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Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material

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ABSTRACT

Nowadays, the concrete production sector is challenged by attempts to minimize the usage of raw materials and energy consumption, as well as by environmental concerns. Therefore, it is necessary to choose better options, e.g. new technologies or materials with improved life-cycle performance. One solution for using resources in an efficient manner is to close the materials' loop through the recycling of materials that result either from the end-of-life of products or from being the by-product of an industrial process. It is well known that the production of Portland cement, one of the materials most used in the construction sector, has a significant contribution to the environmental impacts, mainly related with carbon dioxide emission. Therefore, the study and utilization of by-products or wastes usable as cement replacement in concrete can supply more sustainable options, provided that these types of concrete produced has same durability and equivalent quality properties as standard concrete.

This work studied the environmental benefits of incorporating different percentages of two types of fly ashes that can be used in concrete as cement replacement. These ashes are waste products of power and heat production sectors using coal or biomass as fuels. The results showed that both ashes provide a benefit for the concrete production both in terms of environmental impact minimization and a better environmental performance through an increase in cement replacement. It is possible to verify that the incorporation of fly ashes is a sustainable option for cement substitution and a possible path to improve the environmental performance of the concrete industry.

1. Introduction

The construction industry is an important economic sector in the European Union. This sector affords 20 million direct jobs and generates 10% of the gross domestic product (Commission, 2014). It is responsible for the creation of new jobs, leads to economic growth and allows for the development of solutions to the challenges related to society, climate and energy (Commission, 2014). In sum, the construction industry's output is an important part of the overall national output, being responsible for a significant proportion of the gross domestic product of developed and underdeveloped countries (Crosthwaite, 2000). The economic share of the construction industry is in the range of 7–10% for developed economies and 3–6% for underdeveloped economies (Wibowo, 2003).

Concrete is the material most used in the construction sector (Galvez-Martos and Schoenberger, 2014; Gartner, 2004; Meyer, 2009), exceeded only by water. This is due to the fact that concrete presents good mechanical and durability properties, is moldable, adaptable, significantly fire resistant, as well as available in most parts of the globe and is affordable (Meyer, 2009).

Concrete is essentially composed of cement, gravel, sand, water and additives (Flower and Sanjayan, 2007). The production of cement uses large quantities of raw materials and energy. Additionally, the production releases large amounts of CO_2 into atmosphere, contributing to the environmental problems associated with greenhouse gases emission (Ammenberg et al., 2014; Chen et al., 2010; Damtoft et al., 2008; Feiz et al., 2014; Flower and Sanjayan, 2007; Galvez-Martos and Schoenberger, 2014; Huntzinger and Eatmon, 2009; Josa et al., 2007; Meyer, 2009). The

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cement type most used in concrete production is the Portland cement and more than 90% of it is comprised of a material called clinker (Feiz et al., 2014; Galvez-Martos and Schoenberger, 2014).

Clinker is the product that results from limestone combustion at high temperatures in a cement plant (Feiz et al., 2014; Habert and Roussel, 2009; Habert et al., 2010). During this process, calcium carbonate is decomposed into CaO and CO_2, a process termed "calcination". This process is very important in relation to the question of greenhouse gas emissions, since during the calcination, the carbon present in the materials is released as CO_2 (Feiz et al., 2014; Flower and Sanjayan, 2007; Habert et al., 2010). Some of the CO_2 released is re-absorbed from the atmosphere by the concrete during its carbonation (Flower and Sanjayan, 2007). In this case, the lime present in the concrete pores reacts with the CO_2 present in the atmosphere and produces calcium carbonate (Flower and Sanjayan, 2007). However, during the lifetime of concrete only a very small quantity of CO_2 is re-absorbed. In most cases, this reabsorption's contribution to the life-cycle calculations of CO_2 emission of concrete is consequently not taken into account (Flower and Sanjayan, 2007).

Cement is also responsible for needing considerable thermal energy quantities, mostly used in the calcination of calcium carbonate, but also in the cooling process of clinker and carbon dioxide released from sodium carbonate (Galvez-Martos and Schoenberger, 2014).

To reduce the downsides related to the production of typical concrete, several studies have been dealing with the incorporation of other products that result in a type of concrete with the same properties but lower environmental impact (Chen et al., 2010; Damtoft et al., 2008). Some of these have been developed with the main objective of trying to use by-products that have similar behavior and characteristics to the raw materials (e.g. cement) used to produce typical concrete (Habert and Roussel, 2009). The introduction of residues (materials that are produced as by-products in industrial processes from the construction sector or other economic sectors) as substitutes of the cement appears as a good solution for cement substitution (Meyer, 2009).

Several thermoelectric plants use coal to produce electricity. The combustion of coal generates a significant quantity of residues namely fly ashes. The fly ashes have low particle size and are entrained with the combustion gases and captured in the air emission control devices. It is well known that coal fly ash is considered a pozzolanic material and has been used in concrete since the 1950s or 1960s (Sear, 2001). In comparison with Portland cement, these ashes have several advantages: a lower heat of hydration, their existence as by-products, some concrete presents better strength and durability properties than concrete produced only with cement; and, finally, their use is cheaper than of cement (Meyer, 2009).

