LCA of recycled and conventional concretes designed using the Equivalent Mortar Volume and classic methods

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Abstract

The objective of this investigation is to environmentally evaluate three concrete design methods through a Life Cycle Assessment using the methodology of the Institute of Environmental Sciences (CML), from Leiden University. Included is a novel method for designing recycled aggregate concretes, named Equivalent Mortar Volume. The evaluation is done by comparing certain key life cycle stages of four concretes, two designed through the proposed method and two others designed through widely known methods. These experimentally assessed concretes have equal sets of properties in terms of mechanical resistance, durability, and workability. According to the calculated emission quantities, concretes designed using the novel method show better environmental performance than their counterparts in all of the selected impact categories.

Keywords: Environmental impact, Carbon dioxide equivalent, Global Warming Potential, Cement, Mix proportion.

1. INTRODUCTION

It is widely known that concrete is the most commonly used man-made material worldwide [1, 2, 3, 4], and that this is mainly because of its excellent properties, versatility, availability, and price [5, 6, 7]. Because of the range of variation of its properties, concrete has outstanding suitability for many different uses, achieving great workability, resistance, and durability properties. However, alongside the good qualities of concrete, it also generates relevant environmental impacts due to the huge amount of it that is produced and the use of cement, one of its main components, which is well known for being a relevant contributor to global warming [6, 8, 9].

On the one hand, because aggregates make up three-quarters of the concrete by volume [10], concrete represents a major consumer of natural resources and, when demolished after its service life or deterioration, turns into inert waste, which can occupy large volumes in landfills.

On the other hand, the usage proportions of cement together with its production process may cause important environmental impacts. World cement production in the year 2013 was estimated to be 4 billion tonnes (Bt) [11], which is nearly 600 kg/habitant, and accounts for about 7% of the total CO_2 generated worldwide [6, 12, 13, 14, 15, 9].

Recycled aggregates concrete (RAC) offers some benefits as it uses aggregates obtained from concrete recycling, which are converted into a product through a valorization process, thus avoiding or diminishing the use of natural aggregates (NA) and preventing the use of landfills. Despite this, some authors [16, 17, 18] have found that more cement must be used in order to achieve properties similar to those of a natural aggregates concrete (NAC).

Thus the environmental problem appears again: while avoiding depletion and landfilling of NA, more emissions are caused by cement manufacture.

One of the possible solutions is a novel method for concrete mix proportioning named the Equivalent Mortar Volume method [19, 20]. This method points to a better design of RAC by taking into account the different phases that form part of a recycled aggregate (RA), namely, the original NA and the mortar attached to it. This novel method has a beneficial effect on the general properties of the RAC and, predictably, on its environmental impacts, mainly due to the cement savings that it generates, while maintaining the short- and long-term performances.

This method has been analysed in previous investigations [21, 22, 23, 24, 25, 26] and the results seem to be promising. The properties of the concrete produced by this method correspond with the theoretical assumptions, where the obtained mechanical and durability test results are similar and in some cases better than those of the parent concrete mixes (conventionally designed RAC and NAC), owing to the better-controlled total amount of mortar in the concrete mixes. As well as the mentioned improvement of the properties, due to the lower amounts of cement and the replacement of NA by RA, there should be some additional environmental and economic advantages. The first of these advantages can be evaluated through a Life Cycle Assessment (LCA). Therefore, this study will focus on the environmental assessment rather than the properties and design procedures, which will be only briefly described. In this context, the aim of this paper is to assess, through an LCA, the environmental burdens caused by the use of the Equivalent Mortar Volume, American Concrete Institute, and Bolomey mix proportioning methods for the production of concrete mixes, comprising the use of NA and/or RA. In this way, the quantitative environmental differences of the concretes can be analysed and thus a proper decision can be made when choosing between one method and another.

2. METHODOLOGY

2.1. Concrete mix proportioning methods

The American Concrete Institute [27] and Bolomey [28, 29] mix proportioning methods are broadly acknowledged and used, with the former being the most widely used in the world [30]. The concretes elaborated by these methods act as references for the evaluation carried out in this work. The first method is used as a base to produce an RAC, designated as ACI. This is as simple as replacing a certain percentage of the previously calculated coarse NA by RA, on a volumetric basis, and taking into consideration some recommendations for RAC design, like the high water absorption of the recycled material, which may cause variations in the effective water/cement (w/c) ratios of the concrete. This corresponds to the most common practices used to produce this type of concrete mixture. The Bolomey method is used to produce an NAC, designated as BOLCON. Two other concretes, designated as EMV and BOLEMV, are designed using the Equivalent Mortar Volume method [19] and the American Concrete Institute and Bolomey [25] designs are applied to them, respectively, which means that the mix proportions obtained by these methods are used as a starting point. The basis of this methodology is to determine the attached mortar content of the RA, considered as two-phase materials (NA and attached mortar), counting the attached mortar as part of the total mortar for the mix, and adding a volume of NA equal to the attached mortar volume. By doing this, this RAC will have equal amounts of materials to NAC and thus similar properties. This differs from conventional methods for RAC design. If the RA is considered as a single-phase material (no distinction between attached mortar and NA), the attached mortar is considered as a part of the aggregate. Thus there will be an excessive amount of mortar when the attached one is added to the one already calculated in the design.

