are null.

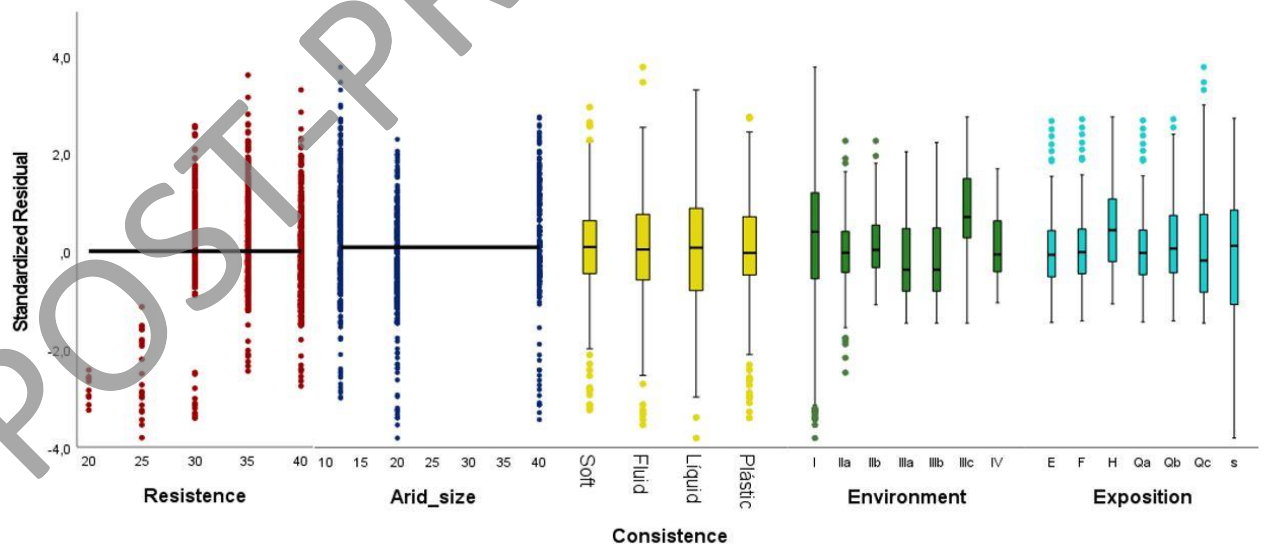


Figure 12. Plots of the standardized residuals against each of the predictor variables.