In Portugal, the use of renewable resources, such as biomass for heat and power production has been increasing (Tarelho et al., 2012). The thermo-chemical conversion of biomass is done by combustion (Barbosa et al., 2013). However, during biomass combustion, a high quantity of ashes is produced and this quantity has been increasing more in the last years due to the larger amounts of biomass used (Tarelho et al., 2012). Biomass fly ashes are classified as solid waste and are in most cases disposed in landfills. Nevertheless, the actual disposal context has important environmental, societal and economic impacts (Tarelho et al., 2012).

Previous studies show that the use of pozzolanas from biomass in concrete could have positive results (Barbosa et al., 2013; Cheah and Ramli, 2011; Cordeiro et al., 2009; Rajamma et al., 2009; Wang et al., 2008). The use of biomass fly ashes as partial cement substitution leads to a minimization in the use of raw materials used in cement production (Tarelho et al., 2012), a mitigation of greenhouse gases emissions and to a better solution for environmental and economical ash manage ment.

Therefore, it is important to analyze and compare the potential environmental impacts related to the production of plain cement (PC) concrete and the impacts resulting from the production of a concrete that uses residues as raw material substitution. One of the best approaches to develop this type of study is to use the life cycle assessment (LCA) method (Feiz et al., 2014). This method makes possible 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 (Celik et al., 2015; Chau et al., 2015). The LCA allows for estimating the potential impact on humans and nature and enables identifying areas with improvement potential (Celik et al., 2015).

The use of LCA is done according to the ISO 14040 standard, which provides a consensual framework, terminology and methodological phases (Celik et al., 2015). 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 (Celik et al., 2015; Chau et al., 2015). The goal and scope express the purpose, objectives, product system, boundaries and functional unit. In the inventory analysis, the data necessary to analyze 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 analyzed system (Celik et al., 2015; Rajamma et al., 2009).

The environmental impact of concrete with wastes or by-products was studied by several authors (Ahlman et al., 2015; Celik et al., 2015; De Schepper et al., 2014; Dosho, 2007; Flower and Sanjayan, 2007; Ondova and Estokova, 2014; Schuurmans et al., 2005). Some studies showed that the environmental impact of concrete production is strongly related to the binder content (De Schepper et al., 2014). The use of wastes as cement replacement allows the production of more environmentally friendly concrete (Celik et al., 2015; Ondova and Estokova, 2014; Schuurmans et al., 2005). The use of by-products, such fly ash, leads to significant CO_2 emission reduction, reduces the disposal areas of those materials and increases the lifetime of concrete structures. Flower and Sanjayan concluded that the use of fly ashes can reduce the CO_2 emissions by 13–15%, compared with typical concrete (Flower and Sanjayan, 2007). Turk et al. (2015) studied the environmental performance of concretes with several by-products from different industrial processes and compared the results with the performance of conventional concrete. Compared to conventional concrete, this study allowed concluding that it is possible to reduce the environmental impacts in about 75% in concrete with fly ash, 85% on concrete with foundry sand and between 65 and 95% in concrete with steel slag.

Based both in the abovementioned context and methodological approach, the main goal of this study was to quantify and compare the potential environmental impacts resulting from the production of 1 m^3 of concrete, using different types of binder: i) Portland cement; ii) Portland cement and coal fly ashes, iii) Portland cement and biomass flay ash; iv) and Portland cement, coal and biomass fly ashes.

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2. Studied concrete formulations

Concrete is a material that is typically composed by a proportional mixture of aggregates (sand and gravel), hydraulic binder (cement), water and, sometimes, by an admixture or/and additions (Guerra, 2008). Nevertheless, nowadays the market is challenging the concrete industry to develop new types of concrete with improved environmental life-cycle performance. Therefore, there is a vast field of research within the study of the effects of using other materials to improve the concrete performance. For that, this study compares the environmental performance of concretes with incorporation of biomass fly ash, coal fly ash or a blend of the two ashes (with equal mass content) as cement substitution in a typical concrete (reference).

The formulations studied in this work are composed by a water-binder (w/b) ratio of 0.5 and a binder (sum of cement and fly ashes) content of 350 kg/m^3 and are presented in Table 1. In this study, three percentages of cement substitution (20, 40 and 60%) were studied. These values were chosen because several studies showed good results in terms of mechanical and durability properties for concretes with up to 60% weight (wt) of cement replacement by coal and/or biomass fly ashes (Chusilp et al., 2009; Horsakulthai et al., 2011; Sata et al., 2007; Sua-Iam and Makul, 2014).

In the first mixture (FA0), the processes necessary to produce a PC concrete (only with Portland cement as binder) are considered and this concrete was used as the reference (for the other concretes). In the mixtures C_FA20, C_FA40, and C_FA60 (coal fly ashes – Table 1) and B_FA20, B_FA40 and B_FA60 (using biomass fly ashes) the processes necessary to produce a concrete with partial cement substitution were considered. The last three mixtures (CB_FA20, CB_FA40 and CB_FA60 in Table 1) are related to the study of environmental impact, attempting to produce a concrete with partial cement substitution through a blend of the two types of ashes (at an equal mass content).