2.2. Description of the concrete mixes

The four different concrete mixes are classified into two categories in accordance with their main characteristics, as described in the European Standard for concrete EN 206-1 [31]. The aim of this is to make a proper comparison between equivalent materials, which fulfil an equal set of parameters in terms of resistance, workability, and durability. The categories are $C35\text{-}S3\text{-}D_{max}20\text{-}X0$ and $C40\text{-}S3\text{-}D_{max}20\text{-}X0$, where *C* stands for concrete, *35* and *40* represent the resistance class in terms of the concrete characteristic strength (f_{ck}), measured at 28 days in newtons per square millimetre by single compression test and considering the average of three cylindrical test specimens 150 mm in diameter and 300 mm in height [32], *S3* represents the consistency class, measured in centimetres according to EN 12350-2 standard [33] and ranging from 10 to 15 with a tolerance of ± 2 cm, $D_{max}20$ represents the maximum size of the aggregate, and *X0* represents the exposure class, which is related to the environmental characteristics of the surroundings of the concrete (in this case a non-aggressive environment).

The mixes of the first category correspond to ACI and EMV concretes, both taking into account the available recommendations for RAC design. In these mixes, 100% and 65% of the coarse NA, respectively, were replaced by RA (in terms of the total coarse aggregate weight), thus closely following the novel method mix proportions of the original research [19] that was under analysis. The mix design of the second category corresponds to BOLCON and BOLEMV concretes. The first of these was fully made with NA and the second used a 20% replacement of NA by RA (in terms of the total coarse aggregate weight). The 20% replacement was chosen by considering the actual recommendations for the RAC design [34, 35].

The materials used for the elaboration of the concrete mixes were cement type CEM I 42,5 R [36], tap water, calcareous coarse and fine aggregates, coarse RA, superplasticizing admixture (SP; Glenium Sky 604), based on polycarboxylates, and air entraining admixture (AE; Micro-Air 100). The RA was produced entirely by recycling concrete material and was classified according to the EN 933-11 standard [37].The results of these concrete characteristics come from an extensive experimental campaign [25]. Their composition and main results are detailed in Table 1.

Table 1. Concrete mix proportions and characteristics

Concrete type	Water/ cement (w/c)	Water (kg)	Cement (kg)	NA		RCA (kg)	AE (g)	SP (g)	Air (%)	Slump (cm)	Real density (kg/m^3)	f_{ck} (N/mm^2)	Max. water penetration (mm)	Aggregates max. size (mm)
				Fine (kg)	Coarse (kg)									
ACI*	0.45	184	409	752	–	786	82	1227	9	15	2010	35.2	<20	20
EMV	0.45	140	311	577	421	782	62	2176	8	10	2145	35.5	<20	20
BOLCON*	0.45	184	409	796	1085	–	–	1500	–	15	2309	41.2	<10	20
BOLEMV	0.45	169	376	732	941	235	–	2100	–	15	2303	43.7	<10	20

* Reference concrete

The EN 206-1 standard [31] recommends some limiting values for the composition and the properties of the concrete, depending on the selected exposure class. In the cases considered in this investigation, for an *X0* exposure class, there are no specific requirements regarding maximum water/cement ratio (w/c), minimum cement content, and minimum air content. The only recommendation is that the strength class of the concrete should be higher than 12 N/mm^2 (in terms of the cylindrical 150 × 300 mm specimen). In the case of the durability properties, the Spanish Code for Structural Concrete EHE-08 [35] states that for a Class I exposure type of environment (non-aggressive environment), the concrete should have a w/c ratio of at least 0.65 and 200 kg of cement per cubic metre. Also, it is recommended that the concrete should have a characteristic compression resistance (fck) of at least 20 N/mm^2 and, for some exposure classes, a maximum penetration depth of water under pressure of 50 mm according to EN 12390-8 [38].

All concretes fulfil the properties prescribed within their classification and, furthermore, they can be used in other type of exposure environments as well.

