Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash

Rawaz Kurda [1], José D. Silvestre [2], Jorge de Brito [3*]

[1] PhD in Civil Engineering (rawaz.saleem@gmail.com), [2] Assistant Professor (jose.silvestre@ist.utl.pt), [3*] Full Professor (jb@civil.ist.utl.pt). CERIS-ICIST, DECivil, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisbon, Portugal. *Corresponding author

Abstract:

Since concrete is the most widely used construction material in the world, it is important to improve its environmental performance. A possibility is to use supplementary cementitious materials and recycled aggregates. Therefore, the objective of this work is to compare the environmental impacts (EI) of concrete mixes, which contain different incorporation ratios of fly ash (FA) and recycled concrete aggregates (RCA), with and without Superplasticizer (SP). The Life Cycle Assessment methodology was used for environmental assessment, according to ISO 14040 (2006) and EN 15804 (2012). Contrary to most of the previous studies, this one separately obtained the impact for each life cycle stage in detail (e.g. the impact of raw materials production, transportation, and mixing procedure), and explains the reason behind selecting each dataset. Thus, the results of this study can be used for other case studies. The results show that the EI slightly increased when SP was used. Moreover, the incorporation ratio of fine RCA did not change the results for most of the EI categories. Nevertheless, the EI of most of the categories decreased when coarse NA was fully replaced with coarse RCA. Despite the long transportation distance between the coal power plant and the concrete plant considered in the case study, the EI significantly decreased in most categories with increasing amounts of FA.

Keywords:

Sustainability, concrete, recycled concrete aggregates, fly ash, Life Cycle Assessment.

Acronyms list:

ADP - Abiotic Depletion Potential; AP - Acidification potential; CDW - construction and demolition waste; EI - environmental impacts; EP - Eutrophication potential; EPD - Environmental Product Declaration; FA - fly ash; GWP - Global warming potential; LCA - Life Cycle Assessment; NA - natural aggregates; OPC - Ordinary Portland cement; PE-NRe - Non-renewable primary energy resources; POCP - Photochemical ozone creation potential; RCA - recycled concrete aggregates; SCM - supplementary cementitious materials; SP - Superplasticizer.

1 Introduction

Generally, Life Cycle Assessment (LCA) of materials is obtained according to standards ISO 14040-14044 (2006). Frequently, researchers only complete the LCA from "cradle to gate", and more rarely consider the "Use" and "End of life" stages (Fraile-Garcia et al., 2017; Fraile-Garcia et al., 2015), or optimize the products according to their LCA (Fraile-Garcia et al., 2016). LCA studies usually rely on commercial software tools suitable for any product, process or activity (e.g. GaBi, SimaPro or openLCA software) and where various environmental impacts (EI) assessment methods can be used to characterize EI indicators according to EN 15804 (2012). Each method has a limited range of impact categories and CML "from the Centre of Environmental Science - Leiden University" (Guinée et al., 2002) is the one prescribed in EN 15804 (2012) for Environmental Product Declaration (EPD) development. The majority of the studies are mainly focused on the "cradle to gate" stages, and consider most of the following environmental categories: abiotic depletion (ADP), acidification (AP), eutrophication potential (EP), global warming (GWP), photochemical ozone creation potential (POCP) and non-renewable primary energy resources (PE-NRe). CML baseline method is often used to quantify all the categories except PE-NRe, for which the Cumulative Energy Demand method is used.

The construction sector is one of the major contributors to EI, regarding energy consumption, emissions released into the atmosphere and extracted natural resources. Thus, it is essential that sustainability in construction is promoted, to reduce the ecological footprint during the construction, service, maintenance and end-of-life stages of a structure.

Since concrete is the utmost used construction material worldwide, the annual demand of aggregates (major components of concrete) will increase up to an expected value of $52x10^9$ tonnes in 2019 (Freedonia, 2016).

Kurda et al. (2018) combined results of different studies and showed that the demand of cement was 4,400 million tonnes and it is expected to increase to up to 6,000 million tonnes. The impact of cement is considered as a lion share of the total EI of concrete (Kurad et al, 2017), and it is responsible for more than 5% of yearly CO_2 emissions worldwide (CSI, 2017).

One alternative to decrease the EI of concrete is by replacing cement and natural aggregates (NA) with supplementary cementitious materials (SCM) such as fly ash (FA), and recycled aggregates such as recycled concrete aggregates (RCA), respectively. To answer these needs, there are several studies on single effect of high volume of RCA (Marinkovic´ et al., 2010; Tošić et al., 2015) and FA (NRMCA, 2014; Tait and Cheung, 2016) on the EI of concrete. However, studies regarding the simultaneous effects of high FA and RCA content on concrete EI are very scarce and limited (Marinković et al., 2016). In addition, previous investigations aggregated all the "Life cycle stages" impacts (e.g. the impact of transportation, raw materials and mixing procedure) for specific case scenarios. This makes it very difficult to separate the impacts of each stage and compare their output data with other studies, or to use them in other case studies. So far, to the best of the authors' knowledge, there is no detailed study to show the impacts of raw materials (e.g. cement, FA, fine and coarse RCA, fine and coarse NA, water, SP), transportation and production procedures individually and jointly, and justifying in detail the selection of the datasets to model concrete containing different amounts of FA and RCA. Since the impacts of raw materials and concrete are presented with and without transportation and mixing procedure impacts, the results of this study can be used in other case studies. Broadly speaking, the objective of this work is to compare the EI of the concrete mixes, which contain different incorporation ratios of FA and RCA, with and without SP, and the LCA methodology based on EN 15804 (2012) and ISO 14040 (2006), was considered for environmental assessment.