3. Methodology

3.1. Goal and scope

The main goal of this study was to evaluate the environmental performances of the various concrete formulations using fly ash as a cement replacement. The method used in this study followed the phases of a LCA. The comparative analysis and the aggregation of indicators were developed using the multi-criteria decision support Methodology for the Relative Sustainability Assessment of Building Technologies (MARS-SC) (Mateus and Bragança, 2010; Mateus et al., 2013). The MARS-SC methodology is based on three groups of sustainability categories: environmental, functional and economic (Mateus et al., 2013). Since this research aimed at assessing the environmental performance of different concrete formulations, only the environmental category of MARS-SC was considered.

Table 1
Binders fraction used in the concrete formulations.

Concrete mixture ID	%wt		
	Cement	Biomass fly ash	Coal fly ash
FA0	100	0	0
C_FA20	80	0	20
C_FA40	60	0	40
C_FA60	40	0	60
B_FA20	80	20	0
B_FA40	60	40	0
B_FA60	40	60	0
CB_FA20	80	10	10
CB_FA40	60	20	20
CB_FA60	40	30	30

The MARS-SC methodology is processed in five steps (Fig. 1): 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 (Mateus and Bragança, 2010; Mateus et al., 2013).

3.1.1. Functional unit and system boundaries

In this study the object of analysis is concrete. The MARS-SC methodology allows for assessing all different life-cycle stages (Mateus and Bragança, 2010; Mateus et al., 2013). However, 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 to limit 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. The declared functional unit is dependent on the goal of life cycle analysis and therefore constitutes 1 m^3 of concrete in this case.

Fig. 2 displays in a simplified way the processes that are included in the LCA analysis and the boundaries of the study. The system presented was adapted according to the mixture in question.

3.2. Inventory analysis

To quantify the sustainability indicators it is necessary to first develop the inventory analysis (Mateus et al., 2013). 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 (Li et al., 2010). As mentioned before, in this study the production of raw materials, their transportation to the concrete plant and the production of concrete were included in the inventory.

Table 2 shows the inventory of the materials and transportation considered for each concrete formulation. 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 figures used are described in the public Environmental Declaration (Secil – Compania Geral de Cal e Cimentos, 2013) of this cement plant. For this research, it was taken into account 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. 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 accordingly to the place of production. Allocation is necessary in the case of joint co-production, where the processes cannot be sub-divided, as is the case in fly ashes production (Van Den Heede and De Belie, 2012). Allocation shall respect the main purpose of the processes studied, allocating appropriately 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

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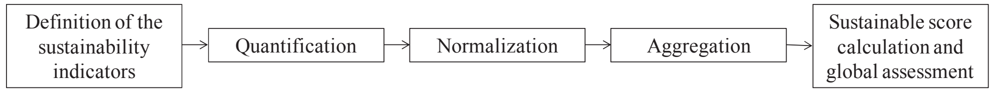

Fig. 1. Structure of the MARS-SC methodology for the environmental sustainability indicator.
Adapted from Mateus and Bragança (2010).

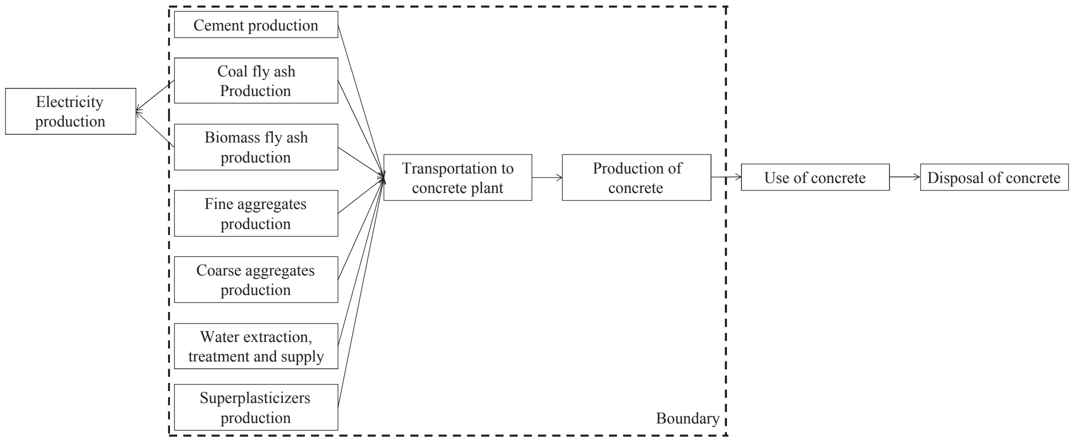

Fig. 2. Processes considered in the environmental analysis of the different concrete formulations.

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.

Due to the environmental report (Central Termoeléctrica do Pego, 2011) from a major Portuguese coal power plant (located in center 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 coal fly ashes produced during coal combustion. In Portugal, the commercial value of coal fly ashes is about 21€/ton and the value of the electricity is 0.22€/kWh (ERSE – Entidade Reguladora dos Serviços Energéticos, 2015). Therefore, the economic allocation coefficient of 0.03% 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 in consideration the quantified economic allocation coefficient of 0.03%.

