

Cradle-to-gate life cycle assessment of self-compacting concrete incorporating alternative materials: a case study

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ABSTRACT

Many studies have described the successful incorporation of wastes and industrial byproducts, here called alternative materials (AMs), into self-compacting-concrete (SCC) mixtures from a technical point of view. Such studies usually considered a universal truth that incorporating these materials into the concrete matrix helps improve their eco-efficiency. Therefore, the objective of this study is to associate SCC production that incorporates AM with the life cycle assessment (LCA) methodology to compare mixtures in a specific United States scenario. SimaPro software, the IMPACT 2002+ impact assessment method, the Ecoinvent database and a 1 m³ functional unit with the cradle-to-gate system boundary were used. An analysis of total impact, global warming, impact intensity and most impactful processes was performed. According to the criteria analyzed, the mixtures with the best environmental gains are characterized by the partial or total replacement of cement by AMs classified as supplementary cementing materials (SCMs). Other cases did not yield significant environmental gains, such as the use of concrete and glass waste as aggregates, serving only as an alternative to their final disposal. In addition, when there was excessive energy consumption for waste recycling, such as for rubber and polyethylene terephthalate (PET) recycling, the environmental efficiency of the SCC deteriorated.

Keywords: Self-compacting-concrete (SCC). Life cycle assessment (LCA). Wastes. Alternative materials (AM). Environmental impact.

RESUMO

Muitos estudos descreveram a incorporação bem-sucedida de resíduos e subprodutos industriais, aqui denominados materiais alternativos (MAs), em misturas de concreto autoadensável (CAA) do ponto de vista técnico. Tais estudos geralmente consideram uma verdade universal que a incorporação desses materiais na matriz de concreto ajuda a melhorar sua ecoeficiência. Portanto, o objetivo deste estudo é associar a produção de CAA que incorpora AM à metodologia de avaliação do ciclo de vida (ACV) para comparar misturas em um cenário específico dos Estados Unidos. Foram utilizados o software SimaPro, o método de avaliação de impacto IMPACT 2002+, o banco de dados Ecoinvent e uma unidade funcional de 1 m³ com o limite do sistema do berço ao portão. Foi realizada uma análise do impacto total, aquecimento global, intensidade do impacto e processos mais impactantes. De acordo com os critérios analisados, as misturas com melhores ganhos ambientais caracterizam-se pela substituição parcial ou total do cimento pelos MAs classificados como materiais cimentícios suplementares (MCSs). Outros casos não renderam ganhos ambientais significativos, como o uso de resíduos de concreto e vidro como agregados, servindo apenas de alternativa à sua destinação final. Além disso, quando havia consumo excessivo de energia na reciclagem de resíduos, como na reciclagem de borracha e tereftalato de polietileno (PET), a eficiência ambiental do CAA se deteriorou.

Palavras-chave: Concreto autoadensável (CAA). Avaliação do ciclo de vida (ACV). Resíduos. Materiais alternativos. Impacto ambiental.

1 Introduction

To improve eco-efficiency indicators in the construction sector, it is increasingly sought to replace materials in the various types of concrete, with a focus on the production of sustainable raw materials and new manufacturing technologies with low environmental impact (PROSKE *et al.*, 2013; FEIZ *et al.*, 2015; MILLER; HORVATH; MONTEIRO, 2016). Several studies have analyzed the use of solid wastes and industrial byproducts in the concrete matrix (GRDIC *et al.*, 2010; YUNG; YUNG; HUA, 2013; LIU; POON, 2016; SADRMOHTAZI *et al.*, 2016), with the use in self-compacting-concrete (SCC) mixtures being an alternative because this type of concrete offers the possibility of incorporating large amounts of mineral additions (ZAO *et al.*, 2015) and its production cycle generates important environmental loads.

SCC has technical advantages over conventional concrete (PEREIRA-DE-OLIVEIRA *et al.*, 2014; BROUWERS; RADIX, 2005) and is increasingly being used for the construction of highly reinforced concrete elements and for massive concrete structures, such as dams, thick foundations, tall buildings, bridges, tunnels and off-shore structures (ZAO *et al.*, 2015). Therefore, the use of waste and industrial byproducts in the composition of SCC can increase its ecological value, help partially reduce waste disposal in landfills and thereby contribute to the reduction of environmental impacts on a global scale (GRDIC *et al.*, 2010; PEREIRA-DE-OLIVEIRA *et al.*, 2014). It is worth noting that the use of a certain waste is not usually associated with any environmental impact when it is included in a new production system (LANER; RECHBERGER, 2009; CLEARY, 2010; GENTIL; GALLO; CHRISTENSEN, 2011) because only the impacts from its recycling, transportation and use are accounted for as an environmental burden.

In this sense, many studies over the years have described the successful incorporation of waste and industrial byproducts into SCC mixtures from the technical point of view. In summary, the studies indicate that to replace parts of the cement, the most-used mineral additions are classified as cementing and pozzolans, which are called supplementary cementing materials (SCMs) and which include granulated blast-furnace slag (GBFS) and fly ash (FA) (YUNG; YUNG; HUA, 2013; ZAO *et al.*, 2015). Other studies also analyze the addition of SCMs that act only as fillers, such as limestone filler (LF) and ornamental rock waste

(CALMON *et al.*, 2005; CELIK *et al.*, 2015). In addition, to replace parts of the aggregates, recycled aggregates such as glass, rubber, recycled concrete and waste from other industries can be used (GRDIC *et al.*, 2010; ISMAIL; HASSAN, 2016; KOU; POON, 2009).

In studies that evaluate technical properties, it is generally considered a universal truth that the incorporation of these materials into the concrete matrix helps improve their eco-efficiency. However, there is a lack of analyses providing an exact quantification of their real influence on environmental impacts, covering the impacts and the possible consequences of these impacts for living beings. Life cycle assessment (LCA) is considered an effective tool for this task (CORTI; LOMBARDI, 2004; FERALDI *et al.*, 2013) and has been increasingly used in studies that analyze the environmental viability of concrete, such as Ingrao *et al.* (2014), Celik *et al.* (2015), Vieira, Calmon and Coelho (2016) and Vieira *et al.* (2018).

LCA is a methodology capable of providing instrumental support in projects to evaluate the environmental impacts of products and processes throughout their life cycle, presenting clear and scientifically based results (BJÖRKLUND; FINNVEDEN, 2007; GENTIL *et al.*, 2010; MARINKOVIĆ *et al.*, 2010; BUYLE; BRAET; AUDENAERT, 2013; TAKANO *et al.*, 2014). A detailed diagnosis of the conditions of raw material extraction, production, distribution, use and final disposal in a production process is essential for reliable data. This information helps in the elaboration of strategies that allow the minimization of costs and optimization of the flow of materials and energy in the analyzed system (REBITZER *et al.* 2004; GENTIL; GALLO; CHRISTENSEN, 2011; VAN DEN HEEDÉ; DE BELIE, 2012).