2 Materials and methods

2.1 Functional unit

The functional unit of the present study is one cubic meter of concrete with different amount of FA (0%, 30% and 60%), fine RCA (0%, 50% and 100%) and coarse RCA (0% and 100%), with or without SP (1%) (Table 1). The rationale behind these mix compositions and their fresh properties were presented in Kurda *et al.* (2017). In addition, the compressive strength of these concrete mixes, obtained from 15 mm cubic samples according to specification EN 12390-3 (2009), are detailed in Kurad et al. (2017). For this functional unit, complementary assumptions, limits and conditions are shown in §2.2.

2.2 System boundaries

In this study, the production of the raw materials used in concrete mixes was considered from "cradle to gate". Similarly to raw materials, the life cycle stages considered for concrete was also from "cradle to gate" (A1-A3). A1 is the extraction/production of the raw materials required to produce the concrete mixes. A2 is the impact from transportation of the raw materials to the concrete plant. A3 is the concrete production process at the plant.

As shown in the following points, the validity of this study has some limitations:

- Some EI categories were not considered, particularly those that are not significant or commonly used to access EI of construction activities. Therefore, only 6 EI categories were considered (e.g. a detailed analysis of ODP and PE-Re is not included in the paper because of their lower relevancy);

Table 1 - Concrete mixes and required materials for 1 m^3 (kg)

Mixes	**M1**	**M1sp**	**M2**	**M3**	**M3sp**	**M4**	**M5**	**M5sp**	**M6**	**M7**	**M7sp**	**M8**	**M9**	**M9sp**
Characteristics [a]	C0F0FA0	C0F0FA0SP	C0F50FA0	C0F100FA0	C0F100FA0SP	C0F0FA30	C0F50FA30	C0F50FA30SP	C0F100FA30	C0F0FA60	C0F0FA60SP	C0F50FA60	C0F100FA60	C0F100FA60SP
Fine RCA	0	0	320	634	684	0	312	338	613	0	0	317	598	649
Coarse RCA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fine Sand	305	350	148	0	0	268	129	151	0	230	246	150	0	0
Coarse Sand	458	474	227	0	0	479	237	245	0	498	531	222	0	0
"Rice grain"	226	241	223	220	236	225	222	236	218	224	239	220	224	232
Fine gravel	228	241	226	224	236	230	229	240	225	234	250	222	225	241
Coarse gravel	606	639	596	590	626	611	603	637	595	616	658	588	597	635
Cement	350	350	350	350	350	245	245	245	245	140	140	140	140	140
FA	0	0	0	0	0	105	105	105	105	210	210	210	210	210
Water (litre)	186	140	205	223	176	179	197	151	216	172	126	191	209	165
Mixes	**M10**	**M10sp**	**M11**	**M12**	**M12sp**	**M13**	**M14**	**M14sp**	**M15**	**M16**	**M16sp**	**M17**	**M18**	**M18sp**
Characteristics [a]	C100F0FA0	C100F0FA0SP	C100F50FA0	C100F100FA0	C100F100FA0SP	C100F0FA30	C100F50FA30	C100F50FA30SP	C100F100FA30	C100F0FA60	C100F0FA60SP	C100F50FA60	C100F100FA60	C100F100FA60SP
Fine RCA	0	0	318	629	680	0	311	336	611	0	0	303	595	644
Coarse RCA	919	972	906	898	952	926	913	967	898	933	986	920	906	962
Fine Sand	303	346	146	0	0	266	127	149	0	293	324	108	0	0
Coarse Sand	456	474	227	0	0	475	237	245	0	429	458	247	0	0
"Rice grain"	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fine gravel	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coarse gravel	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cement	350	350	350	350	350	245	245	245	245	140	140	140	140	140
FA	0	0	0	0	0	105	105	105	105	210	210	210	210	210
Water (litre)	196	155	218	233	187	189	212	168	226	182	137	206	229	185

[a] where "C" is for coarse RCA, "F" for fine RCA and "FA" for fly ash, and the values represent their incorporation ratio in concrete

- Due to the lack of information supplied by the companies, some emissions from different stages for production/extraction of raw materials (e.g. diffuse dust emissions in the processes developed at the quarry and at construction and demolition waste (CDW) recycling plant) could not be accounted for. Nonetheless, in this type of study, these emissions are usually insignificant and disregarded;
- The impacts associated with moving waste inside the CDW recycling plant were not considered;
- The Life Cycle of the concrete mixes was considered from "cradle to gate", without considering their application, maintenance and demolition. However, the durability (e.g. chloride ion penetration resistance) and mechanical (compressive strength) characteristics of the mixes were studied by Kurda et al. (2018) and Kurad et al. (2017), respectively, thus representing the performance during the use stage;
- Some data were collected and estimated by company's technicians. Therefore, some input and consumptions were not recorded separately by production sub-stage;
- The data used to obtain the EI of the RCA, coarse NA and concrete production was collected from Portuguese companies;
- The emissions of some activities (e.g. emissions from raw materials transportation) could not be evaluated by using site-specific data. In those cases, reference databases from SimaPro software

(Ecoinvent 3 and ELCD) were used.

2.3 Life cycle inventory (LCI)

Table 2 presents the source and location of the data used in the present study. Ordinary Portland cement (OPC) (CEM I) EPD report developed by European Cement Research Academy (ECRA, 2015) was adopted to obtain the cement production impact. The LCI data for coarse NA and coarse and fine RCA, was registered from Braga et al. (2017) and collected on site (Portuguese companies). Additionally, the EPD report prepared by the Danish Technological Institute (DTI), according to specifications EN 15804 (2012) and EN ISO 14025 (2011), was used to obtain the impacts of FA, based on economic allocation. Regarding the fine NA, the data were obtained from Marinkovic´ et al. (2010). In addition, SP data were obtained by the European Federation of Concrete Admixtures Associations (EFCA, 2015) in 2015, and published in an EPD. As for modelling, the SimaPro software was used to calculate the impact of transportation and water soil extraction from ELCD-3.1 and Ecoinvent-3 databases, respectively. Furthermore, the impact of the mixing process to produce 1 m^3 of concrete was obtained based on a database of Braga et al. (2015). The NativeLCA method, developed by Silvestre et al. (2015), was considered to elect some of these environmental datasets as generic data.