Regarding the biomass fly ashes, it is important to highlight that in Portugal this kind of fly ashes are considered a waste product and therefore they do not afforded 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 biomass fly ashes.

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 (Mateus et al., 2013). For this reason and due to the lack of publically 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 (Hischier et al., 2010). This database covers the average inventory data of the main building materials and processes in different regional contexts (Mateus et al., 2013). 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 (Torgal and Jalali, 2011) and since the Portuguese energy mix is different from the

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

	FA0	C_FA20	C_FA40	C_FA60	B_FA20	B_FA40	B_FA60	CB_FA20	CB_FA40	CB_FA60	Unit
Material input											
Portland cement	350	280	210	140	280	210	140	280	210	140	kg
Gravel	1100	1100	1100	1100	1100	1100	1100	1100	1100	1100	kg
Sand	750	750	750	750	750	750	750	750	750	750	kg
Water	175	175	175	175	175	175	175	175	175	175	kg
Superplasticizer	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	kg
Coal fly ash		70	140	210				35	70	105	kg
Biomass fly ash					70	140	210	35	70	105	kg
Transportation											
Portland cement	14.4	11.5	8.6	5.7	11.5	8.6	5.7	11.5	8.6	5.7	tkm
Sand and gravel	577.2	577.2	577.2	577.2	577.2	577.2	577.2	577.2	577.2	577.2	tkm
Superplasticizer	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	tkm
Coal fly ash		11.6	23.1	34.7				5.8	11.5	17.3	tkm
Biomass fly ash					10.1	20.2	30.2	5.0	10.1	15.1	tkm

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European average (Jalali, 2007), 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 take into account the Portuguese energy mix.

In the inventory of the transportation processes the study took into account the distances between the Portuguese places of raw material extraction or raw materials storage facilities and the concrete mixing plant in question. The kilometers considered as the transportation distance of cement, sand and gravel, coal fly ashes, biomass fly ash and superplasticizer were therefore 41, 312, 164, 144 and 326 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 (CONCRETOPE – Fabrica de Betão pronto S.A, 2005), where the different concrete formulations are supposedly produced. From this EPD, only the flows related to the concrete mixing phase were considered.

3.3. Impact assessment

The life cycle inventory data was converted into potential environmental impact, using the life-cycle impact assessment (LCIA) methods.

In MARS-SC, the definition of the sustainability indicators depends, above all, on the type of analyzed 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 (Table 3): 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 the impact categories found in the EN15804:2012 (CEN EN 15804:2012, 2012) standard, MARS-SC does not consider the Depletion of abiotic resources-elements as an impact category.

3.3.1. Normalization

In order 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 others "lower is better", it is necessary normalize the indicators (Mateus et al., 2013). The normalization was done using the Diaz-Balteiro (Díaz-Balteiro and Romero, 2004) equation (Equation (1)).

$$\overline{P}_i = \frac{P_i - P_{*i}}{P_i^* - P_{*i}} \quad \forall i \tag{1}$$

In this equation, P_i is the value of ith parameter. P_i^* and P_{*i} are the best and worst value of the ith sustainability parameter among the analyzed products. Normalization converts the values into a scale bounded between 0 (worst value) and 1 (best value) and turns the value of each indicator dimensionless (Mateus et al., 2013).

Table 4
Weight for each environmental indicator (Mateus and Bragança, 2010).

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

3.3.2. Aggregation and global assessment

Equation (2) calculates the aggregation of each environmental indicator in terms of a global indicator, describing the overall environmental performance (ND_A).

$$ND_A = \sum_{i=1}^{n} w_i \cdot \overline{P}_i \tag{2}$$

The global indicator ND_A results from the weighting average of each normalized indicator $\overline{P_i}$, while w_i is the contribution of the ith indicator for the overall environmental performance. The sum of all weights must be equal to 1 (Mateus et al., 2013). For aggregation, this study considers the weights (Table 4) set in a study developed by the US Environmental Protection Agency's Science Advisory Board (SAB) (EPA Science Advisory Board, 2000). Reasoning for this is that there are no specific studies in Portugal or in a nearby regional context regarding the relative importance of each environmental impact category in the quantification of the global environmental performance. According to the MARS-SC, this is the approach recommended for the Portuguese context and one of the most accepted by the international scientific community in the field (Mateus and Bragança, 2010). In the application of this methodology to a different context, if there are specific weights, they should be used in the assessment of the global environmental performance.

The results are also presented in a "radar" or Amoeba diagram, also known as a sustainable profile. In the diagram, the number of rays is equal to the number of indicators that are analyzed. In each sustainable profile, the global performance of a respective concrete with fly ash is monitored and compared with that of the reference concrete.

3.3.3. Sensitivity analysis

In the inventory of biomass fly ashes, their transportation from the power plant to the concrete plant was the only parameter considered (Scenario 1), due to the fact that, as described above, the biomass fly ashes do not have market value. Nevertheless, it is important to understand the effects that a possible evolution of the market value of biomass fly ashes might have for the obtained results.

In this life cycle analysis study, two additional scenarios were thus considered: one assuming that the biomass ashes gain a market value that is half of the coal fly ashes value (10.5 €/ton) –

Table 3
Indicators, units and quantification methods.