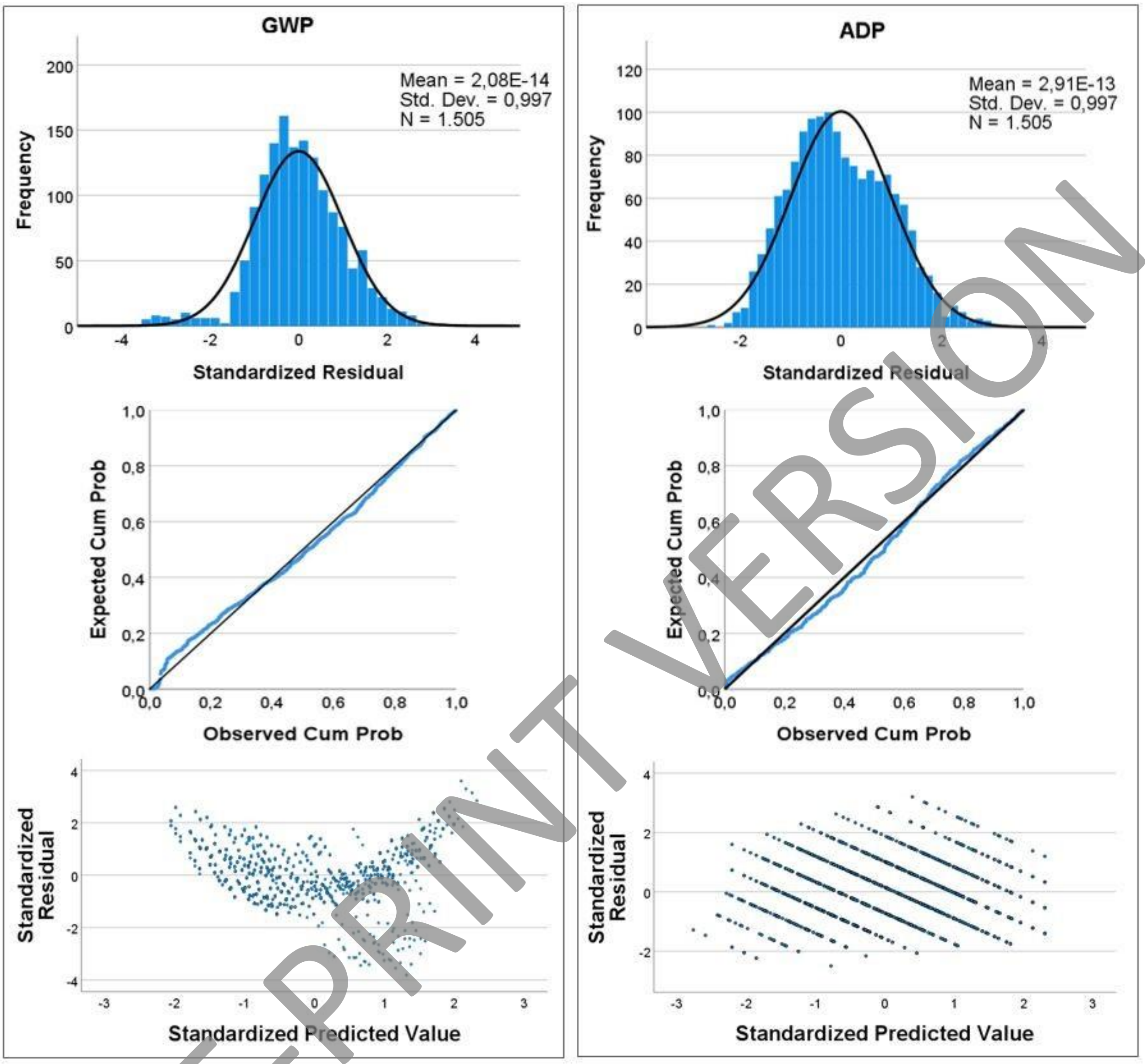


Figure 13. Graphic results for Global Warming Potential (left) and Abiotic Depletion Potential (right): a) Histogram, b) Normal P-P Plot of regression standardised residual and standardised predict value, c) Scatterplot of standardised residual and standardised predicted value.

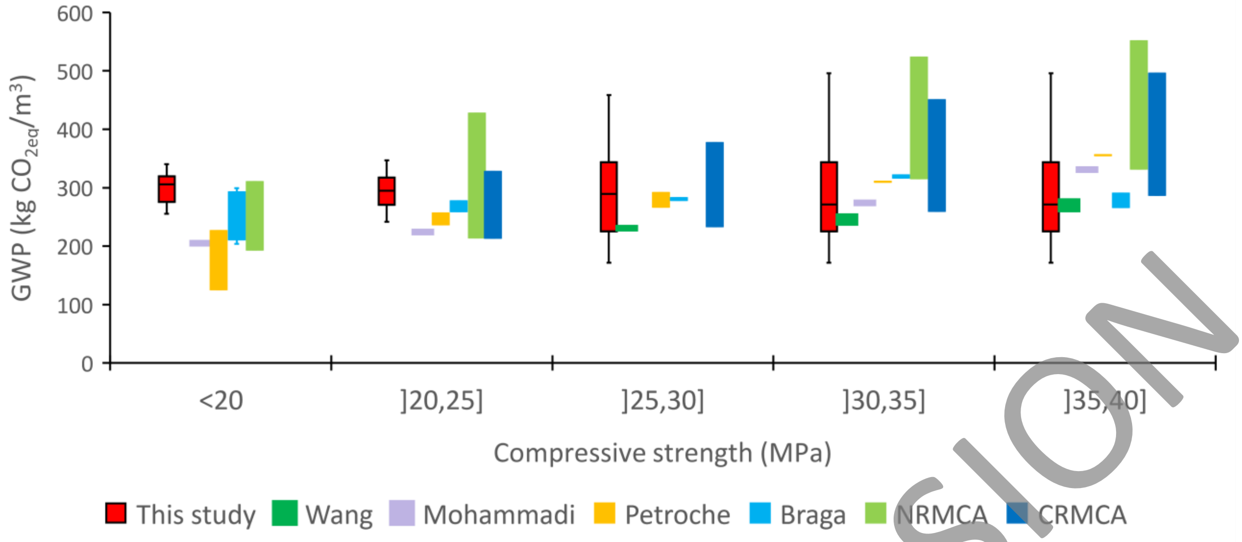


Figure 14. Global Warming Potential (kg CO$_{2eq}$) for 1m3 of ready-mixed concrete in literature [5,13,22,45,46,53] and this study.