Table 2 - Location and source of the databases used

Raw materials	Details	Location	Sources
Cement	CEM I	EU	International EPD system (ECRA, 2015)
SP	High performance	EU	International EPD system (adapted from (EFCA, 2015)
FA	Type (f)	EU/Denmark	International EPD system (adapted from (DTI, 2013)
Water	Water well	EU/Portugal	Site-specific data (adapted from (Braga et al., 2017)
Water	Tap water	EU	Ecoinvent 3
Coarse NA	Crushed limestone	EU/Portugal	Site-specific data (adapted from (Braga et al., 2017)
Fine NA	River sand	Serbia	Site-specific data (adapted from (Marinkovic´ et al., 2010)
RCA	Coarse and fine	EU/Portugal	Site-specific data (adapted from (Braga et al., 2017)

2.3.1 Raw materials (A1)

A search was carried out to gather information concerning each raw material manufacturing. As a result, several environmental datasets were collected from different countries. The details of the process of selecting each database are presented in Supplementary Information I, II, III, IV, VI and VII for cement, FA, SP, water, coarse NA, and fine NA and RCA, respectively. Furthermore, in order to select an accurate LCA dataset for FA, to be used as generic data in the current study, the NativeLCA method (Silvestre et al., 2015) was applied to each environmental dataset identified (Chen et al., 2010; DTI, 2013; Teixeira et al., 2016). This method was only applied on FA datasets because the knowledge concerning the EI of FA is still very scarce and it is difficult to select the best source. Native LCA is a method used to select the environmental datasets as generic data for a national context, which was developed by Silvestre et al. (2015) and already applied to construction products (Supplementary Information II). As explained from the mentioned Supplementary Information sections, among different datasets, only the database were adapted to the scenario of the present study were selected (Table 3).

Table 3 - EI for the production of 1 kg of each raw material from cradle to gate (without transportation impact from supplier to the concrete plant)

	Baseline CML method					Cumulative Energy
Materials (kg)	ADP	GWP	POCP	AP	EP	Pe-NRe
	kg Sb eq	kg CO_2 eq	kg C_2H_4 eq	kg SO_2 eq	kg PO_4^{-3} eq	MJ
CEM I	0.000001	0.898	0.000142	1.48E-03	0.000211	3.7
SP	1.10E-09	0.002	3.12E-07	2.92E-06	1.03E-06	0.031
Fly ash	3.29E-10	0.004	5.49E-07	7.26E-06	1.05E-06	0.043
Water	1.57E-11	0.00E+00	3.87E-08	9.70E-07	4.99E-08	0.002
Fine NA	0.00E+00	0.002	1.25E-07	9.58E-06	2.49E-06	0.018
Coarse NA - Source I	5.92E-09	0.053	1.75E-05	2.63E-04	6.10E-05	0.74
Coarse NA - Source II	6.56E-09	0.005	1.33E-06	6.22E-05	1.37E-05	0.062
Coarse NA -Average	6.24E-09	0.029	9.42E-06	1.63E-04	3.74E-05	0.401
Coarse RCA	1.09E-09	0.005	1.41E-06	3.02E-05	7.07E-06	0.076
Fine RCA	1.09E-09	0.005	1.41E-06	3.02E-05	7.07E-06	0.076

2.3.2 Transportation (A2)

The transportation distance is variable from each supplier of raw material to the concrete plant. Thus, the location of most of the main suppliers related to concrete production has been identified (Supplementary Information VIII). However, in this study, only the most probable base scenario for the centre of Portugal was considered (Figure 1). Moreover, the average transportation distance from regional sources to a recycling plant in the centre of Lisbon was considered to be 25 km (Braga et al., 2017). Coelho and de Brito (2013) estimated that the average distance between a recycling plant and demolition sites is 26, 26, 25, 23, 22, 21 and 21 km in the following locations of Portugal: Barreiro, Moita, Seixal, Almada, Oeiras, Amadora and Odivelas, respectively.

To calculate the transportation impact, two main types of Lorries were considered (Table 4). The first one is medium sized (lorry transport, maximum capacity 17.3 tonnes) and was considered to transport RCA (from the CDW site) to the recycling plant. The same kind of lorry was considered to transport RCA from the recycling plant to the concrete plant. The 2nd lorry is bigger, with a maximum capacity of 27 tonnes - “Articulated lorry transport”. It was used to transport all the other products mentioned in Table 2, and their transportation was considered from the supplier to the concrete plant. For both lorries, the distance of transportation was increased by 70% in order to consider the impact of the empty return of the vehicles to the supplier.

Table 4 - Impact assessment results to transport 1 kg per km (ELCD core database V 3.0)

Lorry/maximum capacity (tonnes)	Baseline CML method					Cumulative Energy Demand
	ADP	GWP	POCP	AP	EP	PE-NRe
	kg Sb eq	kg CO_2 eq	kg C_2H_4 eq	kg SO_2 eq	kg PO_4^{-3} eq	MJ
Articulated Lorry transport/27 t	1.98E-12	4.98E-05	1.59E-08	2.24E-07	5.14E-08	6.73E-04
Lorry transport/17.3 t	2.62E-12	6.57E-05	2.24E-08	3.11E-07	7.20E-08	9.27E-04

Figure 1 - Transportation distance adapted for the Portuguese reference case, namely Lisbon region

2.3.3 Production process (A3)

After transporting all raw materials to the concrete plant, the EI of the production process (mixing the materials in concrete plant), namely energy (electricity and diesel, etc.) and water consumption, should be also estimated in order to obtain the cradle-to-gate EI (A1-A3) of the concrete mixes. This data were collected by Braga et al. (2017) from a Portuguese company from the centre of Portugal (Table 5).