Environmental indicators	Units	LCIA methods
Global warming (GWP 100)	[kg CO_2 eq]	CML 2 baseline 2000 V2.05
Ozone layer depletion (ODP)	[kg CFC-11 eq]	CML 2 baseline 2000 V2.05
Acidification potential (AP)	[kg SO_2 eq]	CML 2 baseline 2000 V2.05
Eutrophication potential (EP)	[kg PO_4 eq]	CML 2 baseline 2000 V2.05
Formation potential of tropospheric ozone (POCP)	[kg C_2H_4 eq]	CML 2 baseline 2000 V2.05
Abiotic depletion potential of fossil resources (ADP_FF)	[MJ eq]	Cumulative energy demand V1.08

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Scenario 2; and other assuming the same market value to that of the coal fly ashes (21 €/ton) – Scenario 3.

As there is no publically available environmental declaration for biomass power plants, in Portugal, the inventory of the considered plant is based on the generic data presented in the Ecoinvent report V2.2 on cogeneration biomass power plants. However, the Ecoinvent process was edited and thereby adjusted to the Portuguese context. In Portugal, biomass is mostly used as a raw material in the pulp and paper industries. During the preparation of biomass for the process of manufacturing, some residual biomass is produced (mainly during the wood log peeling/shelling/stripping processes) and this waste is used to produce energy in cogeneration power plants located within the pulp and paper industries. Because the biomass used to produce energy is a waste product, its economic value has no significance in terms of allocation rules. Therefore, the flows related to the supply of biomass were deleted from the considered Ecoinvent process. Additionally, the energy inputs were changed so as to comply with the Portuguese energy mix. Using the Ecoinvent report, it is also possible to relate the quantity of energy produced to the quantity of biomass fly ashes. Therefore, in the abovementioned Scenarios 2 and 3, the environmental impact of biomass ashes production was considered, using the allocation process previously described for the coal fly ashes. The allocation coefficients were 0.01% and 0.02%, for Scenarios 2 and 3 respectively.

4. Results and discussion

4.1. Environmental impacts

Table 5 presents the results of the quantification of the potential environmental impacts related with the production of 1 kg of different types of binder, according to the Portuguese context.

Table 6 summarizes the values obtained in the quantification of the environmental impacts categories, related with the production of the different concrete mixtures, taking into consideration Scenario 1. Analyzing the results, it is possible to verify that the concrete that uses only cement as binder presents the highest values for all environmental impacts, having higher observed values for the ADP_FF and CO_2. The high emission of CO_2 is a result of the chemical reactions (calcination) that occur during clinker production (Chusilp et al., 2009; Huntzinger and Eatmon, 2009).

When compared with typical concrete, the incorporation of fly ashes allows for a reduction in all environmental impacts. The potential environmental impacts decrease with increasing cement substitution, regardless of the type of fly ashes used.

The use of concrete mixtures with the combination of the two types of ashes led to a decrease in the environmental impacts when compared to the reference concrete, regardless of both the percentage of cement substitution and the ratio between the quantities of the two ashes. The results also show that values for the concretes with higher content of biomass ashes are lower than for the concretes with higher content of coal ashes. At this stage, it is necessary to highlight the effect of the allocation step in the obtained results. In Portugal, biomass fly ashes are considered a waste product without economic value (Tarelho et al., 2012) and therefore there are no flows from the biomass power plant allocated to its production. The same does not happen with hard coal fly ashes, as they have a market value and consequently a percentage of the power plant's flows are allocated to their productions (García-Gusano et al., 2015).

The normalization of the values obtained for each environmental impact category was obtained and results are presented in Table 7. This enables a better perception for which of the concretes has a better environmental performance. It is observed that, among all concrete formulations analyzed, the concrete in which 60% of cement was replaced by biomass fly ashes (B_FA60) has the best environmental performance.

4.2. Sustainability analysis

Table 8 presents the sustainability profiles and the overall environmental performances are represented in. In the profiles, the shadowed area represents the performance of each concrete analyzed. At the level of each impact category, the best concrete is the one that has a value closest to one. It is verified that B_FA60 concrete presents the best environmental performance ($ND_A = 1.00$) and normal concrete (FA0) presents the worst performance ($ND_A = 0.00$).

Therefore, these results makes possible the conclusion that using a high content of biomass fly ash 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

Table 5
Quantification of the environmental impact categories related with the production of 1 kg of binder (specific values for Portugal).

Impact category	Unit	Cement	Coal fly ash	Biomass fly ash	
				Scenario 2[a]	Scenario 3
GWP 100	kg CO_2 eq	1.79E+00	1.01E−02	2.80E−05	1.40E−05
ODP	kg CFC-11 eq	2.58E−08	7.16E−11	6.31E−06	3.15E−06
AP	kg SO_2 eq	9.24E−03	2.07E−05	6.28E−04	3.14E−04
EP	kg PO_4 eq	2.09E−03	2.56E−05	5.76E−11	2.88E−11
POCP	kg C_2H_4 eq	2.14E−04	9.52E−07	5.72E−07	2.86E−07
ADP_FF	MJ eq	6.87E+00	1.99E−01	5.94E−03	2.97E−03

[a] The potential environmental impact resulting from the production of biomass fly ash (Scenario 1) was not considered (as described in Section 3.3).