2.3. Life Cycle Assessment (LCA)

LCA is an acknowledged method of determining the environmental burdens of certain processes or products. The ISO 14040:2006 standard [39] defines it as a “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle”. It is composed of four main stages: i) definition of the scope and objectives, ii) inventory analysis, iii) impact evaluation, and iv) interpretation of results.

2.3.1. Objectives, scope, and declared units

The aim of this study is to carry out an evaluation of the environmental burdens resulting from applying different mix proportioning methodologies to the production of concrete, involving the use of natural and/or recycled aggregates. The specific objectives are:

- to determine the environmental impacts implied by the use of the studied mix proportioning methods in the production of concretes (cradle to gate);
- to evaluate the environmental burdens of the different stages within the concrete systems;
- to establish the best options among these concretes, in terms of their environmental impacts;
- to determine whether the Equivalent Mortar Volume method provides environmental benefits to the studied concretes while achieving performances equal to those of its counterparts;
- to evaluate the environmental effects of using different types of binders in the production of these concretes.

The procedure used to assess the environmental impacts of the studied concretes is the one prescribed by ISO:14040 [39], performed from a cradle to gate perspective. Two declared units (DUs) are defined in this study: i) *the production of 1* m^3 *of class C35-S3-*D_{max}*20-X0 concrete in a central mix plant,* and *ii) the production of 1* m^3 *of class C40-S3-*D_{max}*20-X0 concrete in a central mix plant.* These DUs have been chosen in order to put some boundaries on the large number of options among existing concrete types and also because their characteristics represent concretes used commercially.

2.3.2. System boundaries

As shown in Figure 1 the system comprises the stages from raw materials extraction until the production of concrete, excluding the subsequent phases of construction, use and maintenance, and demolition. The decision to omit the mentioned phases is because this study aims to analyse the environmental properties inherent in the material itself at the design stage and, as concrete has many uses, different results could appear depending on the selected application. Moreover, as the studied concretes have the same set of properties (experimentally assessed), they are assumed to achieve equal performances, so no differences will appear during their lifespans.

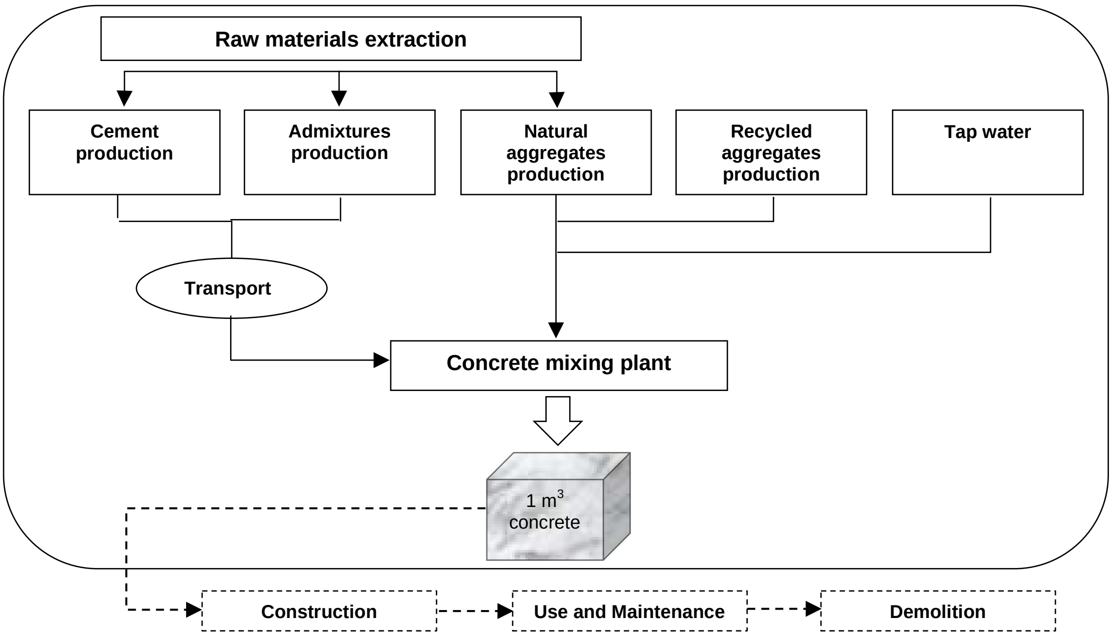

Figure 1. System boundaries of the concrete production system

The materials used for the production of concrete come from local suppliers although their environmental data correspond to those available in databases or specialized documents. The transportation system used was the one suitable for the case and was available from the accessed databases. The concrete plant and energy usage come from existing examples of concrete production, which were adapted to the actual system requirements. The same production processes and energy requirements were applied to the concrete groups as they have almost equal characteristics. The RA production only takes into account crushing and screening operations, as the previous stages of demolition and transport of waste are considered as part of the previous life cycle system. The transport distances of the cement and additives (75 and 100 km) correspond to the normal distances between the concrete plant facilities and suppliers [40, 41]. Cement, admixtures, and NA production include raw materials extraction processes, transportation inside the factory, and machinery use.