The objective of this study is to fill a gap by performing a comparative LCA and evaluating the actual influence that the incorporation of wastes and industrial byproducts has on the environmental performance of SCC production, analyzing the influence of 14 different types of additions/substitutions. The study uses a specific scenario in the city of Berkeley, California, USA. We analyzed 162 mixtures of potentially eco-efficient SCCs extracted from 15 scientific articles that demonstrated the technical viability of the analyzed concretes. Regarding the boundaries of the system, the studies fits the cradle-to-gate approach, encompassing extraction and processing of raw materials, manufacturing and processing of materials, preparation and treatment of

waste and byproducts, extraction and processing of additional products, and transport of raw materials and products within the system.

2 Methods, procedures and tools

2.1 Life Cycle Assessment (LCA) methodology

The description of the LCA methodology is based on the requirements of the ISO 14.040 (2006) and ISO 14.044 (2006) international standards, which consist of four distinct analysis steps: goal and scope definition, creation and analysis of a life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation of results. The LCA applied here also follows the guidelines of ISO 13.315-1 (2012) and ISO 13.315-2 (2014), which provide basic structures for LCA of concrete.

In this study, the LCA was conducted using the software SimaPro 8.2 (2016), the Ecoinvent 3.2 database (2015), the IMPACT 2002+ impact analysis method and the functional unit of 1 m³. The software follows a process-based LCA and has recently been considered an effective tool for performing LCA of concrete, among other available tools (SETO; PANESAR; CHURCHILL, 2017). The IMPACT 2002+ method has been widely used by scientific studies in the field of environmental analysis of concrete (INGRAO *et al.*, 2014; VIEIRA *et al.*, 2018). According to Jolliet *et al.* (2003), the LCIA methodology proposes a feasible implementation of an approach encompassing

impact categories (midpoints) and damage categories (endpoints). To facilitate interpretation of the impacts, normalization factors can be applied in the midpoint and endpoint classes and are determined by the impact ratio per unit of emission per person per year. The unit commonly used for the normalized impacts is the single score (Pt), which in the case of the IMPACT 2002+ method represents the proportion of the normalized total environmental impact of one person in Western Europe over a one-year period. This unit serves as a guide for comparative analysis, not as an absolute measure. The impact categories adopted by the IMPACT 2002+ method are shown in Table A.1 of Appendix A.

2.2 Analyzed mixtures

To collect the mixtures analyzed, four premises were established: (1) concrete mixtures should be contained in articles published in an internationally well-known journal; (2) the articles should address the analysis of the technical performance of the incorporation of industrial wastes or byproducts into SCC mixtures; (3) the waste or industrial byproducts studied should have regional feasibility to be used in the chosen scenario; and (4) the articles should contain the complete composition of each mixture studied in units of kg/m³ and also data regarding the compressive strength at 28 days. Thus, 15 articles were selected, as listed in Table 1.

Table 1 – Articles selected for analysis

#	AUTHORS	PC TYPE	AM AS SCM	AM AS AGGREGATE OR FIBER	# OF MIXTURES
1	Ismail and Hassan (2016)	A	FA, GBFS, MK	CR	33
2	Nguyen <i>et al.</i> (2016)	A	CFA, FA, GBFS	-	7
3	Sadromontazi <i>et al.</i> (2016)	A	FA, SF	PETW	10
4	Liu and Poon (2016)	A	FA, RM	-	5
5	Ghernouti <i>et al.</i> (2015)	B	LF	PBWF	13
6	Zhao <i>et al.</i> (2015)	A	FA, GBFS	-	7
7	Celik <i>et al.</i> (2015)	A	FA, LF	-	13
8	Pereira-de-Oliveira <i>et al.</i> (2014)	A	LF	RC	4
9	Sua-lam and Makul (2013)	A	-	AW	20
10	Yung, Yung and Hua (2013)	A	FA, GBFS	CR	13
11	Gesoglu <i>et al.</i> (2012)	A	FA	ASA	6
12	Ali and Al-Tersawy (2012)	A	SF	RG	18
13	Liu (2011)	A	-	RG	6
14	Grdic <i>et al.</i> (2010)	C	LF	RC	3
15	Kou and Poon (2009)	A	FA	RG	4

The following materials comprise the general mixtures: Portland cement (PC) type A, B or C; sand; gravel; water and superplasticizer (SP). Additions, wastes and byproducts included as alternative materials (AMs) are classified as SCMs, aggregates and fibers. The following AMs are used as SCMs: GBFS, FA, LF, metakaolin (MK), circulating fluidized bed combustion fly ash (CFA), silica fume (SF), and red mud (RM). The following materials are used as aggregates or fibers: crumb rubber (CR), polyethylene terephthalate waste (PETW), recycled concrete (RC), alumina waste (AW), artificial slag aggregate (ASA) and recycled glass (RG). The cements used in the study were divided into three types to be compatible with the cements used in the articles collected and to meet the specifications of the suppliers in the proposed scenario. PC type A includes all cements that have 95% or more of clinker in the mixture, PC B includes those with 6-20% clinker replacement, and PC C includes those with 21-35% clinker replacement. From the selected

articles, 162 mixtures were extracted. To access the complete composition of the mixtures from the studies referenced in Table 1, see Table A.2 of Appendix A.

2.3 Scenario for simulation

The scenario chosen for the simulation considers a concrete plant located in the city of Berkeley, California, USA, which was also used in the study of Celik *et al.* (2015), and their mixtures were also evaluated in this study. California is the most populous state in the US, with almost 40 million inhabitants, and has the largest gross domestic product (GDP), nearly \$2 trillion, which would be one of the 10 largest economies in the world if California were an independent country. The consumption of building materials, such as concrete, is directly linked to a large population with a strong economy. Table 2 presents detailed information about the simulation scenario.

