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EFFECT OF USING BIOMASS FLY ASH ON THE CONCRETE SUSTAINABILITY

Elisabete Rodrigues Teixeira[a,*], Aires Camões[b], Fernando G. Branco[c]

[a] *University of Minho, ISISE, Department of Civil Engineering, Guimarães, Portugal*

[b] *CTAC, Department of Civil Engineering, School of Engineering, University of Minho, Campus de Azur'em, 4800-058 Guimarães, Portugal*

[c] *University of Coimbra, ISISE, Department of Civil Engineering, Coimbra, Portugal*

[*] corresponding author: b8416@civil.uminho.pt

Abstract.

Biomass fly ash has been studied has a partial cement material, since this material has a positive effect on concrete properties. Even though, some mixes with BFA presents a positive benefit, they need to be economically competitive and present a good environmental performance. So, the analyse and comparison of concrete that uses BFA as raw material substitution in terms of environmental impacts related to the production of conventional concrete. One of the best approaches to develop this type of study is to use the life cycle assessment (LCA) method. This method quantifies both the input flows, such as energy, water and materials, as well as the output flows, such as CO_2 emission, solid wastes and liquid wastes. Based both on the abovementioned context and methodological approach, a quantification and comparison of potential environmental impacts resulting from the production of 1 m^3 of concrete was made, using different types of binder and quantities of cement substitution.

Keywords: Life cycle analysis, sustainability, wastes.

1. Introduction

Biomass fly ash (BFA) has an effect on concrete properties, presenting similar results to concrete with traditional pozzolanic materials such as coal fly ash [1]. Moreover, the analysis of the potential environmental impacts related to the production of a concrete that uses BFA as raw material substitution is mandatory. This analysis needs to be compared with the production of plain cement concrete. One of the best approaches to develop this type of study is using the life cycle assessment (LCA) method [2]. This method enables the quantification of the potential environmental impacts of products or services. It quantifies both the input flows, such as energy, water and materials, as well as the output flows, such as CO_2 emission, solid wastes and liquid wastes [3]. LCA allows estimating the potential impact on humans and nature and enables identifying areas with improvement potential [3]. Based both on the abovementioned context and methodological approach, a quantification and comparison of potential environmental impacts resulting from the production of 1 m^3 of concrete was made, using different types of binder: i) Portland cement; ii) Portland cement and CFA or/and BFA, iii) Portland cement and CFA and HL; and iv) Portland cement, CFA, BFA and HL. This work was presented for the defence of the first author PhD degree and it is presented in [4].

2. Methods and Methodology

2.1. Goal and Scope

The main goal of this study was to evaluate the environmental performances of various concrete formulations using biomass fly ash as a cement replacement material (Table 1) [4]. The method used in this study followed the phases of an LCA. The use of LCA is done according to the ISO 14040 standard, which provides a consensual framework, terminology and methodological phases [3]. The implementation of this method is based on four major phases: i) goal and scope definition; ii) inventory analysis; iii) impact assessment; and iv) interpretation [3]. The goal and scope express the purpose, objectives, product system, boundaries and functional unit. In the inventory analysis, the data necessary to analyse the life cycle of the product is collected. In the impact assessment, the life cycle inventory (LCI) flows are classified, characterized and normalized, using one of many possible Life Cycle Impact Assessment (LCIA) methodologies to estimate the potential environmental impacts. The last phase, interpretation, is very important to : i) identify, quantify and evaluate the information that results from the last two phases; ii) communicate the information in a correct way; and iii) recommend improvements within the analysed system [3, 4].

The comparative analysis and the aggregation of indicators were developed using the multicriteria decision support Methodology for the Relative Sustainability Assessment of Building Technologies (MARS-SC) [5]. The MARS-SC methodology is

Concrete Mix	%wt				w/b
	Cement	BFA	CFA	HL	
REF	100.0	0.0	0.0	0.0	0.50
CFA20	80.0	0.0	20.0	0.0	0.50
BFA20	80.0	20.0	0.0	0.0	0.50
CFA40	60.0	0.0	40.0	0.0	0.50
BFA40	60.0	40.0	0.0	0.0	0.50
CFA50	50.0	0.0	50.0	0.0	0.50
CFA50b	50.0	0.0	50.0	0.0	0.35
BFA50	50.0	50.0	0.0	0.0	0.5
CFA60	40.0	0.0	60.0	0.0	0.5
BFA60	40.0	60.0	0.0	0.0	0.5
CFA49.5HL0.5	50.0	0.0	49.5	0.5	0.35
CFA49.5BFA0.5	50.0	0.5	49.5	0.0	0.35
CFA48.8BFA1.3	50.0	1.3	48.8	0.0	0.35
CFA45BFA5	50.0	5.0	45.0	0.0	0.35
CFA48.8BFA0.6HL0.6	50.0	0.6	48.8	0.6	0.35