2.3.3. Data sources

The compiled data were acquired mainly from the Ecoinvent v3.01 database [42] and, in the cases of the RCA and chemical admixtures, from the literature [43, 44, 45], as they were not included in the database referred to. The software Simapro 8.0 [46] was used to organize the data, assemble each system case, and obtain the environmental results.

2.3.4. Allocation

An unavoidable allocation problem appears due to the concrete recycling outputs (coarse and fine RA). This was solved through a mass allocation procedure, taking into account a reclamation ratio of 60% for the coarse part, so 600 and 400 kg of coarse and fine RA, respectively, are created per 1 ton of recycled material. This reclamation ratio has already been presented by other authors [47, 43]. The choice of using a mass allocation procedure instead of economical allocation was made taking into account what the EN 15804 and ISO 14044 [48, 49] standards state. This is due to the fact that both the fine and coarse recycled fractions have similar fractions and prices on the local market, and so a physical property relation seems appropriate. It is worth reminding that the concretes of this investigation have been designed using only the coarse fraction.

2.3.5. Impact assessment

The analysis was done using CML methodology. The selected mid-point impact categories of this study were Abiotic Depletion (ADP; kg Sb eq.), Abiotic Depletion of fossil fuels (ADP fossil fuels; MJ), Global Warming Potential (GWP; kg CO_2 eq.), Ozone Layer Depletion (ODP; kg CFC-11 eq.), Human Toxicity (HTP; kg 1,4-DB eq.), Fresh Water Aquatic Ecotoxicity (FAETP; kg 1,4-DB eq.), Marine Aquatic Ecotoxicity (MAETP; kg 1,4-DB eq.), Terrestrial Ecotoxicity (TETP; kg 1,4-DB eq.), Photochemical Oxidation (POCP; kg C_2H_4 eq.), Acidification (AP; kg SO_2 eq.), and Eutrophication (EP; kg PO_4 eq.)

2.3.6. Sensitivity analysis

A sensitivity analysis regarding different cement types was carried out. Its main purpose is to check whether the use of types of cement other than Portland type I have an influence on the total emissions of the concretes considered in this investigation. Cement has been chosen for this sensitivity analysis as it represents the major environmental loads with regard to the different impact categories of the studied concrete systems. The GWP category is selected as it is the one where cement accounts for the highest burden as well as being one of the most significant impact categories due to its recognition as an environmental benchmark in many areas. The amount of alternative cements used corresponds to the same amount of the original mixtures. The selected cement types used for this evaluation are Portland cement type I (P; almost no additions), Portland cement type II (F; with additions of 11–35% fly ash), and Portland cement type II (S; with additions of 18–30% blast furnace slag). Both type II cements have been selected as they are supposed to give the concrete at least the same properties as cement type I. The data were obtained from the Ecoinvent v3.01 database [42] and processed with the software Simapro 8.0 [46].

3. RESULTS AND DISCUSSION

3.1. Inventory analysis

Table 2 shows the inventory data for the present investigation. It is divided into two categories with two concrete mixes each, specifying the phase of the product system and the single unit data per DU.

Table 2. Inventory of the different concrete systems per DU

Stage	**Data per DU**	**Unit**	**Product System**			
			C35-S3-Dmax20-X0		**C40-S3-Dmax20-X0**	
			ACI*	**EMV**	**BOLCON***	**BOLEMV**
Materials	Tap water	kg	184	140	184	169
	Cement (Portland I)	kg	409	311	409	376
	Natural aggregate	kg	752	998	1881	1673
	Recycled aggregate	kg	786	782	0	235
	Admixtures	kg	1.3	2.2	1.5	2.1
Facilities	Concrete plant	u	4.6E-07	4.6E-07	4.6E-07	4.6E-07
Transport	Lorry 16-32t (EURO5**)	tkm	30.8	23.5	30.8	28.4
Energy	Production	MJ	55	55	55	55

* Reference concrete

** European emission regulation class

The major changes occurring among the concretes are due to their compositions. The Equivalent Mortar Volume method presents important differences when compared to the reference concretes. Their main constituents (water, cement, and aggregates) differ due to the proportioning method, in which it is worth noting that the cement content decreases by 24 and 8% in the cases of the first and second groups of concretes respectively. Admixture amounts in both concretes proportioned by the Equivalent Mortar Volume method are higher than in their comparison concretes so that their slump test values become comparable. These mixes produce a lower slump caused by the diminution in the fresh mortar content, when counting the hardened one attached to the RA as part of the total needed by the design.