Table 5 - EI results for the production (mixing procedure) of 1 m3 of concrete (Braga et al., 2017)

Baseline CML method					Cumulative Energy Demand
ADP kg Sb eq	GWP kg CO_2 eq	POCP kg C_2H_4 eq	AP kg SO_2 eq	EP kg PO_4^{-3} eq	PE-NRe MJ
5.50E-07	4.65	1.36E-03	3.40E-02	1.75E-03	67.81

3 Results

3.1 Compressive strength of the concrete mixes

Generally, the results of this study show that the RCA content in concrete is detrimental on the compressive strength (Table 6). This unfavorable effect is higher with the addition of fine RCA than that of coarse RCA. However, the strength development rate increases after 28 days with increasing amount of RCA. The development rate of strength is higher in mixes containing fine RCA than coarse RCA. Similarly to the effect of RCA content, the amount of FA in concrete is harmful regarding compressive strength, especially at younger ages. After 28 days, the strength development rate of the OPC concrete is significantly lower than that of the mixes with FA for older ages. After 28 days, concrete mixes with both RCA and FA have higher strength development rates than those with only RCA or FA. Furthermore, the influence of incorporating RCA was higher in mixes with SP, followed by NA concrete (M1) and mixes with FA (Table 6). These facts have been explained in further detail in Kurad et al. (2017).

Table 6 - Compressive strength of concrete mixes

Fine RCA (%)	FA (%)	Coarse RCA (%)	Mixes	Age (days)					Mixes	Age (days)				
				7	28	90	180	365		7	28	90	180	365
				0% SP						1% SP				
				$f_{\text{cm, cube}}$ (MPa)						$f_{\text{cm, cube}}$ (MPa)				
0	0	0	M1	50.7	55.8	59	59.1	61.3	M1sp	71	73.5	76.7	82.3	83
50			M2	41	46.2	50	50.4	52						
100			M3	37.4	45	47.5	50	51.5	M3sp	52	54.1	58	61.7	63.7
0	30		M4	31	40.2	55.7	56.6	60						
50			M5	27.5	36.4	49	51.7	57.2	M5sp	45.1	60.4	62.7	75.5	79
100			M6	25.1	34	46.4	48.6	54.2						
0	60		M7	17.7	24	35.3	37.6	42.2	M7sp	25.7	42.4	49.7	55.6	58
50			M8	17.3	23.6	33.4	38.3	42.5						
100			M9	15.4	21.5	30.9	35.3	40	M9sp	21.5	37.1	44	51.6	57
0	0	100	M10	45.5	51.9	56.5	57.1	59.2	M10sp	59.9	63	66	71.2	73
50			M11	36	42.8	46.1	49.2	51						
100			M12	34.2	42	44.1	48.7	50.2	M12sp	47.1	49	57.9	58.3	60.6
0	30		M13	29.3	39	51.3	55.4	62						
50			M14	24.5	33	46.1	48.5	56.6	M14sp	39.5	53.8	57.5	69.4	74
100			M15	24	32.8	46	48.9	53.4						
0	60		M16	16.6	23	30.6	36.8	41	M16sp	22.5	38	45.2	56.6	59
50			M17	14.3	21.1	30.1	34.8	38.8						
100			M18	13.9	21	29.9	35.5	38	M18sp	18.5	32.3	44.3	51.3	54

3.2 Life cycle impact assessment (LCIA) results of the concrete mixes

The EI for the production of each raw material (A1 - without including the transportation to the concrete plant production), transportation (A2) and concrete production process (A3) were obtained. These life stages (A1, A2 and A3) are summed up (Figure 2) in order to obtain the EI of the production of one cubic meter of concrete according to their mix composition (Table 3):

- A1 considers the EI of raw materials' production, namely NA, RCA, OPC, FA and SP;
- A2 is the impact of the transportation of the raw materials from the supplier to the concrete plant (Figure 1);
- A3 is the process of producing concrete, including the impact of the water (water well) used to obtain the concrete mixes.

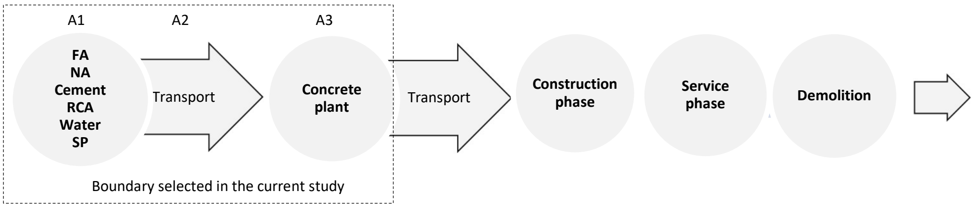


Figure 2 - Concrete life cycle (dash line represents the boundary considered for the study of each concrete mix)

The EI of all raw materials and concrete mixes were obtained using SimaPro software and the LCA methodology. Using the EI of the raw materials, namely cement, FA, SP, water, coarse NA, fine NA and RCA (Table 3), of the transportation (2.3.2§2.3.2) of each raw material, and of concrete production - "mixing procedure" (§2.3.3), it was possible to model the life cycle and to evaluate the EI of each concrete mix (Table 7).