Table 1. Binder fraction and water/binder ratio used in the concrete formulations [4].

based on three groups of sustainability categories: environmental, functional and economic [6]. Since this research aimed at assessing the environmental performance of different concrete formulations, only the environmental category of MARS-SC was considered. The MARS-SC methodology is processed in five steps: i) definition of the sustainability indicators; ii) quantification of the indicators (including the life cycle inventory); iii) normalization of the indicators; iv) aggregation of the indicators; and v) sustainable score calculation and global assessment [5].

2.2. System Boundaries and Functional Unit

The boundaries of this work mark the embodied environmental impacts (cradle-to-gate) of the different concrete compositions as well as the environmental impacts that result from the transportation of the materials to the concrete plant and their mixing. The choice of limiting the study to the cradle-to-gate stage is justified by the fact that, in the studied compositions, the use and disposal of concrete will result in similar environmental impacts [4]. The declared functional unit is dependent on the goal of life cycle analysis and therefore constitutes 1 m^3 of concrete.

2.3. Inventory Analysis

To quantify the sustainability indicators, it is necessary to first develop the inventory analysis [6]. The inventory is used to quantify the inputs (e.g. energy, materials and chemical) and outputs (e.g. emissions and wastes) of the product system [7].)

Table 2 shows the inventory of the materials and transportation considered for each concrete formulation [4]. This inventory took into consideration the specific context of the Portuguese concrete industry. The life cycle analysis software SimaPro 7.3.3 was used to facilitate the quantification of the impact categories. In this study, the specific consumption of raw materials, energy and fuels and the emissions released to air, water and soil during the cement production of an important Portuguese cement plant, located in the south of Portugal, was considered. The data used are described in the public Environmental Declaration [8] of this cement plant. For this research, it was considered that this plant supplied the cement used for the preparation of the different concrete formulations. It was necessary to quantify the impact categories, since the environmental declaration did not cover all impact categories necessary for this study, being limited to those mandatorily declared according to Portuguese environmental legislation [4]. Using the inventory listed in the environmental declaration, the SimaPro software was used to assess the potential environmental impacts of the used Portland cement. Regarding each type of fly ashes, it was necessary to make the allocation of flows of the power plant according to the place of production. Allocation is necessary in the case of joint coproduction, where the processes cannot be sub-divided, as is the case in fly ashes production [9]. Allocation shall respect the main purpose of the processes studied, appropriately allocating all relevant products and functions. Since the main purpose of a thermal power plant is to produce electricity and since the difference in revenue between the electricity and the fly ashes is high, it is not possible to use an allocation process based on physical proprieties (e.g. mass and volume). Therefore, the allocation process used in this research was based on economic values [4].

Due to the environmental report [10] from a major Portuguese coal power plant (located in the centre