The variation of transportation figures depends on the amount of material transported rather than the distance to the suppliers, as all the concretes are produced in the same place. Regarding transportation, cement content becomes the parameter with the greatest influence, as it accounts for more than 99% of the whole figure, whereas admixtures account for less than 1%. The Facilities and Energy stages present the same values for each of the studied concretes as they have no relevant differences concerning the plant and technologies used for their production.

3.2. Impact assessment of concrete systems

The results from the characterization phase of the LCA are presented in Table 3, in which the total results for every one of the chosen impact categories are listed according to the concrete systems, which are divided into the same two groups as before. The percentage difference in the results of every impact category between the concretes designed using the novel method and the conventionally designed ones is also presented for each group.

Table 3. Characterization phase results by concrete type and impact category

			C35-S3-Dmax20-X0			**C40-S3-Dmax20-X0**		
Impact categories	**Abbreviation**	**Unit**	**ACI**	**EMV**	**%Δ**	**BOLCON**	**BOLEMV**	**%Δ**
Abiotic depletion	ADP	kg Sb eq.	3.22E-04	3.20E-04	–1%	4.60E-04	4.24E-04	–8%
Abiotic depletion (fossil fuels)	ADP (fossil fuels)	MJ	2.20E+03	1.82E+03	–17%	2.32E+03	2.18E+03	–6%
Global warming	GWP	kg CO_2 eq.	4.03E+02	3.16E+02	–21%	4.10E+02	3.81E+02	–7%
Ozone layer depletion	ODP	kg CFC-11 eq.	8.83E-06	7.71E-06	–13%	9.68E-06	9.23E-06	–5%
Human toxicity	HTP	kg 1.4-DB eq.	3.79E+01	3.29E+01	–13%	4.22E+01	3.96E+01	–6%
Fresh water aquatic ecotoxicity	FAETP	kg 1.4-DB eq.	2.86E+01	2.43E+01	–15%	3.13E+01	2.93E+01	–6%
Marine aquatic ecotoxicity	MAETP	kg 1.4-DB eq.	1.02E+05	8.84E+04	–13%	1.13E+05	1.06E+05	–6%
Terrestrial ecotoxicity	TETP	kg 1.4-DB eq.	1.18E-01	1.06E-01	–10%	1.37E-01	1.30E-01	–5%
Photochemical oxidation	POCP	kg C_2H_4 eq.	4.27E-02	3.53E-02	–17%	4.61E-02	4.30E-02	–7%
Acidification	AP	kg SO_2 eq.	1.15E+00	9.40E-01	–18%	1.20E+00	1.12E+00	–7%
Eutrophication	EP	kg PO_4 eq.	2.45E-01	2.01E-01	–18%	2.54E-01	2.38E-01	–6%

In both cases, the results of the concretes designed with the Equivalent Mortar Volume method are lower than their analogous concretes for every one of the selected impact categories

3.2.1. C35-S3-Dmax20-X0

EMV concrete behaves in almost the same way as the ACI concrete in the ADP impact category, with only 1% difference due to the emissions balance among their stages. EMV concrete uses less cement and consequently reduces the emissions due to transportation as well, but ACI has a smaller amount of NA and admixtures, leading to a total emissions balance between them. The difference is much greater for all of the other impact categories, ranging from 10 to 21%, the second being the GWP impact category, where such a difference is due to the difference in cement contents and to the fact that cement is by far the largest contributor in this impact category. Cement generates such high emissions due to the energy usage in its production process (about one third for Portland cements without additions) and the chemical decomposition of calcium carbonates, at high temperatures when producing clinker, into calcium oxides and carbon dioxide (CO_2, which represents the other two thirds of the emissions for Portland cements without additions). In fact, every kilogram of type I Portland cement produced releases around 800 g of CO_2 [50] a figure that may be lower depending on the selected type of cement.

3.2.2. C40-S3-D_{max}20-X0

BOLEMV concrete has lower emissions, ranging from 5 to 8%, in all of the studied impact categories. The smallest difference occurs for the

TETP impact category, which is related to toxic substances emitted in terrestrial ecosystems in terms of 1.4 DB-eq. kg, where cement, NA, and admixtures are the largest contributors. Contrary to what was mentioned regarding the C35-S3-D_{max}20-X0 concretes, the ADP impact category has the largest difference between the two concretes, mainly due to the differences in cement and NA contents. BOLCON concrete is completely elaborated with NA and has more cement than BOLEMV concrete, and although the latter uses a greater quantity of admixture, this has a considerably lower significance in the results due to the amounts utilized. Cement and NA mineralogies are characterized by elements that are directly related to natural non-renewable resources, thus having a direct relationship with the ADP impact category [51]. This, together with the important role that they play in the concrete, occupying more than 80% of its volume, explains the weight they have in the results of this particular case.