Table 7 - Baseline CML method results and Cumulative Energy Demand (CED) for the production of 1 m^3 of concrete

Mixes	Fine RCA (%)	FA (%)	Coarse RCA (%)	SP (%)	ADP (kg Sb eq)	Δ[a]	GWP kg CO_2 eq)	Δ[a]	POCP (kg C_2H_4 eq)	Δ[a]	AP (kg SO_2 eq)	Δ[a]	EP kg PO_4^{-3} eq)	Δ[a]	PE-NRe (MJ)	Δ[a]
Supplementary information					IX		X		XI		XII		XIII		XIV	
M1	0	0	0	0	3.58E-04	1.00	3.62E+02	1.00	6.00E-02	1.00	7.80E-01	1.00	1.30E-01	1.00	1.95E+03	1.00
M2	50				3.58E-04	1.00	3.61E+02	1.00	6.00E-02	1.00	7.80E-01	1.00	1.30E-01	1.00	1.94E+03	0.99
M3	100				3.58E-04	1.00	3.60E+02	0.99	6.00E-02	1.00	7.80E-01	1.00	1.30E-01	1.00	1.94E+03	0.99
M4	0	30			2.53E-04	0.71	2.69E+02	0.74	5.00E-02	0.83	6.30E-01	0.81	1.10E-01	0.85	1.58E+03	0.81
M5	50				2.53E-04	0.71	2.68E+02	0.74	5.00E-02	0.83	6.30E-01	0.81	1.10E-01	0.85	1.57E+03	0.81
M6	100				2.53E-04	0.71	2.67E+02	0.74	5.00E-02	0.83	6.30E-01	0.81	1.10E-01	0.85	1.56E+03	0.80
M7	0	60			1.48E-04	0.41	1.76E+02	0.49	4.00E-02	0.67	4.80E-01	0.62	9.00E-02	0.69	1.21E+03	0.62
M8	50				1.48E-04	0.41	1.74E+02	0.48	4.00E-02	0.67	4.70E-01	0.60	8.00E-02	0.62	1.19E+03	0.61
M9	100				1.48E-04	0.41	1.74E+02	0.48	4.00E-02	0.67	4.80E-01	0.62	9.00E-02	0.69	1.19E+03	0.61
M10	0	0	100	0	3.52E-04	0.98	3.31E+02	0.91	5.00E-02	0.83	6.10E-01	0.78	9.00E-02	0.69	1.53E+03	0.78
M11	50				3.52E-04	0.98	3.31E+02	0.91	5.00E-02	0.83	6.10E-01	0.78	9.00E-02	0.69	1.53E+03	0.78
M12	100				3.52E-04	0.98	3.30E+02	0.91	5.00E-02	0.83	6.10E-01	0.78	9.00E-02	0.69	1.53E+03	0.78
M13	0	30			2.47E-04	0.69	2.38E+02	0.66	4.00E-02	0.67	4.60E-01	0.59	7.00E-02	0.54	1.16E+03	0.59
M14	50				2.47E-04	0.69	2.38E+02	0.66	4.00E-02	0.67	4.60E-01	0.59	7.00E-02	0.54	1.15E+03	0.59
M15	100				2.47E-04	0.69	2.37E+02	0.65	4.00E-02	0.67	4.60E-01	0.59	7.00E-02	0.54	1.15E+03	0.59
M16	0	60			1.42E-04	0.40	1.45E+02	0.40	3.00E-02	0.50	3.10E-01	0.40	5.00E-02	0.38	7.83E+02	0.40
M17	50				1.42E-04	0.40	1.45E+02	0.40	3.00E-02	0.50	3.10E-01	0.40	5.00E-02	0.38	7.81E+02	0.40
M18	100				1.42E-04	0.40	1.44E+02	0.40	3.00E-02	0.50	3.10E-01	0.40	5.00E-02	0.38	7.79E+02	0.40
M1sp	0	0	0	1	3.58E-04	1.00	3.64E+02	1.01	7.00E-02	1.17	7.90E-01	1.01	1.30E-01	1.00	1.98E+03	1.02
M3sp	100				3.58E-04	1.00	3.63E+02	1.00	7.00E-02	1.17	7.90E-01	1.01	1.30E-01	1.00	1.97E+03	1.01
M5sp	50	30			2.53E-04	0.71	2.70E+02	0.75	5.00E-02	0.83	6.40E-01	0.82	1.10E-01	0.85	1.61E+03	0.83
M7sp	0	60			1.48E-04	0.41	1.79E+02	0.49	4.00E-02	0.67	5.00E-01	0.64	9.00E-02	0.69	1.25E+03	0.64
M9sp	100				1.49E-04	0.42	1.77E+02	0.49	4.00E-02	0.67	4.90E-01	0.63	9.00E-02	0.69	1.23E+03	0.63
M10sp	0	0	100	1	3.52E-04	0.98	3.32E+02	0.92	5.00E-02	0.83	6.20E-01	0.79	9.00E-02	0.69	1.54E+03	0.79
M12sp	100				3.52E-04	0.98	3.31E+02	0.91	5.00E-02	0.83	6.20E-01	0.79	9.00E-02	0.69	1.53E+03	0.78
M14sp	50	30			2.47E-04	0.69	2.38E+02	0.66	4.00E-02	0.67	4.70E-01	0.60	7.00E-02	0.54	1.16E+03	0.59
M16sp	0	60			1.42E-04	0.40	1.46E+02	0.40	3.00E-02	0.50	3.20E-01	0.41	5.00E-02	0.38	7.93E+02	0.41
M18sp	100				1.43E-04	0.40	1.45E+02	0.40	3.00E-02	0.50	3.20E-01	0.41	5.00E-02	0.38	7.89E+02	0.40

[a] All the mixes are relative to the conventional concrete (M1)

In terms of concrete mixes, the EI slightly increased when SP was used. Furthermore, the incorporation ratio of fine RCA did not change most of the EI in all categories. Contrary to the incorporation ratio of fine RCA and the use of SP, and despite the long transportation distance between the coal power plant and the concrete plant considered in the current study, the EI significantly decreased in most categories with increasing incorporation ratios of FA. Similarly to the incorporation ratio of FA, the EI of most of the categories decreased when coarse NA was fully replaced with coarse RCA, except ADP (Table 7). In addition, the results shown in Table 7 are detailed in Supplementary Information IX - XIV. The total EI of the mixes changed almost proportionally to the incorporation ratio of non-traditional materials (e.g. FA). However, the two parameters are not directly proportional. For example, the water content decreased with increasing incorporation ratio of FA. Thus, the total EI of concrete is expected to decrease when the incorporation ratio of FA is increased, both because of lower cement and lower water content, but not proportionally to the cement content. Furthermore, a similar situation occurs for fine NA.