Table 2 – Transport scenario for simulation

MATERIAL	ORIGIN	DISTANCE (KM)	TYPE	DISTANCE SOURCE
PC Type A, B and C	(Local Producer) California, USA	60	Truck	Celik <i>et al.</i> (2015)
Sand	(Local Producer) California, USA	50	Truck	
Gravel	(Quarry) British Columbia, CANADA	1000	Barge	
		10	Truck	
Water	(Local Network) California, USA	-	-	
SP	(Factory) Wyoming, USA	1000	Truck	
FA	(Jim Bridger Power Plant) Point of Rocks, Wyoming, USA	1000	Railroad	
LF	(Local Producer) California, USA	130	Truck	Google Maps
ASA, GBFS	(Lafarge North America Inc.) Seattle, Washington, USA	1300	Railroad	
CR, RC, PBWF, PETW, RG	(Recology) San Francisco, California, USA	30	Truck	
CFA	(Unit 3 - East Kentucky Power Cooperatives - Spurlock Power Station) Maysville, Kentucky, USA	3500	Railroad	
RM	(Alcoa) Point Comfort, Texas, USA	3150	Railroad	
MK	(Imerys) Sandersville, Georgia, USA	4000	Railroad	
AW	(Picon) San Pablo, California, USA	16	Truck	
SF	(CC Metals and Alloys) Calvert City, Kentucky, USA	3000	Railroad	

2.4 Allocation of the materials and input of the mixtures in Simapro

The materials used in the concrete mixtures were allocated according to five criteria: (1) material used

as product, (2) material used as untreated waste, (3) material used as recycled waste, (4) material used as untreated byproduct, and (5) material used as treated byproduct. Table 3 presents the range of environmental impacts related to the five allocation criteria used.

Table 3 – Allocation criteria

ALLOCATION	SCOPE
Product - PR	The end result of a manufacturing process. Absorbs the entire environmental impact of processes until its generation.
Untreated waste - UW	Material left over after a production process. No environmental impact is attributed prior to the generation of the waste.
Recycled waste - RW	Waste that has received some type of recycling to be used in a new production process. Only the impact of the recycling process is attributed.
Untreated byproduct - UB	Secondary product resulting from a manufacturing process. May have environmental impact from processes prior to its generation.
Treated byproduct - TB	Byproduct that has received some type of treatment before use (Example: heat treatment)

After determining the allocation criteria, it was possible to input each material in SimaPro. The materials were input in different modules containing the particularities regarding material consumption, transport consumption and energy consumption to produce 1 kg of the material, taking into account the allocation criterion of each. Material and energy

consumption data that did not exist in Ecoinvent 3.2 were located on the website of machine manufacturers and in articles that already analyzed the material in question. Table 4 presents the input of each material, specifying the allocation criterion and the source of the data.

Table 4 – Input of materials in SimaPro

MATERIAL	ALLOCATION AS	1 kg OF MATERIAL	SOURCE OF MATERIALS DATA	SOURCE OF ADDITIONAL DATA ON MATERIALS AND ENERGY CONSUMPTION
ASA	TB	0.90 kg of slag + 0.10 kg of cement type A + 0.22 kg of water + 0.0016 kWh of electric energy for a pelletizer	Ecoinvent 3.2	Yung, Yung and Hua (2013)
WATER	PR	1 kg of water	Ecoinvent 3.2	-
SAND	PR	1 kg of sand	Ecoinvent 3.2	-
CR	RW	0/24 kWh of electric energy for tire recycling machine	-	WhirlSton - Small Scale Tire Recycling Line (2016)
GRAVEL	PR	1 kg of gravel	Ecoinvent 3.2	-
PC	PR	1 kg of cement type A, B or C	Ecoinvent 3.2	-
FA	TB	0.67 MJ heat from the burning of natural gas	-	Chen <i>et al.</i> (2010) and Celik <i>et al.</i> (2015)
CFA	TB	0.67 MJ heat from the burning of natural gas	-	Chen <i>et al.</i> (2010) and Celik <i>et al.</i> (2015)
RC	RW	1 kg of recycled concrete	Ecoinvent 3.2	-
GBFS	TB	1 kg of granulated blast-furnace slag	Ecoinvent 3.2	Ecoinvent 3.2
PBWF	RW	0.55 kWh electric energy for a machine that transforms waste from plastic bags into plastic bag fiber	-	Wenzhou Hero International Trade Co., Ltd. (2016)
RM	UW	-	-	-
MK	PR	1.16 kg of kaolin + 2.25 MJ of heat supplied by the burning of natural gas for calcination + 0.0058 kWh of electric energy for equipment	Ecoinvent 3.2	Habert, Lacaillerie and Rousset (2011) and Heath, Paine and McManus (2014)
LF	PR	1 kg of limestone powder	Ecoinvent 3.2	-
AW	UW	-	-	-
PETW	RW	0.085 kWh of electric energy for a grinding mill	-	Prosino - Plastic Granulator (2016)
SF	UB	1 kg of active silica	Ecoinvent 3.2	-
SP	PR	1 kg polycarboxylate with 40% active substance + 1000 kgkm truck transport	Ecoinvent 3.2	-
RG	RW	0.0016 kWh power for a glass shredder	-	Andela Products Glass Pulverizer (2016)

The following are data pertaining to the processes to produce 1 m³ of concrete in the plant: 4.114 kWh of electricity + 15.643 MJ of diesel burning + 10.632 of heat from natural gas burning (data from the US energy matrix for concrete production). With the input of all the material modules and the energy module in the processes database in SimaPro, it was possible to analyze the impact of each of the 162 concrete mixtures, taking into account the proportion of materials in kg/m³ of each mixture and the energy consumption module in the factory.