3.3. Disaggregated impact assessment of concrete systems

Figure 2 and 3 show a comparison of the different concretes' stages for each of the selected impact categories and thus emphasizes their individual influences among the total figures. The first column of each impact category in Figure 2 represents ACI concrete and the second represents EMV concrete. In the case of Figure 3, the first and second columns represent BOLCON and BOLEMV concretes respectively.

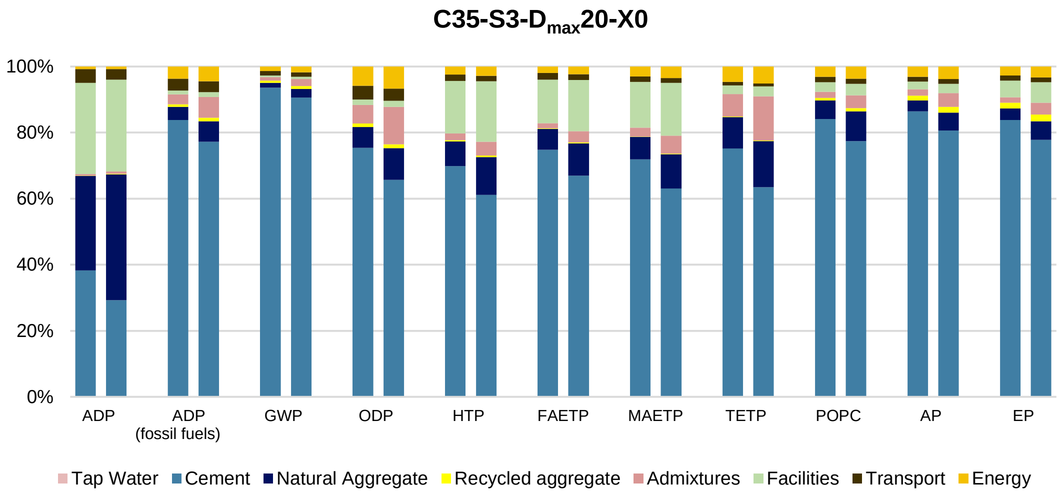

Figure 2. Disaggregation of impact categories of ACI (first of each pair of columns) and EMV (second of each pair of columns) concretes into percentage contributions of DU stages

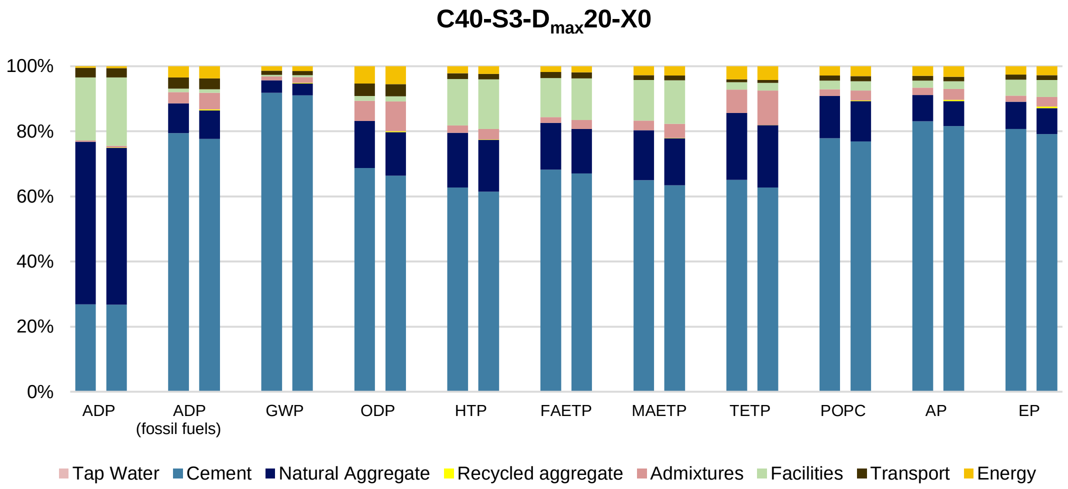

Figure 3. Disaggregation of impact categories of BOLCON (first of each pair of columns) and BOLEMV (second of each pair of columns) into percentage contributions of DU stages