Table 6
Values obtained for the different environmental impacts.

Impact category	Unit	FA0	C_FA20	C_FA40	C_FA60	B_FA20	B_FA40	B_FA60	CB_FA20	CB_FA40	CB_FA60
GWP 100	kg	7.84E+02	6.62E+02	5.39E+02	4.16E+02	6.61E+02	5.37E+02	4.13E+02	6.62E+02	5.38E+02	4.15E+02
ODP	kg	3.13E−05	3.01E−05	2.86E−05	2.72E−05	3.00E−05	2.85E−05	2.70E−05	3.01E−05	2.86E−05	2.71E−05
AP	kg	4.08E+00	3.46E+00	2.81E+00	2.19E+00	3.45E+00	2.82E+00	2.18E+00	3.46E+00	2.82E+00	2.18E+00
EP	kg	9.19E−01	7.80E−01	6.38E−01	4.96E−01	7.78E−01	6.34E−01	4.90E−01	7.79E−01	6.36E−01	4.93E−01
POCP	kg	1.01E−01	8.63E−02	7.18E−02	5.72E−02	8.62E−02	7.15E−02	5.69E−02	8.63E−02	7.16E−02	5.70E−02
ADP_FF	MJ	5.00E+03	4.56E+03	4.12E+03	3.70E+03	4.55E+03	4.09E+03	3.63E+03	4.55E+03	4.10E+03	3.66E+03

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Table 7
Normalized values of the studied environmental impact categories.

Indicator	FA0	C_FA20	C_FA40	C_FA60	B_FA20	B_FA40	B_FA60	CB_FA20	CB_FA40	CB_FA60
GWP 100	0.00	0.33	0.66	0.99	0.33	0.67	1.00	0.33	0.66	1.00
ODP	0.00	0.28	0.63	0.97	0.29	0.65	1.00	0.29	0.64	1.00
AP	0.00	0.33	0.66	1.00	0.33	0.67	1.00	0.33	0.66	1.00
EP	0.00	0.33	0.66	0.99	0.33	0.67	1.00	0.33	0.66	0.99
POCP	0.00	0.33	0.66	0.99	0.33	0.66	1.00	0.33	0.66	1.00
ADP_FF	0.00	0.32	0.64	0.95	0.33	0.67	1.00	0.33	0.66	0.98

compatibility between the construction sector and the goals of Sustainable Development.

The results of the sensitivity analysis (Table 8) show that regardless of the potential market value of the biomass fly ashes, the results will remain similar to the ones presented in Scenario 1. This conclusion is underlined by the fact that, although in Scenarios 2 and 3 the impacts related to biomass combustion are considered, the largest part of this impact can be attributed to the energy production, due to its much higher economical revenue. As a result, the impact attributed to the fly ashes is very small when compared to other system flows, and for that does therefore not affect the environmental performance of concrete.

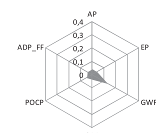
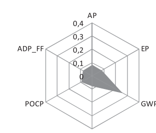
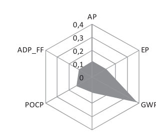
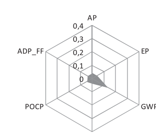
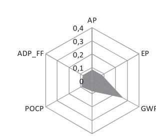
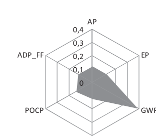
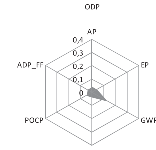
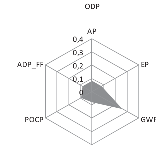
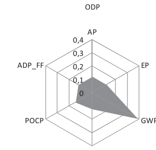
To complement the results presented in this study, showing that pozzolanic concrete presents better environmental performance, it is important to take into account some parameters that are also relevant in the design of concrete products, such as compressive strength and durability. This is crucial since, according to other studies, these parameters can limit the cement substitution ratio (Josa et al., 2004).

Regarding the compressive strength, the CTAC research centre already developed some research to assess this propriety for the case of concretes with reduced Portland cement content and high volume of fly ashes. Based on the results of a previously published work (Anjos et al., 2014) and using the methodology presented in this paper, the environmental performance of two types of self-compacting concrete that showing similar mechanical strength at about 90 days of curing age (Fig. 3) was evaluated to verify the results achieved. The first type (B300) is a conventional plain Portland cement concrete, while in the other (FA) 60% of cement was replaced by coal fly ashes. The compositions of these two types of concrete are presented in Table 9.

Analyzing the results presented in Table 10, it is possible to conclude that the concrete with 60% of cement replacement by coal fly ash (FA) presents a significant improvement in the environmental performance when compared with the plain cement concrete (B300), validating the results achieved in this study.

Nevertheless, it is important to consider that it is possible to produce plain cement concrete without using a superplasticizer (SP), since in the abovementioned research (Anjos et al., 2014) this chemical admixture was only necessary to assure the self-compactability of the concrete. On the other hand, a concrete with high content of coal fly ashes always needs SP as part of its composition (Crouch et al., 2007). Therefore, it is important to assess the environmental performance implications in using and not using SP in the plain cement concrete (B300). Table 10 shows that there is an improvement in the environmental performance of the plain cement concrete without SP (B300_2). It also highlights that B300_2 is better than the FA concrete at the level of two environmental impact categories: ODP and ADP_FF. This indicates that the superplasticizer has high influence on these two impact categories, as also concluded in other studies (e.g. (Sjunnesson, 2005)). In what concerns the other impact

Table 8
Normalized values that described the sustainability profile.