2.5 SCC Production System Boundary

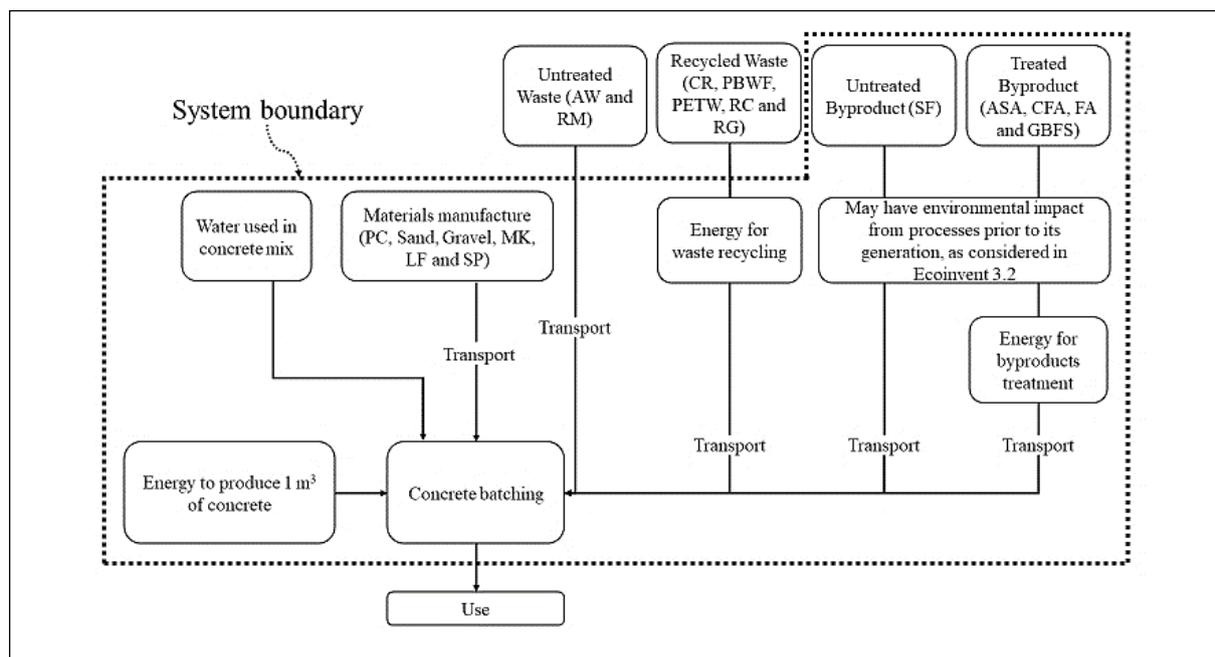
The system boundary used is cradle-to-gate (Figure 1). According to Tables 3 and 4, the materials allocated as products were cement, water, sand, gravel, and superplasticizer, thus encompassing the impacts from the raw material extraction to the finished product and adding the transport to the concrete manufacturing. For the wastes, no prior impact is attributed, accounting only for the transport of the waste to the concrete plant and the recycling energy (if required). However, the byproducts may have environmental impacts from processes prior to its generation (the adopted default was *Ecoinvent 3.2*) in addition to the transport and energy for treatment (if required). Finally, the concrete is produced in the batching plant according to the contents of the mixture.

3 Results and discussion

The results of the environmental impact will be presented for the midpoint category global warming (kg CO₂-eq), which is the category most commonly used in LCA studies and which contributes the most to the total impact in studies on concrete mixtures (VAN DEN HEEDE; DE BELIE, 2012). In addition, the total endpoint impact, in the form of a single score, in mPt, will be used, accounting for all impacts of concrete production in a single unit.

The presentation of the results will be divided into the following: 1) analysis of 1 kg of each material used in the mixtures, 2) analysis of the mixtures from the articles, and 3) process/material analysis of the most- and least-impacting mixtures of each strength class. To analyze the mixtures, analysis of total impact, global warming and intensity of impact will be employed (CELIK *et al.*, 2015; VIEIRA *et al.*, 2018), dividing the total impact in mPt by the mixture's compressive strength at 28 days, thus considering the functional characteristics of the concrete mixtures. The smaller the value of the impact intensity, the more eco-efficient the concrete mixture will be. Although it is difficult to analyze the isolated effect of each AM addition/substitution directly through the result of an individual analysis because each article uses different contents of two or more AMs, the general behavior of the influence of each AM can be noted through the results as a whole.

Figure 1 – Concrete production system boundary



3.1 Materials used in the mixtures

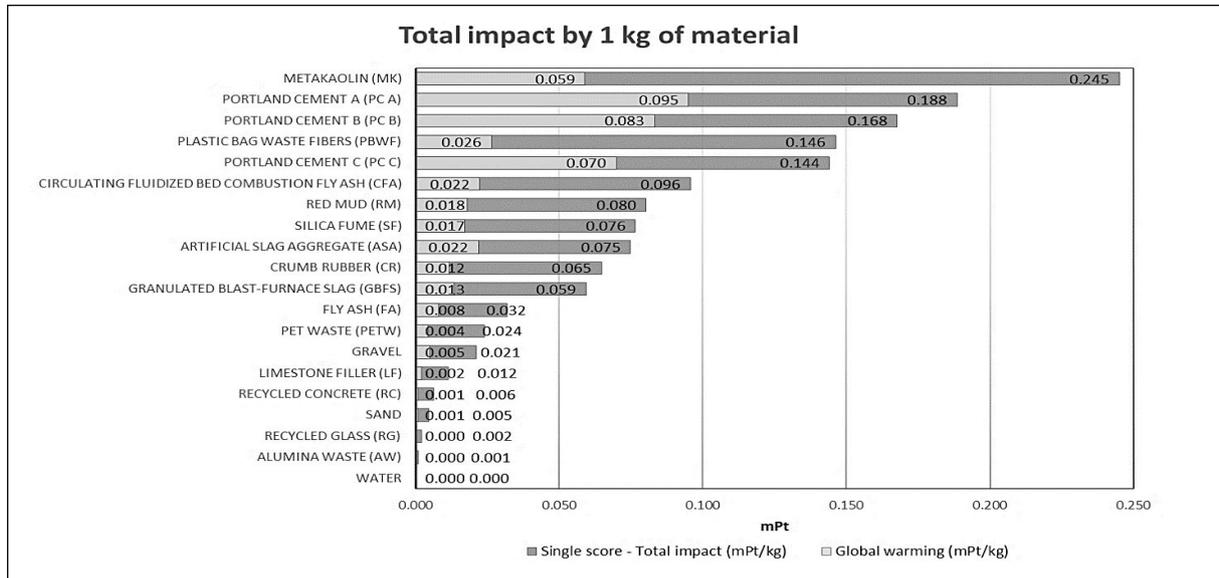
Figure 2 shows the total impact result of 1 kg of each material used in the mixtures analyzed. To obtain the results in kg CO₂-eq for the global warming impact category, it is necessary to multiply the result in the unit of mPt by the factor of 9.9.

By analyzing Figure 2, it is observed that the materials with the highest impact per unit mass are MK, cement and PBWF. The impacts of cement and metakaolin are highly influenced by the extraction, treatment of raw materials and calcination stages because these processes are responsible for the emission of large amounts of particulate matter into the atmosphere, emit large amounts of greenhouse gases and consume a lot of nonrenewable energy. It is also observed that for metakaolin, the impact does not come largely from global warming, as occurs for cement, but rather from other impact categories, such as respiratory effects caused by inorganic substances.

In the recycling of plastic bags for transformation into fiber (PBWF), energy consumption is very high, and the material is low-density, explaining its high impact per unit mass. It can also be observed that although the impact of global warming has great relevance in the total impact of the materials, analyses focused only in this category can hide other important insights of the evaluation.

It is important to note that SCMs frequently used by the construction industry, such as GBFS, FA, SF and LF, have a much lower impact per mass than the cements used (Figure 2). Comparing them with PC A (95% clinker), the total impact per mass is reduced by 69, 83, 60 and 94%, respectively. SCMs that are not yet widely used, such as CFA and RM, also had a total impact lower than that of common cement (PC A), reducing the impact by 49 and 57%, respectively. Thus, they seem to be good candidates for replacing cement, from an environmental point of view.