Formulations	PC*	Gravel	Sand	Water	SP*	CFA	BFA	HL
Material Input (kg)								
REF	350.0	969.2	738.1	200.0	0.0	0.0	0.0	0.0
CFA20	280.0	982.1	756.7	149.5	0.0	70.0	0.0	0.0
BFA20	280.0	985.3	759.1	149.4	0.0	0.0	70.0	0.0
CFA40	210.0	973.0	749.6	149.7	0.0	140.0	0.0	0.0
BFA40	210.0	979.3	754.5	149.5	0.0	0.0	140.0	0.0
CFA50	175.0	968.4	745.1	149.8	0.0	175.0	0.0	0.0
CFA50b	175.0	1044.3	804.5	88.4	8.8	175.0	0.0	0.0
BFA50	175.0	976.3	752.2	149.6	0.0	0.0	175.0	0.0
CFA60	140.0	963.8	742.5	149.9	0.0	210.0	0.0	0.0
BFA60	140.0	973.3	749.9	149.7	0.0	0.0	210.0	0.0
CFA49.5HL0.5	175.0	1049.0	768.6	91.5	5.3	173.5	0.0	1.9
CFA49.5BFA0.5	175.0	1049.0	795.2	91.5	11.4	173.5	1.9	0.0
CFA48.8BFA1.3	175.0	1050.1	842.8	35.5	11.4	170.6	4.4	0.0
CFA45BFA5	175.0	1049.5	838.9	42.4	3.9	160.0	17.8	0.0
CFA48.8BFA0.6HL0.6	175.0	1067.2	832.9	36.9	2.5	170.6	2.2	2.2
Transportation (tkm)								
REF	14.5	357.6	272.4	–	–	–	–	–
CFA20	11.6	362.4	279.2	–	–	12.4	–	–
BFA20	11.6	363.6	280.1	–	–	–	10.2	–
CFA40	8.7	359.0	276.6	–	–	24.8	–	–
BFA40	8.7	361.4	278.4	–	–	–	20.3	–
CFA50	7.3	357.3	274.9	–	–	31.0	–	–
CFA50b	7.3	385.3	296.9	–	2.9	31.0	–	–
BFA50	7.3	360.3	277.6	–	–	–	25.4	–
CFA60	5.8	355.6	274.0	–	–	37.2	–	–
BFA60	5.8	359.1	276.7	–	–	–	30.5	
CFA49.5HL0.5	7.3	387.1	283.6	–	1.7	30.7	–	0.2
CFA49.5BFA0.5	7.3	387.1	293.4	–	3.8	30.7	0.3	–
CFA48.8BFA1.3	7.3	387.5	311.0	–	3.8	30.2	0.6	–
CFA45BFA5	7.3	387.3	309.6	–	1.3	28.3	2.6	–
CFA49.5BFA0.6HL0.6	7.3	393.8	307.3	–	0.8	30.2	0.3	0.3

PC - Portland Cement; SP - Superplasticizer

Table 2. Binder Inventory results of the material and transportation inputs for each concrete (per m^3 of produced concrete) [4].

of the country), it is possible to known how many tons of coal are consumed to produce 1 kWh of electricity as well as the quantity of CFA produced during coal combustion. In Portugal, the commercial value of CFA is about 18 €/ton and the value of the electricity is 0.16 €/kWh. Therefore, the economic allocation coefficient of 0.17 % is applied to the impacts of the extraction, transportation and combustion of the coal from that power plant. As with the cement plant, this environmental report only covered the impact categories that are mandatory according to Portuguese environmental legislation. As a result, all the flows (inputs and outputs) declared in this report were introduced in the SimaPro software, taking into consideration the quantified economic allocation coefficient of 0.17 %. Regarding BFA, it is important to highlight that in Portugal this kind of fly ash is considered a waste product and therefore they do not provide an economic value. Because of this fact and according to the allocation rules presented in ISO 14040, no flows from the thermal power plant are allocated in the production of BFA. With respect to the life-cycle inventory of the other used materials (gravel, sand, water and superplasticizer), generic data was used. Since the development of specific environmental information for products is very time and cost consuming, initial LCA studies, whose main goal was to compare different design scenarios, are normally based on generic (average) data [4,6]. For this reason and due to the lack of public available specific data for the abovementioned materials, this information was gathered from one of the most internationally accredited generic environmental databases of the Ecoinvent report V2.2 [11]. The nearest context to the Portuguese one was considered for this study. Since the energy consumed during the manufacturing process is the parameter that most influences the life-cycle environmental impact [12] and since the Portuguese energy mix is different from the European average [13], a contextualization of the energy used in each process was developed. This means that all used processes from the Ecoinvent database were edited, and all energy input flows were changed to consider the Portuguese energy mix. In the inventory of the transportation processes, the study considered the distances between the Portuguese places of raw material extraction or raw materials storage facilities and the concrete mixing plant in question [4]. The distance between the raw materials production facilities and concrete production was considered for this study. The kilometres considered as the transportation distance of cement (Secil Group), sand and gravel (MIBAL - Minas de Barqueiros, S.A.), coal fly ashes (Pegop-energia Eléctrica Sa), biomass fly ash (Altri), superplasticizer (BASF) and hydrated lime (Lusical-companhia Lusitana De Cal Sa) to the concrete industry considered in this study were 41.5, 369, 177, 145, 329 and 117 km, respectively.

The inventory related to the production of concrete was quantified taking into account the Environmental Product Declaration (EPD) of a specific Portuguese concrete plant [14], where the different concrete formulations are supposedly produced. From this EPD, only the flows related to the concrete mixing phase were considered.