Concrete	Sustainable profile	Performances ND		
	Scenario 1	Scenario 1	Scenario 2	Scenario 3
FA0	–	0.00	0.00	0.00
C_FA20		0.32	0.32	0.32
C_FA40		0.65	0.65	0.65
C_FA60		0.98	0.98	0.98
B_FA20		0.33	0.33	0.33
B_FA40		0.66	0.66	0.66
B_FA60		1.00	1.00	1.00
CB_FA20		0.32	0.32	0.32
CB_FA40		0.66	0.66	0.66
CB_FA60		0.99	0.99	0.99

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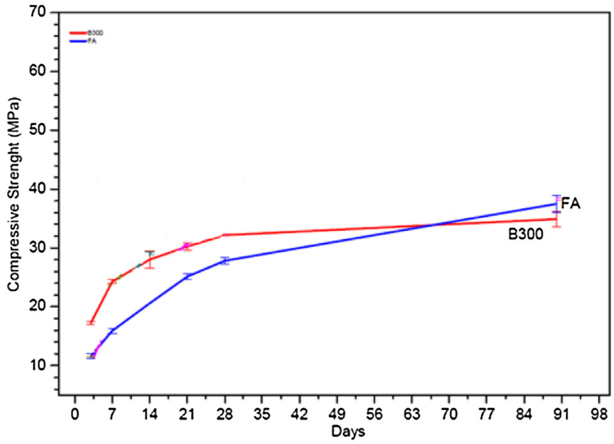

Fig. 3. Evolution of compressive strength with age for the two concrete (B300 and FA). Adapted from Anjos et al. (2014).

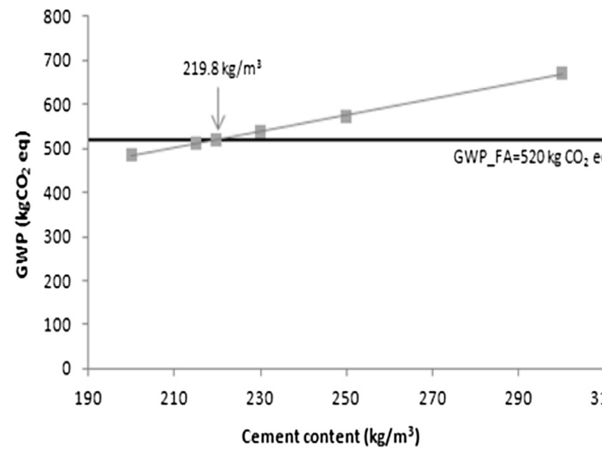

Fig. 4. Influence of the cement content of a plain cement concrete (B300_2) in the GWP impact category.

Table 9
Concrete compositions.

Material input	B300	FA
Portland cement 42.5 (kg/m^3)	300	200
Gravel (kg/m^3)	867	880
Sand (kg/m^3)	1053	870
Water (kg/m^3)	180	170
Superplasticizer (kg/m^3)	7.8	9.0
Coal fly ash (kg/m3)	–	300

Adapted from Anjos et al. (2014).

Table 11
Concrete compositions.

Material input	B219.8	B195	B219.8b	B195b
Portland cement 42.5 (kg/m^3)	219.8	195.0	219.8	195
Gravel (kg/m^3)	897.2	906.5	1089.7	1101.1
Sand (kg/m^3)	1089.6	1101.0	897.2	906.6
Water (kg/m^3)	131.9	117.0	131.9	117.0

categories, including the one (GWP) that most influences (according to Table 4) the overall environmental impact, the concrete with fly ashes (FA) always performs better than the plain cement concrete without superplasticizer (B300_2). These results allow for concluding that with the use of fly ashes it is possible to produce a concrete with lower potential environmental impacts, while maintaining an adequate compressive strength, similar to that of conventional plain cement concrete usually used in structural applications.

The next step of this comparison is to study the composition of a plain cement concrete that has a similar environmental performance to that of FA concrete. In order to do this, the first approach is to study the composition of a concrete that has the same performance of FA at the level of the most important environmental impact category: Global Warming Potential (GWP). To achieve this goal, the cement content of B300_2 was reduced and the aggregates content and water/binder ratio proportionally adjusted to obtain a concrete with similar GWP to the FA concrete, as presented in Fig. 4 and Table 10.

Fig. 4 and Table 10 show that a concrete (B219.8) with 219.8 kg/m^3 of Portland cement presents a similar environmental performance, by the measure of GWP, to that of FA concrete. The composition of this concrete is presented in Table 11. Nevertheless, this concrete still has a higher value in the ODP and AP impacts categories (Table 10).