Figure 2 – Total impact per 1kg of material



In the case of AMs used as aggregates, such as ASA, CR and PETW, they did not achieve satisfactory environmental performance compared with the commonly used aggregates (gravel and sand). The total impact of ASA was 257% higher than that of gravel, an aggregate of equivalent particle size. The impacts of CR and PETW were 1200 and 380% greater than that of sand, an aggregate of equivalent particle size. This high impact value per unit mass is due to the high energy consumption for transformation of the waste into fine aggregates and their low density, being

more adequate a volume comparison. In contrast, the aggregates RC, RG and AW obtained lower total impacts per unit mass. RC had a total impact that was 71% less than that of gravel, an aggregate of equivalent particle size. RG achieves a good environmental performance, considering the low impact of grinding the glass, reducing the impact by approximately 60% in relation to sand. AW reduced the total impact by 80% in relation to sand and 92% in relation to LF, an aggregate of equivalent particle size.

3.2 Total impact of the mixtures

In Figure 3, each study is identified by a number, as specified in Table 1. For readability, the AMs used in each study are identified in the figure legend. The control mixture of the study is marked as a point in the graph, making it possible to analyze whether the substitutions/additions had a positive or negative influence on the total impact.

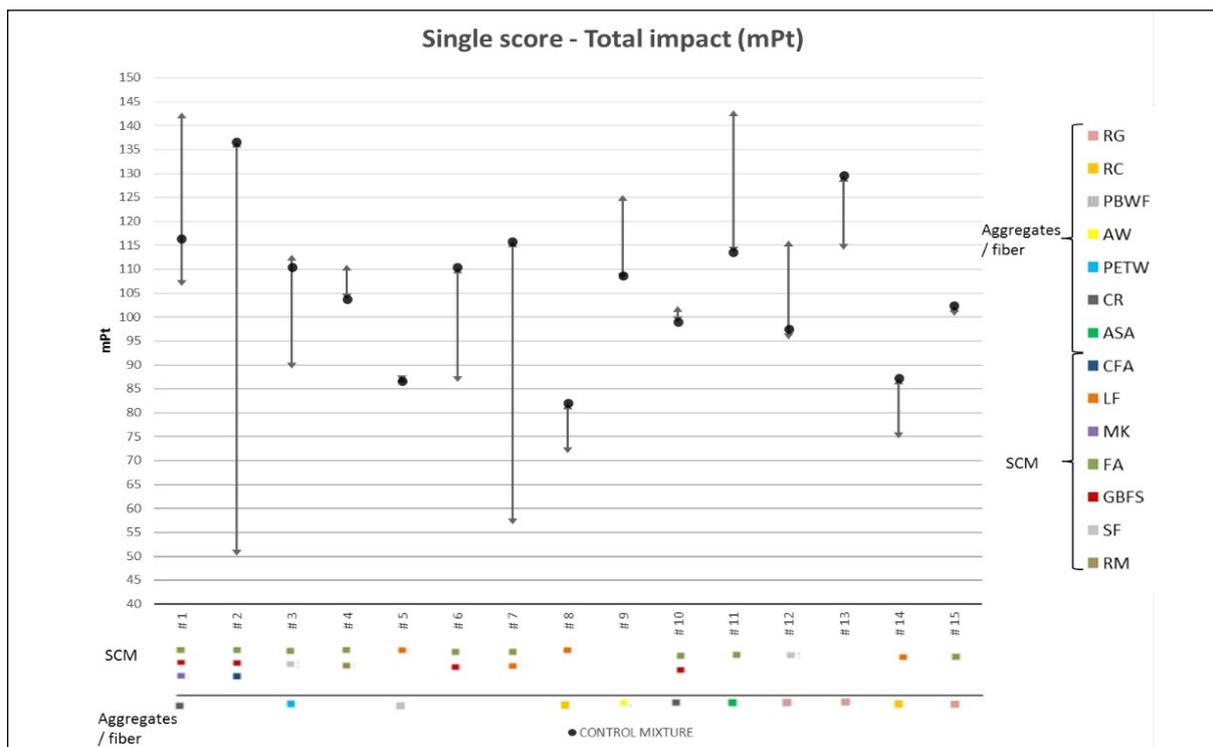
Figure 3 shows the variation in the total impact of the concrete mixtures from the different studies analyzed. The studies in which MAs significantly reduced the impact of the mixtures compared to the control mixture were studies 2, 3, 6, 7, 8, 13 and 14. It is observed that the combination of the following SCMs was beneficial in reducing the total impact: GBFS, FA, LF, CFA and SF. In studies 2 and 7, reductions of up to 63 and 50%, respectively, of the total impact were achieved, and the lowest total impact values were also observed. This result is due to the replacement

of cement, which has a high total impact, by waste/byproducts that have low or no environmental load attributed to it from its generation, combined with a low-impact recycling process.

The studies in which the impact of the mixtures increased in relation to the control were numbers 4, 9, 11, and 12. The largest increase occurred in study 11, up to 26% of the total impact, due to the use of ASA, an aggregate that has cement in its composition. In study number 1, the total impact varied alternately. The inclusion of FA and GBFS helped reduce the impact, but CR and MK increased the total impact of the mixture.

The studies in which the inclusion of AM did not have a significant influence in comparison with the control were numbers 5, 10 and 15. In the specific case of study 5, although PBWF was used, which requires a high energy expenditure for recycling, the amount used was very low (a maximum of 7 kg/m³). For studies 10 and 15, the use of CR and RG, respectively, as a replacement for natural aggregates, combined with the use of SCMs, did not significantly alter the total impact.

Figure 3 – Total impact (mPt) of the different mixtures



Studies 5, 8 and 14 obtained the lowest total impacts for the control mixtures. In the case of studies 5 and 14, this low impact was due to the cement used (type B and C, respectively), which has a low content of

clinker/cement, combined with the use of LF as SCM. In study 8, the consumption of the binder was very low, less than 300 kg/m³.