2.4. Impact Assessment

The life cycle inventory data was converted into potential environmental impact, using the lifecycle impact assessment (LCIA) methods. In MARS-SC, the definition of the sustainability indicators depends, above all, on the type of analysed product or building element and on the aims of the study. In this method, the environmental performance assessment is based on the following six environmental impact categories: i) Global warming; ii) Ozone depletion; iii) Acidification of soil and water; iv) Eutrophication; v) Photochemical ozone creation; and vi) Depletion of abiotic resources-fossil fuels. Compared with the list of impact categories found in the EN15804:2012 [15] standard, MARS SC does not consider the Depletion of abiotic resources-elements as an impact category.

2.5. Normalization, Aggregation and Global Assessment

To avoid the scale effects in the aggregation of parameters of the different indicators and in order to minimize the possibility that some of the parameters are of the type. higher is better and lower is bad, it was necessary to normalize the indicators [15]. The normalization was done using the Diaz-Balteiro [16]. After normalization, is important to calculate the aggregation of each environmental indicator in terms of a global indicator, describing the overall environmental performance (NDA). The global indicator NDA results from the weighting average of each normalized. The sum of all weights must be equal to 1. For aggregation purposes, this study considers the weights (Table 3) set in a study developed by the US Environmental Protection Agency's Science Advisory Board (SAB) [17]. In each sustainable profile, the global performance of a respective concrete with fly ash was monitored and compared with that of the reference concrete.

Indicator	Weight (%)
GWP	38
ODP	12
AP	12
EP	12
POCP	14
ADP_FF	12

Table 3. Weight for each environmental indicator [17].

3. Results and Discussion

Table 4 summarizes the values obtained in the quantification of the environmental impact categories, related with the production of the different concrete mixes. Analysing the results, when it used just cement as binder, concrete presents the highest values of CO_2 emission. The high emission of CO_2 is a result of the chemical reactions (calcination) that occur during clinker production [4,18].

The incorporation of the BFA blended with CFA allows a reduction in all environmental impacts, moreover the environmental impacts decrease with increasing of cement substitution. At this stage, it is necessary to highlight the effect of the allocation step on the obtained results. In Portugal, BFA are considered a waste product without economic value [18] and therefore there are no flows from the biomass power plant allocated to its production [4]. The same does not happen with CFA, as they have a market value and consequently a percentage of the power plant's flows is allocated to their production [19]. Concrete mixes 0.5%wt and 1.3%wt of BFA decreased the environmental impact related with the CO_2 emissions but an increase on the values of the others environmental indicators was observed [4]. This is a not result of the incorporation of BFA, since this result is not noted in the mixes with 5, 20, 40 and 60%wt, but it is due to the fact of these two mixes presented a higher superplasticizer content. It was concluded in other studies that superplasticizer had high influence on e.g. ODP and ADP_FF impact categories, but did not have a significant influence on GWP that most influences the overall environmental impact concrete with ashes, which confirm the results achieved in this study [4]. The normalization of the values obtained for each environmental impact category was obtained and the

Formulations	GWP100 kg ($\times 10^2$)	ODP kg ($\times 10^{-5}$)	AP kg	EP kg ($\times 10^{-1}$)	POCP kg ($\times 10^{-2}$)	ADP_FF kg ($\times 10^3$)
REF	4.02	2.67	1.00	2.53	4.00	2.71
CFA20	3.44	2.55	0.91	2.32	3.64	2.56
BFA20	3.44	2.55	0.91	2.27	3.64	2.53
CFA40	2.83	2.38	0.80	2.08	3.23	2.36
BFA40	2.83	2.38	0.80	1.98	3.22	2.30
CFA50	2.53	2.30	0.75	1.96	3.02	2.26
CFA50b	2.88	2.69	0.90	2.41	3.97	3.10
BFA50	2.53	2.29	0.75	1.83	3.01	2.18
CFA60	2.23	2.21	0.69	1.84	2.82	2.16
BFA60	2.23	2.21	0.69	1.69	2.80	2.07
CFA49.5HL0.5	2.75	2.53	0.84	2.22	3.55	2.77
CFA49.5BFA0.5	2.96	2.77	0.94	2.51	4.20	3.31
CFA48.8BFA1.3	2.99	2.85	0.95	2.54	4.26	3.36
CFA45BFA5	2.75	2.59	0.85	2.22	3.57	2.73
CFA48.8BFA0.6HL0.6	2.73	2.57	0.83	2.18	3.46	2.64

Table 4. Values obtained for the different environmental impacts.