Accordingly, the next step is to study the composition of a plain cement concrete with a better environmental performance at the level of all impact categories. Analyzing Table 10, it is possible to conclude that it is in the ODP category that the bigger differences between the plain concrete B219.8 and the FA lie. For this reason, the composition of a plain cement concrete was adjusted in order to get a similar performance in this category (Fig. 5). The results show (Table 10 and Fig. 5) that only a plain cement concrete (B195) with a maximum content of 195 kg/m^3 of Portland cement has a better or a similar environmental performance to that of FA concrete at the level of all impacts categories. The composition of this concrete is presented in Table 11. Nevertheless, this cement content cannot be used to produce structural concrete with the minimum required mechanical strength, as concluded in several studies (e.g. (Punmia et al., 2007)) and therefore both the durability and quality of concrete with this composition are not similar to the FA concrete.

Usually, a plain cement concrete presents a different aggregate content with higher gravel content than the one used to produce

Table 10
Quantification of the different environmental impacts of B300 and FA and different composition concretes.

Impact category	Unit	Type of concrete							% of impact reduction of FA in relation to:		
		B300	B300_2[a]	B219.8	B219.8b	B195	B195b	FA	B300	B300_2	B219.8
GWP 100	kg	6.93E+02	6.69E+02	5.20E+02	5.19E+02	4.77E+02	4.75E+02	5.20E+02	25	22	–
ODP	kg	3.02E−05	2.93E−05	2.80E−05	2.79E−05	2.76E−05	2.74E−05	2.76E−05	9	6	2
AP	kg	3.59E+00	3.51E+00	2.74E+00	2.73E+00	2.52E+00	2.50E+00	2.69E+00	25	23	2
EP	kg	8.03E−01	2.71E−06	5.99E−06	5.96E−06	5.49E−06	5.45E−06	6.07E−01	24	–	–
POCP	kg	8.88E−02	8.24E−02	6.49E−02	6.44E−02	5.97E−02	5.93E−02	6.88E−02	23	17	–
ADP_FF	MJ	4.60E+03	3.97E+03	3.43E+03	3.41E+03	3.27E+03	3.26E+03	4.07E+03	12	–	–

[a] Concrete without the use of superplasticizer.

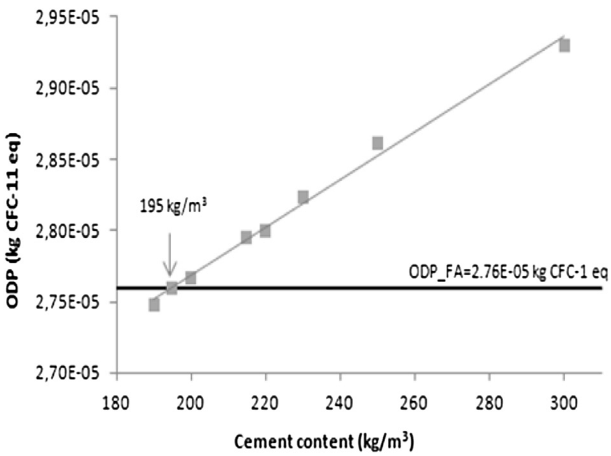

Fig. 5. Influence of cement content to produce a plain cement concrete (B300_2) with same performance of FA for ODP category.

B300_2. The next step therefore is to study the influence that a higher content of gravel than sand (Gravel/Aggregates = 0.55) has on the environmental performance of plain cement concretes. For this study, two new alternatives were studied and are presented in Table 10 as B219.8b and B195b. B219.8b and B195b have similar aggregates ratios to B219.8 and B195, respectively, but have the different gravel/aggregates ratios (0.55 instead of 0.45). The compositions of these two new alternatives are presented in Table 11. Table 10 shows that compared to B219.8 and B195 these two concretes have a better environmental performance. This is mainly due to the lower gravel's specific weight when compared to sand, and this alters positively the transportation-related impacts. Additionally, the process of producing gravel is less energy intensive than that of sand producing. The analysis of results therefore makes it possible to conclude that the utilization of a higher content of coarse aggregates than sand enables the production of a more sustainable concrete.

5. Conclusions

In this work, nine different concretes with different mixtures of binder were studied and compared with a plain cement concrete. The results showed that the potential environmental impact of concrete, mainly the part related with CO_2 emissions, is due to the Portland cement content. This justifies the higher value observed for the reference concrete, and the increase of the environmental performance with the decrease on cement percentage.

Coal and biomass fly ashes used singularly or blended displayed a capability to reduce the environmental impacts of concrete, when compared to the conventional concrete. The results showed that the best concrete is the one in which 60% of cement is replaced by biomass fly ashes. The results also show that it is possible to produce concretes with low Portland cement content, i.e. with improved environmental performance, achieving satisfactory expected compressive strength, thus being a promising alternative instead to plain cement concretes.

This work also showed that the incorporation of biomass fly ashes allows for a better solution for ash disposal (minimization of its disposal in landfill) while contributing to the development of concretes with improved environmental performance. Despite the good results presented here, there is a need for them to be complemented by experimental studies aimed at assessing the strength and durability of pozzolanic concretes that use Portuguese biomass fly ashes as cement substitution. These two parameters could limit the cement substitution even if concretes with higher cement substitute content display a better environmental performance. Those experimental studies will be developed and presented in a further work.

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