3.3 Global warming impact of the mixtures

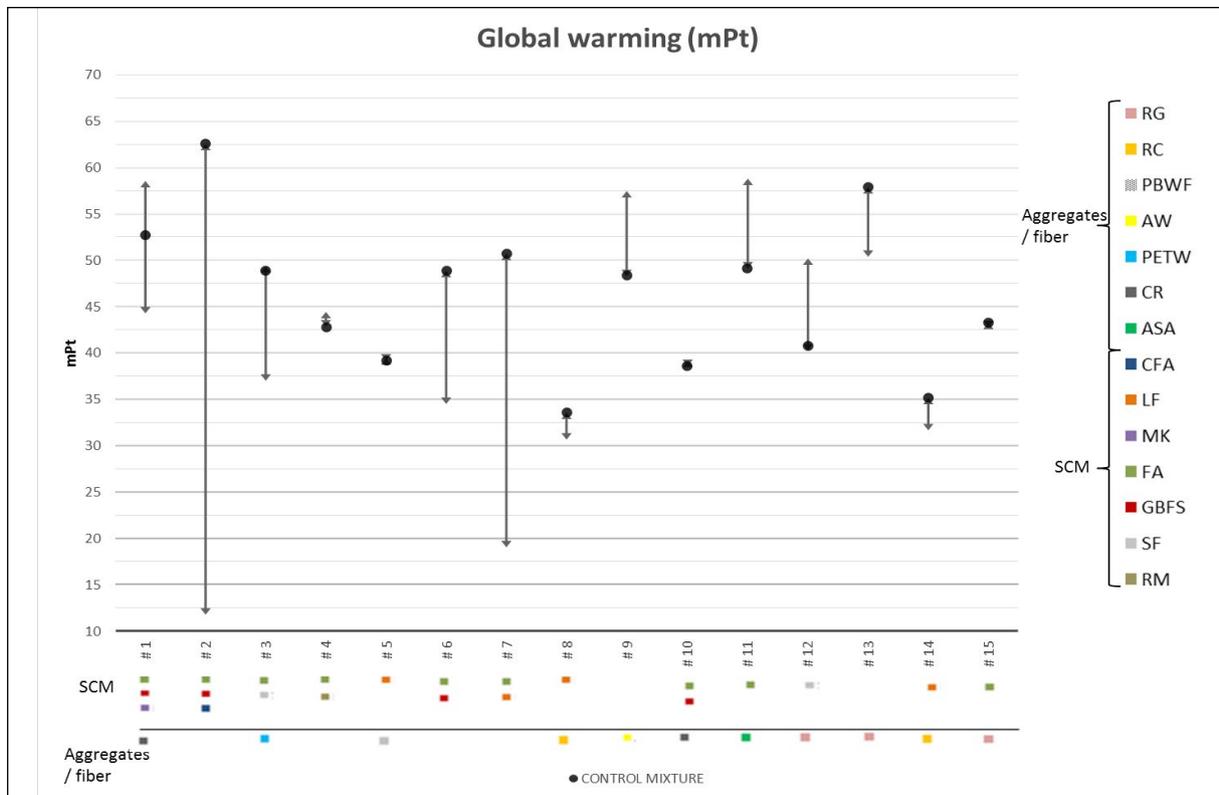
In Figure 4, each study is identified by a number, as specified in Table 1, the AMs used are identified, and the control mixture is marked as a point on the graph. Variation in the global warming impact of the concrete mixtures from the different studies analyzed is observed. Again, to obtain the results in kg CO₂-eq, it is necessary to multiply the result in mPt units by a factor of 9.9. The studies in which the AMs significantly reduced the impact of the mixtures compared to the control mixture were studies 2, 3, 5, 6, 7, 8, 13 and 14. The combination of GBFS, FA, LF, CFA and SF was also beneficial for reducing the impact of global warming.

The greatest reductions were observed again in studies 2 and 7, up to 81 and 62%, respectively, of the global warming impact, and the lowest global warming values were found (Figure 4). In addition to these wastes/byproducts having low or no environmental load attributed to it from its generation, combined with a low-impact recycling process, this result is due to these replacements contributing less than cement to the relative impact of global warming compared to their total impact (Figure 2). In addition, the results obtained

here, through a more detailed LCA computational tool, SimaPro, corroborate the global warming results from Celik *et al.* (2015) (study 7), who employed a new computational tool focused on LCA of concretes, the GreenConcrete LCA. The global warming impact obtained here for the mixtures from study 7 ranged from approximately 20 to 50 mPt (approximately 200 to 500 kg CO₂-eq), whereas their results ranged from 180 to 580 kg CO₂-eq.

Similar to what happened to the total impact, the studies in which the impact of the mixtures increased in relation to the control were numbers 9, 11, and 12 (Figure 4). However, in study 4, the increase in the impact was reduced compared to the total impact owing to the low contribution of global warming to the total impact of the added SCMs. In this study, the amount of cement was kept constant, and the SCMs were added; thus, the impacts increased in both analyses. In study number 1, for this impact category, there was again an alternating variation. In studies 10 and 15, inclusion of AM did not have a significant influence compared to the control because the addition of SCMs (FA, GBFS, and LF) counteracted the increased impact caused by the use of AMs as aggregates (CR and RG).

Figure 4 – Global warming (mPt) of the different mixtures



Studies 8, 10 and 14 exhibited the lowest total impacts for the control mixtures. In the case of study 14, cement with a low clinker/cement content was used. In studies 8 and 10, the binder consumption was 300 kg/m³ or less.