3.3.1. C35-S3-D$_{max}$20-X0

From Figure 2 it is clear that, irrespective of the concrete type, cement is the single element contributing the most to almost all of the impact categories, with just one exception of the ADP impact category for EMV concrete, in which it accounts for 29% of the emissions and where NA is increased to 38%. The explanation is related to the quantities of materials needed to elaborate 1 m^3 of concrete. Whereas cement production initially needs around 1.5 times the amount of material to obtain the final product, mainly due to the release of CO_2 in the calcination process during clinker production, aggregates represent over 3.5 times the amount of cement in the mix. With the exception of the ADP impact category, cement emissions range from 70 to 94% of the other impact categories total amounts in the ACI concrete, and from 61 to 91% in the EMV concrete. In both cases the highest percentage represents the GWP category. From these figures, it seems clear that putting in more effort regarding the environmental performance of this particular material would substantially improve the concretes' environmental performance as well.

NA has an important influence on the results for categories like ADP and TETP, where the former is influenced by the extraction of the product itself, thus contributing to its depletion, and the latter is influenced by the production process. As the EMV concrete needs more NA than ACI concrete, its emissions are about 33% higher regarding NA.

Admixture emissions are mostly important in the ODP and TETP impact categories. Although their emissions could be potentially harmful, their utilization amounts per cubic metre of concrete are so low that they do not end up making an important contribution to the final results of the majority of the impact categories. EMV concrete uses more than 2.2 times (in terms of percentage of cement weight) the amount of admixtures than ACI, and its emissions are 77% higher in this specific system unit. A larger amount of admixtures is necessary to compensate for the workability problems that arise due to the lack of fresh mortar in EMV mix compared to ACI.

The facilities stage emissions are more relevant in the ADP, HTP, MAETP, and FAETP impact categories. The reason for their impacts may be explained, in part, by the utilization of copper, whose extraction directly affects the ADP category and whose processing affects the HTP, MAETP, and FAETP categories. There are no differences in the related emissions of this stage between the studied concretes as they can be produced at the same installations.

The transportation stage does not have a major influence on the different impact categories. The only transportation that takes place is from the cement and chemical admixtures factories to the concrete plant, since the construction, maintenance, and demolition phases are not included.

Energy usage does not represent an important part of the total emissions due to the defined system limits. Tap water and RA emissions are mostly negligible in the majority of the selected impact categories.

In summary, the materials stage alone is accountable for at least 67% of the total emissions in every impact category for both concrete mixes, and is as high as 97%. This was an expected outcome, due to the exclusion of the construction, maintenance, and demolition phases from the system boundaries because of their variability, which depends on the broad scope of specific final applications of concrete.

3.3.2. C40-S3-D_{max}20-X0

Just like in the previous case, as shown in Figure 3, the majority of the emissions, with the exception of the ADP category, are attributable to the cement. Cement in the ADP category accounts for 27% of the total emissions whereas NA accounts for 50 and 48% of emissions for BOLCON and BOLEMV respectively. In the rest of the categories, cement emissions go from 63 to 92% in the case of BOLCON concrete and from 61 to 91% in the case of BOLEMV concrete, with the higher figures belonging to the GWP category, as in the previous cases. Even though some stages were omitted from the analysis, cement production and use might be key points to be aware of when aiming to improve the environmental performance of a whole construction project, although this depends on the specific case (it is more important in civil engineering works, which have a higher percentage of concrete per Functional Unit (FU) than buildings).

NA also has an important influence, especially in the ADP, HTP, MAETP, FAETP, and TETP impact categories. As these concretes use around twice the amount of NA as the previous case, their effects among the different impact categories are indubitably higher. Unlike the previous concrete category, because of the mix proportions, BOLEMV concrete produces 11% less emissions related to NA, in every impact category, than BOLCON concrete.

The amount of admixtures was increased more than 1.5-fold (in terms of percentage of cement weight) in BOLEMV concrete, and its emissions are 40% higher for this specific system unit. This is along the same lines as the previous concrete category.

The facilities, transportation, and energy stages behave similarly to what was mentioned in the case of C35-S3-D_{max}20-X0 concretes. RA and tap water are again the lowest contributors, although in this case RA only affects BOLEMV concrete.

The difference between the concretes' single units is not as high as in the previous case, due to the mix proportions only.

The materials stage is again the main contributor to the total emissions, accounting for at least 75% and as high as 97% of the total emissions in each category for both concrete mixes.

3.4. Cement type sensitivity analysis

A sensitivity analysis is presented regarding the variation of the emissions of the studied concretes when changing the cement type. Three different types of cements are analysed. In terms of the CO_2 emissions related to the concrete elaborated with Portland type I cement, the results of the sensitivity analysis show that cement F replacement reduces the emissions by about 17%. In the case of the replacement by cement S, the reduction is around 27%. The results of the analysis are given in Table 4.