Figure 3 shows that, for the same scenario, the total EI of the mixes made simultaneously with SP, FA and RCA can be assumed by adding up the individual effects of SP, FA and RCA on the EI of concrete. This shows that, similarly to the individual effect, the EI in most of the cases seems to change proportionally to each individual component's content. However, the water content of concrete simultaneously containing SP, FA and RCA cannot be determined by a combination of the effects of each of these materials. In the other hand, the change in water content seemingly did not affect the total EI of concrete because the contribution of water in concrete is insignificant. Therefore, the results seem to be proportional. Regarding the aggregates, the replacement was made in absolute volume. Therefore, the RCA and NA content may change in concrete made with "combined and individual" non-traditional materials. However, the difference between the relative EI of concrete containing FA and RCA, and the sum of the total EI of concrete made either with RCA or FA is small. This is due to the small contribution of the aggregates to the total EI of concrete. Regarding the binders (major contributor to the EI), this did not happen because cement was replaced with FA using the total mass method, which means their mass was equal in all mixes. In addition, these results were compared with previous studies and EPD reports, and the corresponding conclusions are detailed in the following sub-chapters.

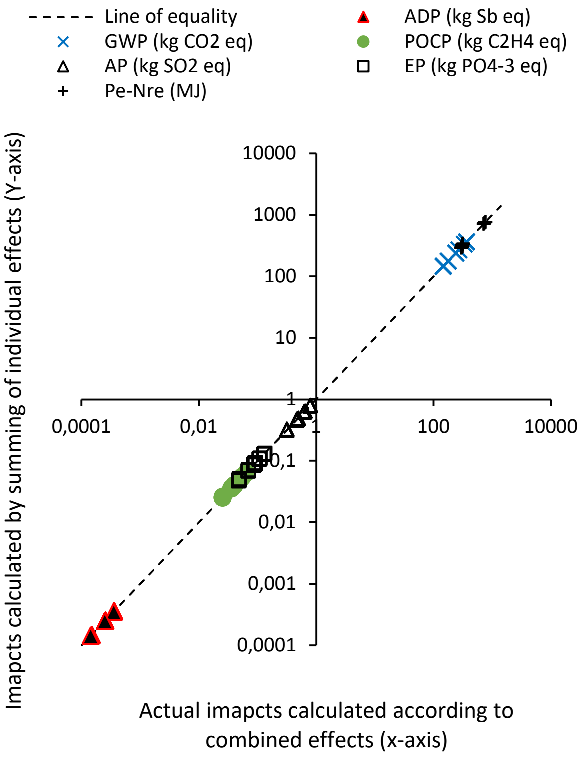


Figure 3 - Impacts calculated by summing individual effects of FA, and/or RCA, and/or SP *versus* actual impacts calculated according to combined effects

4 Discussion

4.1 Baseline CML method

4.1.1 Abiotic Depletion Potential (ADP)

ADP is a method to evaluate the extraction of primary resources (non-renewable materials), including metals, minerals and fossil fuels. This method is essentially influenced by the rate of extraction of resources.

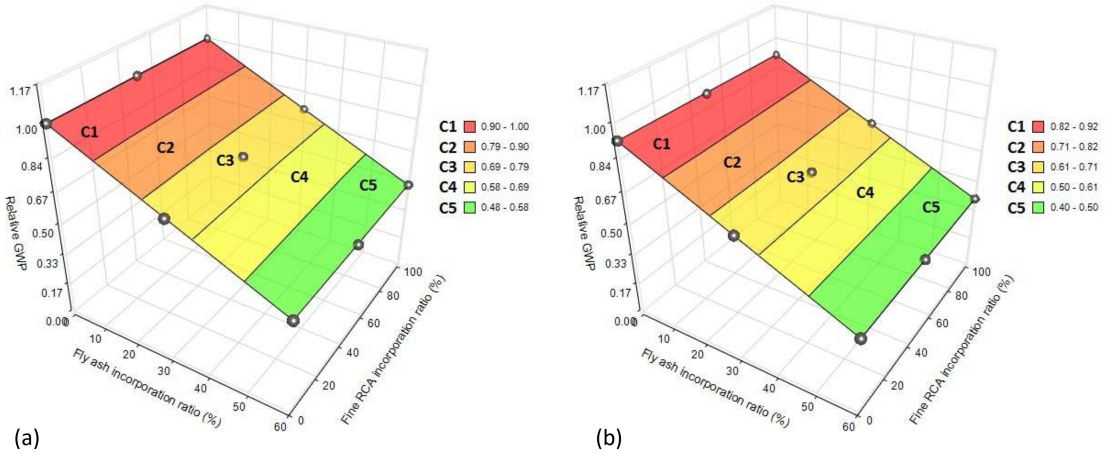
Table 7 presents the ADP of each concrete mix, with various amounts of NA, RCA, cement, FA, and water, with or without SP. In addition, the EI attributable to the process of concrete production (mixing procedure) and the transportation of raw materials were evaluated to find the total ADP for each concrete mix. Table 7 shows that ADP does not change with the increasing incorporation ratio of fine RCA. However, it decreased about 2% when coarse NA were 100% replaced with coarse RCA. Moreover, it decreased about 30% and 60% when incorporating 30% and 60% of FA, respectively. As for fine RCA, SP does not affect ADP. Similar results can be seen in the study of Braga (2015) for RCA concrete and in the EPD report by NRMCA-EPD:10046 (2014) for FA concrete. Concerning the combined effects of incorporating both FA and RCA with or without SP, the ADP linearly changed with the summation of each individual effect. This study reached a conclusion that agrees with the literature (Braga, 2015; NRMCA-EPD:10046, 2014), i.e. cement corresponds to almost 100% of the impacts in ADP. Therefore, incorporating RCA is not the solution to decrease the total ADP of concrete.