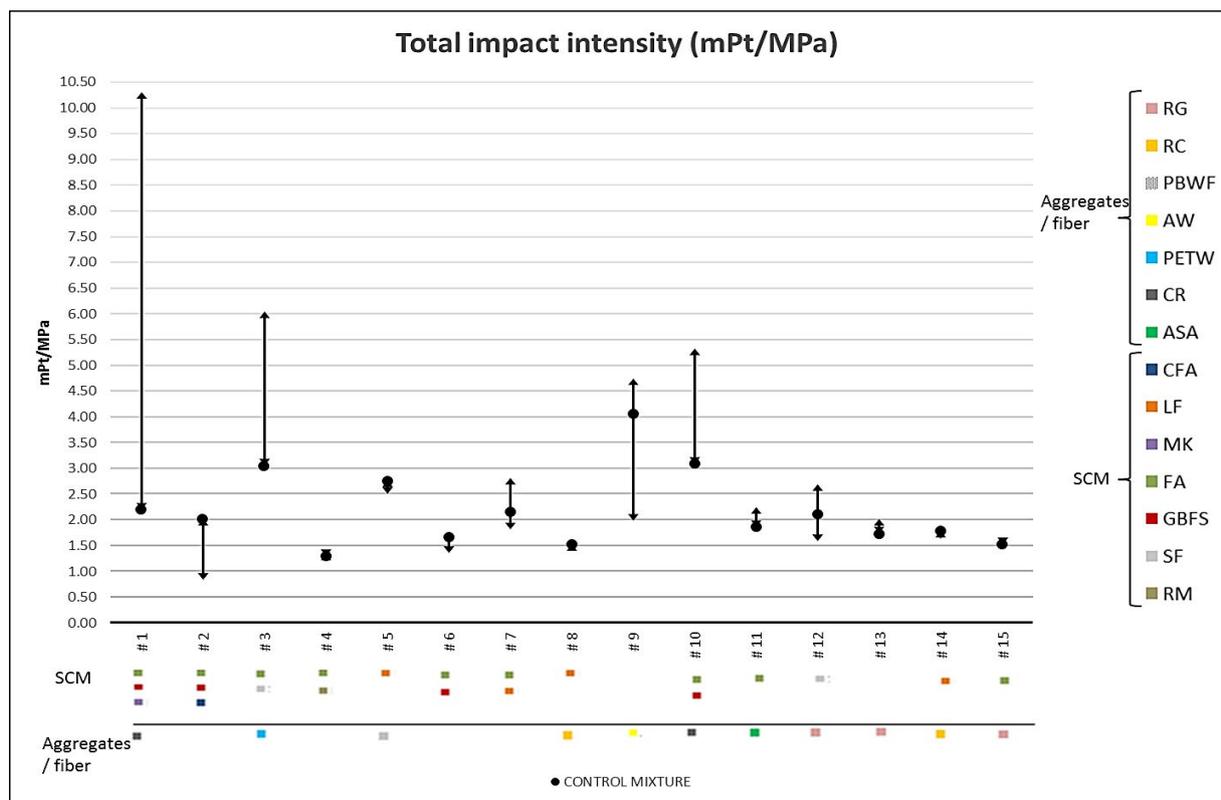
3.4 Impact intensity of the mixtures

In Figure 5, each study is identified by a number, as specified in Table 1, the AMs used are identified, and the control mixture is marked as a point on the graph. The variation of the impact intensity of the concrete mixtures from the different studies can be analyzed. The studies in which the AMs significantly reduced the impact intensity of the mixtures compared to the control mixture were studies 2 and 9. It is noted that the combination of the following SCMs was beneficial for reducing the impact intensity: GBFS, FA, and CFA (studies 2 and 6). Study 2 had the mixtures with the smallest indicators, allowing total replacement of the cement and a high compressive strength performance. This highlights the importance of replacing cement with SCMs that are industrial byproducts, which do

not require environmentally burdensome treatment for their use and which have good cementing and pozzolanic properties. In study 9, the AM used was AW. In the original study, the AW was replaced by sand, with AW classified as an aggregate in this study. However, its particle size is much lower than that of sand and closer to that of a filler. In addition, although the total impact of the mixtures increased (Figure 3), this increase was due to the increase in the SP consumption and cement of mixtures. Therefore, due to its use in the substitution contributing to an increase in compressive strength, a reduction of approximately 50% of the impact intensity index can be noted (Figure 5).

The LF had a beneficial impact on the reduction of the total impact (Figure 3) for studies 5, 7, 8 and 14, but for the reduction of the impact intensity, its influence was not significant (Figure 5). This result is due to SCM not having cementing or pozzolanic properties and thus not contributing to a significant increase in compressive strength; instead, it acts only as a filler, filling the pores when added to the mixture at low concentrations.

Figure 5 – Impact intensity (mPt) of the different mixtures



The studies in which the impact of the mixtures increased in relation to the control were studies 1, 3, 10, 11 and 13. The largest increase, of approximately 370% of the impact intensity, was observed in study 1 due to the use of CR as an aggregate, which causes a significant reduction in compressive strength, and of MK as SCM, which has a high impact per mass (Figure 2), although it helps increase compressive strength. In study 10, despite the use of AF and GBFS as SCM, the impact intensity increased by up to approximately 70%, also due to the use of CR as an aggregate. In study 11, the use of ASA as an aggregate, which has cement in its composition, did not have a significant influence on compressive strength, which compensated for its increase in the total impact.

Reductions in impact intensity were not observed in studies 3, 7 and 13, as in the total impact analysis. In study 3, this lack of a reduction is due to the use of PETW, which negatively affects the compressive strength of the concrete mixtures, increasing the impact intensity indicator by up to 100%, despite the positive effect of increased strength and impact reduction caused by SF and FA. In study 7, a greater replacement of cement by FA combined with LF did not obtain compressive strength results as high when compared with the mixtures with higher cement content. However, it was still possible to obtain mixtures in which this indicator was reduced by approximately 15% compared to the control. The use of RG instead of cement (study 13) was significant for reducing the total impact and global warming indicators, mainly due to the reduction in cement consumption. However, due to its deleterious effect on concrete strength, its impact intensity was greater than the control mixture, increasing by up to 16%. In studies 12 and 15, RG was used instead of the aggregates, and SF and FA were used as SCMs, respectively. Thus, it was possible to keep the impact intensity constant (study 15), or an alternated variation was obtained (study 12), with an increase and decrease in the indicator due to the variation in cement consumption.

Studies 4, 8 and 15 obtained the lowest total impacts for the control mixtures, and there was no significant variation in the indicator. The use of FA and also its replacement by RM allowed a low consumption of cement (study 4) without compromising the compressive strength of the concrete. The use of LF as an SCM and RC in total gravel replacement (study 8 and 14) also allowed a low consumption of cement with good mechanical properties of the mixtures. Moreover,

the use of FA as SCM and replacement of sand by RG (study 15) also resulted in mixtures with good mechanical properties and low environmental impact.