Formulations	GWP100 [kg CO_2 eq]	ODP [kg CFC-11 eq]	AP [kg SO_2 eq]	EP [kg PO_4 eq]	POCP [kg C_2H_4 eq]	ADP_FF [MJ eq]
REF	0.00	0.24	0.00	0.01	0.18	0.50
CFA20	0.32	0.44	0.30	0.26	0.42	0.62
BFA20	0.32	0.44	0.31	0.32	0.43	0.65
CFA40	0.66	0.72	0.65	0.54	0.71	0.78
BFA40	0.66	0.72	0.65	0.66	0.71	0.82
CFA50	0.83	0.86	0.82	0.68	0.85	0.85
CFA50b	0.64	0.20	0.32	0.16	0.20	0.20
BFA50	0.83	0.86	0.83	0.83	0.86	0.91
CFA60	1.00	0.99	0.99	0.82	0.99	0.93
BFA60	1.00	1.00	1.00	1.00	1.00	1.00
CFA49.5HL0.5	0.71	0.47	0.52	0.37	0.49	0.46
CFA49.5BFA0.5	0.59	0.09	0.21	0.04	0.04	0.03
CFA48.8BFA1.3	0.58	0.00	0.17	0.00	0.00	0.00
CFA45BFA5	0.71	0.37	0.50	0.38	0.47	0.49
CFA48.8BFA0.6HL0.6	0.72	0.41	0.54	0.42	0.55	0.56

Table 5. Normalized values of the studied environmental impact categories [4].

results are presented in Table 5. This enables a better perception of which of the concretes has a better environmental performance. It is observed that, concrete in which 60% BFA had the best environmental performance, being REF and CFA48.8BFA1.3 the mixes that presented the lowest environmental performance.

Figure 1 present the sustainability profiles and the overall environmental performances. At the level of each impact category, the best concrete is the one that has the value closest to one. It is verified that the BFA60 concrete presented the best environmental performance ($ND_A = 1.00$) and plain cement concrete (REF) presented the worst performance ($ND_A = 0.12$) [4].

Therefore, these results allow the conclusion that using a high content of BFA significantly increases the environmental performance of concrete production, since the overall environmental performance of concrete is improved. Additionally, the usage of these materials contributes to a better compatibility between the construction sector and the goals of Sustainable Development [4].

4. Conclusions

BFA used alone or blended displayed a capability to reduce the environmental impacts of concrete, when compared to conventional concrete. The results showed that 60% of BFA presented the best results. Besides the good results observed, it is important to refer that the concrete formulations with 0.5 and 1.3%wt of BFA presented a low environmental performance, but better than that of plain cement concrete. The environmental issues related with

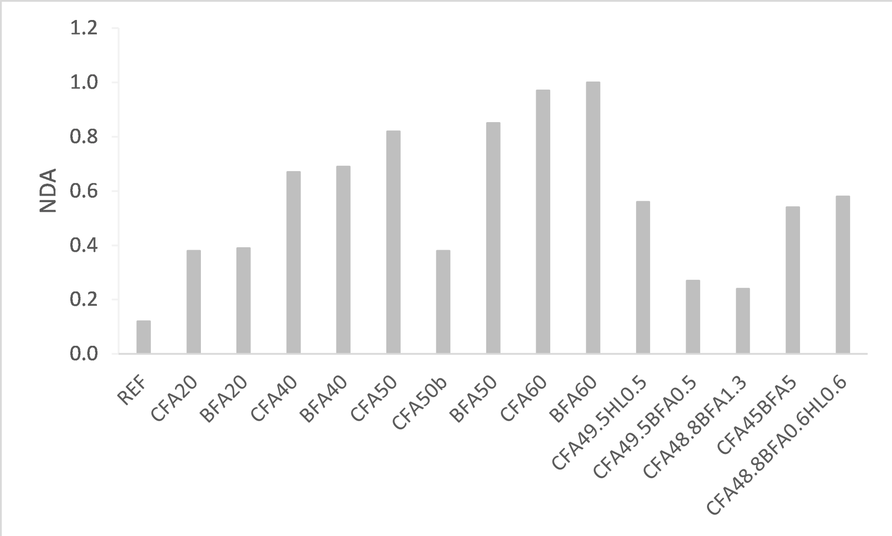

Figure 1. Normalized values that described the sustainability profile.

these two concrete formulations are due to the use of a higher content of superplasticizer when compared with the other formulations. The effect of superplasticizer on the environmental indicators is known, but the results showed that it is possible to slightly reduce the content of SP, without having a significant effect on the workability, maintaining the values similar to those of the concrete formulation with 5%wt of BFA [4]. The decrease of the content of SP has an important contribution on the improvement of environmental performance of these two concrete mixes.