4.1.2 Global warming potential (GWP)

GWP, also referred to as “Greenhouse effect”, evaluates the trapped heat in the atmosphere by the greenhouse gases, including methane, carbon dioxide and chlorofluorocarbons (CFCs). At a global scale, the temperature further rises with the increase of the amount of greenhouse gases (IPCC, 2013).

Table 7 shows the GWP of the concrete mix, produced with various amounts of cement, RCA, NA, FA, and water, with or without SP. In addition, the EI attributable to the process of concrete production (mixing procedure) and the transportation of raw materials were evaluated to find the total GWP for each mix.

Figure 4 shows the GWP of concrete mixes without SP and shows that it strongly decreased when cement was replaced with FA. The corresponding rate was 26% and 51% with incorporation of 30% and 60% of FA, respectively. Although the GWP to obtain fine NA (0.00173 kg CO_2 eq/kg) is slightly lower than that of fine RCA (0.00524 kg CO_2 eq/kg), the total GWP of fine RCA concrete is similar to the one obtained by the fine NA concrete. This is due to the difference between the transportation distance of the fine NA (32-65 km) and RCA (9 km) supplier to the concrete plant. Since the GWP to produce coarse RCA (0.005 kg CO_2 eq/kg) is lower than that of the coarse NA (0.029 kg CO_2 eq/kg), the GWP decreased up to 8% when 100% of coarse RCA were incorporated in the concrete mix. This is mainly related to the transportation distance of the coarse NA (65 km) and coarse RCA (9 km) plant to the concrete plant. Similarly to the use of fine RCA, the use of SP did not influence the GWP of mixes as much. In addition, the GWP of concrete mixes increased up to 1% when 1% SP was introduced. Moreover, for mixes made with both RCA and FA, the GWP linearly changed with the summation of each individual effect. Similarly to previous studies (Marinković et al., 2017; 2010; Tošić et al., 2015), in this one cement is the largest contributor to the GWP (87-96%). This is due to the heating process ($CaCO_3$ + heat$\rightarrow$ CaO + CO_2) during cement production.



(a) (b)

Figure 4 - Relative GWP of mixes with various amounts of FA and fine RCA (a) without and (b) with 100% of replacing coarse NA with coarse RCA. Black dots - relative results; shades - qualitative levels of GWP - green being the best. Figures (a and b) are relative to the conventional concrete (M1)

Apart from the variability between the methods used, the EI of materials also depend on the transport distance. Therefore, it is difficult to compare results of two different studies. However, it is reliable to compare the EI of different concrete mixes for the same scenario (in each individual study), namely transport distances. Figure 5 shows the GWP of 1 m^3 of concrete obtained by some studies (Braga et al., 2017; Marinković et al., 2010; NRMCA-EPD:10046, 2014; Tošić et al., 2015). Similarly to our study, the results of these studies show that the GWP is mainly affected by cement content and that it significantly decreases with the incorporation ratio of FA. Additionally, the GWP slightly changes by incorporating RCA.

4.1.3 Photochemical ozone creation (POCP) potential

According to Guinée et al. (2002), oxidants have a negative impact on ecosystems and human health, since they are highly toxic.

Table 7 presents the POCP of each concrete mix, made with various amounts of NA, RCA, cement, FA, and water, with or without SP. For each concrete mix, the EI due to the process of concrete production (mixing procedure) and transportation of raw materials (from supplier to concrete plant) were considered to calculate the total POCP. As for GWP, the results show that POCP decreased by 22% and 45% when 30% and 60% of cement was replaced with FA, respectively, and decreased about 16% when coarse NA were fully replaced with coarse RCA, being however less affected by the incorporation of fine RCA (Table 7). These trends were also found for mixes with SP. The same factors concerning the effect of incorporation of RCA, FA and the use of SP on GWP of concrete mixes (§4.1.24.1.2) can be invoked for POCP.

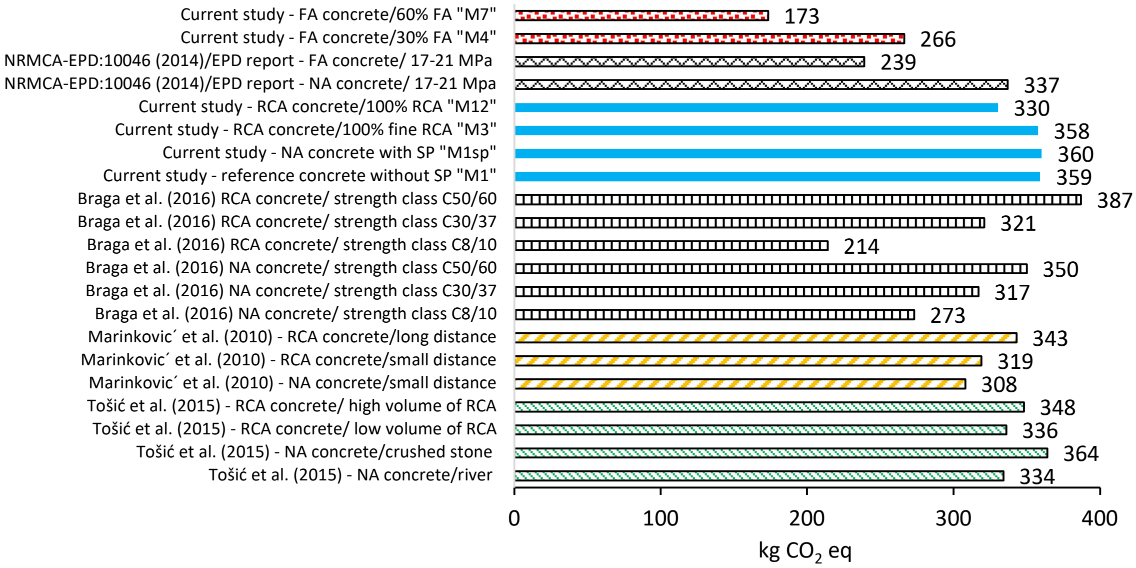


Figure 5 - GWP of concrete mixes, per cubic meter of concrete, incorporating different quantities and types of binders and aggregates