3.5 Analysis of the most impactful processes

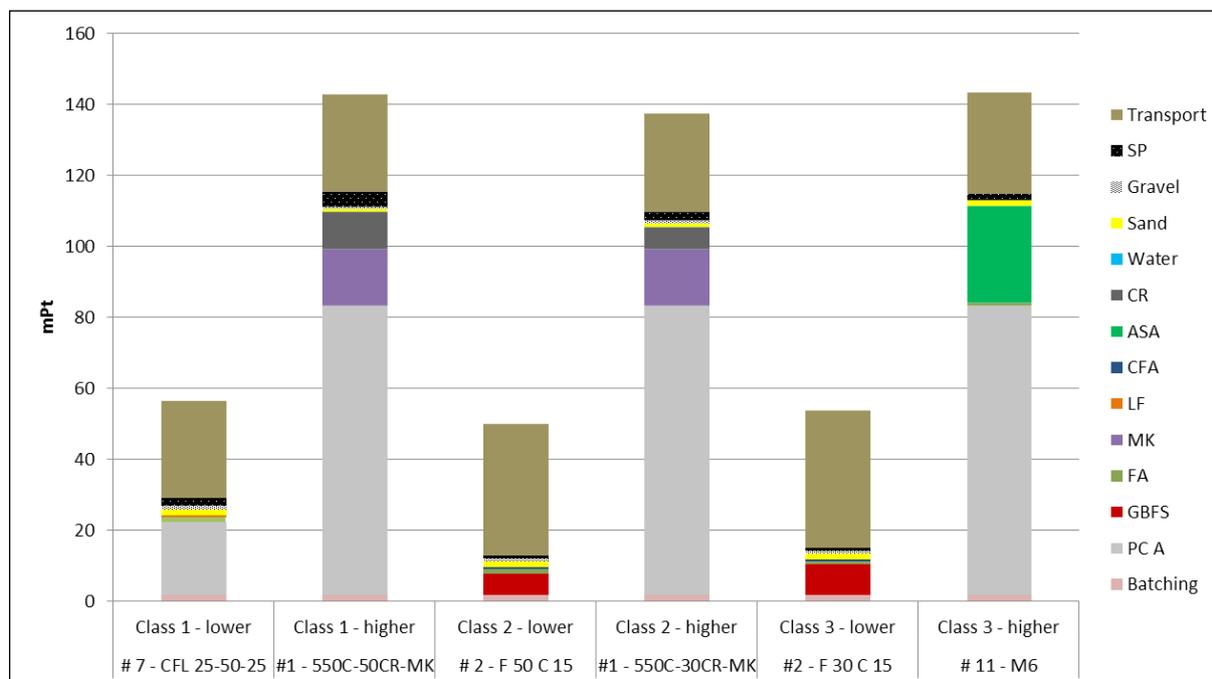
To perform the analysis of the most impactful impacts by process/material, the mixtures were divided into three strength classes, as specified in Table 5, and the mixtures with the smallest and greatest total impacts were considered. In this analysis, the results will be presented while mentioning the numbers of the article listed in Table 1 and the name referring to the mixture given by the author of the article in question.

Table 5 – Number of mixtures by compressive strength class

STRENGTH CLASS	COMPRESSIVE STRENGTH	NUMBER OF MIXTURES
Class 1	15 to 35 MPa	77
Class 2	35 to 50 MPa	31
Class 3	50 to 80 MPa	54

Figure 6 shows the proportion represented by each component of the mixture with the lowest and highest total environmental impact of each strength class. It is observed that the most striking processes in the mixtures with the greatest environmental impact are cement production (57% average) and transportation (20% average), totaling 77% of the total impact of the mixtures. The additions of some AMs, such as MK, CR and ASA, also represented a high impact, on average 11, 5 and 19%, respectively. In the case of MK, its allocation as a product causes it to bear all the environmental impact from the materials extraction related to its production, not behaving like a good material to minimize the environmental impacts of concrete. In the case of CR, although it is a recycled product, its recycling process involves many steps and high energy consumption. Finally, in the case of ASA, although it is a byproduct, its process involves cement and energy consumption; therefore, it also does not behave as a good material to minimize environmental impacts.

Figure 6 – Total impact of the different mixtures by process/material



Mixtures using SCMs (GBFS, FA, LF and CFA) as partial or total cement replacement exhibited the best environmental performance (Figure 6). The class 1 mixture (study 7) contains cement, whereas class 2 and 3 mixtures (study 2) do not contain cement. In the first case, the most relevant processes are transportation, with 48%, and cement production, with 36%. In the second case, transportation is the most relevant process, representing more than 70% of the total impact. The impact of GBFS in the latter case is relevant because its allocation as a byproduct allows it to bear part of the impact of steel production. In the mixtures with a large representation of transportation, the responsibility of minimizing impacts requires analysis of transportation logistics and the modes of transportation used.

4 Conclusions

The influence of the incorporation of 14 different alternative materials in self-compacting concrete mixtures was evaluated, based on the results of 15 different studies, from the point of view of the environmental impacts of the production process for a specific US scenario. The following conclusions can be drawn:

1 - Mixtures with low environmental impact are characterized by the use of products, wastes or

byproducts classified as SCMs (GBFS, FA, LF and CFA) in partial or total replacement of cement. These mixtures also exhibit good compressive strength performance. The use of cements with lower levels of clinker/cement also provided relevant environmental gains. The use of SF improves the environmental performance of the mixtures, but this was not as evident as for the other SCMs due to the combination with other AMs that deteriorate the properties of the concrete and increase its environmental impact. The partial replacement of fine aggregates by AW, which has technical properties similar to the fillers, also provided improvements in the impact intensity indicator.

2 - The mixtures in which the use of AMs did not lead to significant improvements in environmental performance were in the studies in which wastes and byproducts were used in the partial replacement of aggregates and have similar technical properties as natural aggregates, such as the use of GR and RC, MR as SCM, and PBWF as fiber. These wastes do not provide significant improvements to the environmental characteristics of the concrete. However, their use in concrete is characterized as an alternative source of disposal of the waste in question, not for the purpose of improving the environmental characteristics of the concrete. The use of RM in the concrete mixtures has logistical challenges due to the large transportation

distance in the studied scenario, although it appears as an alternative to its final disposal.

3 - The mixtures with the greatest environmental impact are characterized mainly by a high consumption of cement and the use of MK. MK worsens the environmental performance because it requires a lot of energy, like cement, for its production. In addition, mixtures that use PETW, CR and ASA as partial or total replacement of natural aggregates did not have good environmental performance. These wastes confer poor environmental characteristics to the concrete, as they incur high energy costs for their treatment or recycling. In addition, they confer technical losses and losses in compressive strength, explaining the higher cement levels used and the addition of MK in an attempt to overcome the losses in the technical properties. The use of these materials goes against the logic of eco-efficiency.

4 - In most studies regarding the environmental assessment of concretes, global warming is the most-analyzed category. Although the impact of global warming is highly relevant to the total impact of materials, and the overall impact analysis is largely consistent with the global warming analysis alone, an analysis focused only on this impact category may conceal other important insights from the assessment.

5 - The high consumption of cement, high content of clinker/cement and high dependence on the transportation of materials in the processes and operations, that is, the logistics of the suppliers, are the major contributions to concrete's environmental impact. LCA is an efficient method to compare possible scenarios to seek a logistic optimization between concrete suppliers and producers to facilitate the decision-making process for ecological criteria.

6 - This study provides a method to assist the construction industry in choosing sustainable concrete, minimizing environmental damage and promoting sustainable waste management. Mixtures with alternative materials had their environmental impacts of production quantified, and the best and worst options were identified. This comparison of concrete mixtures, which are called eco-concrete, can help clarify and quantify more precisely the environmental impacts and thus promote green construction.

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