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References

[1] R. Rajamma, L. Senff, M. J. Ribeiro, et al. Biomass fly ash effect on fresh and hardened state properties of cement based materials. *Composites Part B: Engineering* **77**:1-9, 2015. https://doi.org/10.1016/j.compositesb.2015.03.019.

[2] R. Feiz, J. Ammenberg, L. Baas, et al. Improving the CO2 performance of cement, part I: utilizing life-cycle assessment and key performance indicators to assess development within the cement industry. *Journal of Cleaner Production* **98**:272-81, 2015. https://doi.org/10.1016/j.jclepro.2014.01.083.

[3] K. Celik, C. Meral, A. Petek Gursel, et al. Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended portland cements containing fly ash and limestone powder. *Cement and Concrete Composites* **56**:59-72, 2015. https://doi.org/10.1016/j.cemconcomp.2014.11.003.

[4] E.R. Teixeira, High Volume Coal and Biomass Fly Ash Eco-Efficient Concrete, School of Engeneering, University of Minho, 2019.

[5] J. Fernandes, R. Mateus, L. Bragança. The potential of vernacular materials to the sustainable building design, in: Vernac. Herit. Earthen Archit. Contrib. Sustain. Dev., p. 623-629, 2013. https://doi.org/10.1201/b15685.

[6] R. Mateus, S. Neiva, L. Bragança, et al. Sustainability assessment of an innovative lightweight building technology for partition walls - Comparison with conventional technologies. *Building and Environment* **67**:147-59, 2013. https://doi.org/10.1016/j.buildenv.2013.05.012.

[7] X. Li, Y. Zhu, Z. Zhang. An LCA-based environmental impact assessment model for construction processes. *Building and Environment* **45**(3):766-75, 2010. https://doi.org/10.1016/j.buildenv.2009.08.010.

[8] S.A. Secil - Compania Geral de Cal e Cimentos, Secil Outão - Environmental Declaration, (2013).

[9] P. Van den Heede, N. De Belie. Environmental impact and life cycle assessment (LCA) of traditional and green concretes: Literature review and theoretical calculations. *Cement and Concrete Composites* **34**(4):431-42, 2012. https://doi.org/10.1016/j.cemconcomp.2012.01.004.

[10] Central Termoeléctrica do Pego, Environmental Declaration, 2011.

[11] R. Hischier, B. Weidema, H. Althaus, et al, Implementation of Life Cycle Impact Assessment Methods. ecoinvent report No. 3, v2.2 2010. https://ecoinvent.org/wp-content/uploads/2020/08/201007_hischier_weidema_implementation_of_lcia_methods.pdf.

[12] F.P. Torgal, S. Jalali. Eco-efficient Construction and Building Materials: Life Cycle Assessment (LCA), Eco-Labelling and Case Studies, Woodhead Publishing Series in Civil and Structural Engineering, 2011. https://doi.org/10.1007/978-0-85729-892-8.

[13] F.P. Torgal, S. Jalali, Construção Sustentável . O Caso Dos Materiais Deconstrução, Congr. Construção 2007 - 3o. Congr. Nac., p. 1-10, 2007. https://repositorium.sdum.uminho.pt/bitstream/1822/7542/1/Artigo%204.pdf.

[14] CONCRETOPE - Fabrica de Betão pronto S.A, Environmental Product Declaration for Ready-mixed concrete, (2005).

[15] CEN EN 15804:2012. Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products, CEN:Brussels, 2012.

[16] L. Díaz-Balteiro, C. Romero. In search of a natural systems sustainability index. *Ecological Economics* **49**(3):401-5, 2004. https://doi.org/10.1016/j.ecolecon.2004.02.005.

[17] EPA Science Advisory Board, Toward Integrated Environmental Decision-Making, Washington, DC, United States. EPA-SAB-EC-00-011, 2000.

[18] E. R. Teixeira, R. Mateus, A. F. Camões, et al. Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material. *Journal of Cleaner Production* **112**:2221-30, 2016. https://doi.org/10.1016/j.jclepro.2015.09.124.

[19] D. García-Gusano, D. Garraín, I. Herrera, et al. Life Cycle Assessment of applying CO2 post-combustion capture to the Spanish cement production. *Journal of Cleaner Production* **104**:328-38, 2015. https://doi.org/10.1016/j.jclepro.2013.11.056.