Table 4. Cement-type sensitivity analysis in terms of CO_2 emissions

			C35-S3-Dmax20-X0		C40-S3-Dmax20-X0	
Cement type	**Abbreviation**	**Unit**	**ACI**	**EMV**	**BOLCON**	**BOLEMV**
Portland type I	P	kg CO_2 eq.	403.0	316.5	410.4	380.6
Portland type II	F	kg CO_2 eq.	332.2	262.6	339.6	315.5
Portland type II	S	kg CO_2 eq.	294.0	233.6	301.4	280.4

The difference in the CO_2 reductions between cement F and cement S is due to the proportioning percentages used in cement manufacturing. Ground granulated furnace slag production has greater impact in terms of CO_2 emissions than fly ashes, but the former is frequently dosed in bigger proportions in cement manufacturing. The differences between their emissions may be explained through their production processes: when used as a binder, ground granulated furnace slag has to be milled down to a size similar to that of cement, whereas fly ashes do not need such a process as their size is already suitable for use with cement.

While these figures are important, cement types F and S continue to have a significant influence on the total CO_2 emissions of the concretes in which they are used. Fly ash and slag cements represent reductions of around 2 and 3% respectively, in terms of the weight of these materials in the whole concrete system, when compared to the weight of Portland type I cement in its corresponding concrete system.

These theoretical figures suggest promising advances if proper measures are taken regarding cementitious materials for concrete production. If these binders make no difference to the desired properties of the concrete, they should be selected when designing certain mixes, if the concern is to improve their environmental value, at least regarding CO_2 emissions.

4. CONCLUSIONS

This paper shows how different mix proportioning methods (American Concrete Institute, Bolomey, and Equivalent Mortar Volume) can influence the environmental impact categories of the studied concretes, when equivalent short- and long-term behaviours are attained and natural aggregates (NA) and/or recycled aggregates (RA) are used. Four concretes were subjected to the analysis, two of them acting as references (ACI, BOLCON) and designed by conventional methods, and other two (EMV, BOLEMV) designed by a novel method.

The results show that cement is, by far, the most influential material in almost all of the analysed impact categories of the different concrete systems in terms of its released emissions. Thus leading efforts on lowering its environmental burden, while maintaining the concrete’s short- and long-term behaviour, may represent a big leap forward in this field. However, it should be noted that when comparing complete Functional Units (FUs) like bridges or buildings, the effect of cement and concrete can be very low in relation to the total impact and may have a positive influence on other life-cycle stages or parameters such as construction, maintenance, or energy efficiency.

After cement, NA and facilities are the most significant contributors to the majority of the impact categories for the different concrete systems. Their major influences are found in the Abiotic Depletion Potential (ADP) impact category, where NA accounts for 28–50% of the emissions and facilities accounts for 19–28%. After the ADP impact category, the major influence of NA is on the Terrestrial Ecotoxicity impact category (TETP), contributing at least 9% and up to 21% of the emissions. In the case of the facilities, also after the ADP impact category, the major influences observed are for the Human Toxicity (HTP), Fresh Water Aquatic Ecotoxicity (FAETP), and Marine Aquatic Ecotoxicity (MAETP) impact categories, contributing at least 12% and up to 18% of the emissions.

The influence of chemical admixtures emissions is rather small, and a significant increase in their quantities does not jeopardize the environmental achievements obtained by the concretes in this investigation. The chemical admixtures' main emissions contributions are related to the Ozone Layer Depletion (ODP) and TETP impact categories.

In all of the studied concrete systems, the materials stage represents the major contribution to emissions, reaching at least 67% in every impact category and over 96% in the Global Warming Potential (GWP) category.

According to the results, the Equivalent Mortar Volume method accomplishes better environmental performance than the conventional methods for designing recycled aggregates concrete and natural aggregates concrete. Although this is achieved by adding higher quantities of admixtures to the mix, their emissions contribution is small, and thus results in an appropriate solution.

The results of the sensitivity analysis indicate that the use of cements with additions of fly ash and slag improves the concretes' environmental performances with regard to the GWP impact category by reducing their CO_2 emissions by around 17 and 27% respectively, when compared to concretes using Portland cement type I. However, it must be taken into account that the same short- and long-term behaviours must be ensured for the different mixtures compared.

As an overall conclusion, it can be said that the actual initiatives toward the reutilization of construction waste in concrete could be improved and updated with the use of the Equivalent Mortar Volume method, while lowering the cement content of the concretes currently used and maintaining their short- and long-term behaviours.

5. AKNOWLEDGMENTS

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