Similar trends can be seen in previous studies of RCA concrete (Marinković et al., 2010; Tošić et al., 2015) and FA concrete (NRMCA-EPD:10046, 2014). In addition, the POCP of most of the concrete mixes increased about 1% when 1% SP was used. As for incorporating fine RCA, the use of SP did not influence the POCP of mixes as much. Furthermore, the results show that by using 100% of coarse RCA and 30% or 60% of FA either with or without SP, the POCP is lower than that of the reference concrete.

4.1.4 Acidification potential (AP) and eutrophication potential (EP)

According to Blengini (2006), the main gases responsible for acidification are sulphur (SO_2), oxides of nitrogen (NO_x) and reduced nitrogen (NH_x), mainly from the combustion of fossil fuels. In the process of acidification, these gases are transformed into chemical substances and transported by the wind, altering the equilibrium of different ecosystems. Acidification also adversely affects the built environment, since it chemically alters the materials (Guinée et al., 2002).

Eutrophication consists of the enrichment of a given zone by nutrients, mainly nitrogen and phosphorus from polluting emissions, wastewater and fertilizers. High rates of nutrients lead to excessive development of algae and plants, which leads to low rates of oxygen and solar energy in the case of aquatic eutrophication, and contamination of flowers and groundwater in terrestrial eutrophication.

Table 7 shows the AP and EP of each concrete mix, made with various amounts of NA, RCA, cement, FA, and water, with or without SP. In addition, the EI attributable to the process of concrete production (mixing procedure) and the transportation of raw materials were evaluated to find the total AP and EP for each mix.

The results show that the AP to produce fine NA (9.58E-6 kg SO_2 eq/kg) is slightly lower (up to 1%) than that of fine RCA (3.02E-5 kg SO_2 eq/kg). This is due to the same factors mentioned for GWP (4.1.2§4.1.2), namely a different transport distance. In addition, the AP decreased up to 21% when coarse NA were fully replaced by coarse RCA. This is mainly attributed to the fact that the AP to produce coarse RCA (3.02E-5 kg SO_2 eq/kg) was significantly lower than that of coarse NA (1.63E-4 kg SO_2 eq/kg), and the transport distance from the supplier to the concrete plant of coarse NA (65 km) was longer than that of coarse RCA (9 km). As for coarse RCA incorporation ratio, the transport distance between the coal power plant "FA producer" and concrete plant was 2.7 times longer than the distance between the cement plant and the concrete plant. However, the AP decreased about 20% by incorporating 30% of FA, and the AP linearly decreased with an increasing incorporation ratio of FA (Table 7).

This difference is related to the fact that the AP to produce FA (7.26E-06 kg SO_2 eq/kg) is significantly lower than that of the cement (1.48E-03 kg SO_2 eq/kg). In addition, the AP of all concrete mixes slightly increased (up to 3%) when 1% SP was used.

Broadly speaking, the percentage of changes due to the incorporation ratio of FA and RCA either without (Table 7) or with SP is very close to the one found for AP. Therefore, the same conclusions that were mentioned for AP can be adapted to EP. In addition, relative to other used materials, the contribution of coarse aggregates and cement to the total EP is significant.

4.2 Cumulative Energy Demand

4.2.1 Consumption of primary energy, non-renewable (PE-NRe)

Non-renewable energy consumption is another EI under study. Its consumption is faster than its speed of regeneration, contributing to the exhaustion of natural reserves of fossil (coal, petroleum and natural gas) and nuclear (uranium) energy. The use of nuclear energy, despite not producing polluting gases, has a major risk: an accident at a nuclear power plant could lead to an extremely negative impact on the environment due to the danger of nuclear explosion, radioactive leakage and contamination (AGENEAL, 2015).

Table 7 presents the PE-NRe of each concrete mix made with various amounts of NA, RCA, cement, FA, and water, with or without SP. In addition, the EI attributable to the process of concrete production (mixing procedure) and the transportation of raw materials were evaluated to find the total PE-NRe for each mix

Although the energy consumption to produce fine NA (0.018 MJ) is lower than that for fine RCA (0.076 MJ), Figure 6 shows the EI is almost the same in concrete made with them because the NRe is highly dependent on the transport distance, and the distance from the fine NA plant to the concrete plant (32-65 km) is higher than that for fine RCA (9 km). Therefore, the PE-NRe of concrete slightly changed with the incorporation ratios of fine RCA. Moreover, relatively to incorporation ratios of fine RCA, PE-NRe significantly decreased (about 22% with the incorporation of 100% of coarse RCA) with the incorporation ratio of coarse RCA. This is due to the energy consumption required to produce coarse NA (0.40 MJ/kg) that is significantly higher (5 times) than that of coarse RCA (0.08 MJ/kg), and because the transport distance of the coarse NA (65 km) is much longer than that of the coarse RCA (9 km), from the supplier to the concrete plant. Although the selected distance between the FA plant and the concrete plant is 2.7 times longer than that of the cement plant, the PE-NRe of concrete decreased by 19% and 38% with the incorporation of 30% and 60% of FA, respectively. This is due to the fact that the PE-NRe to produce FA (0.043 MJ) is 86 times lower than that of cement (3.7 MJ) production.

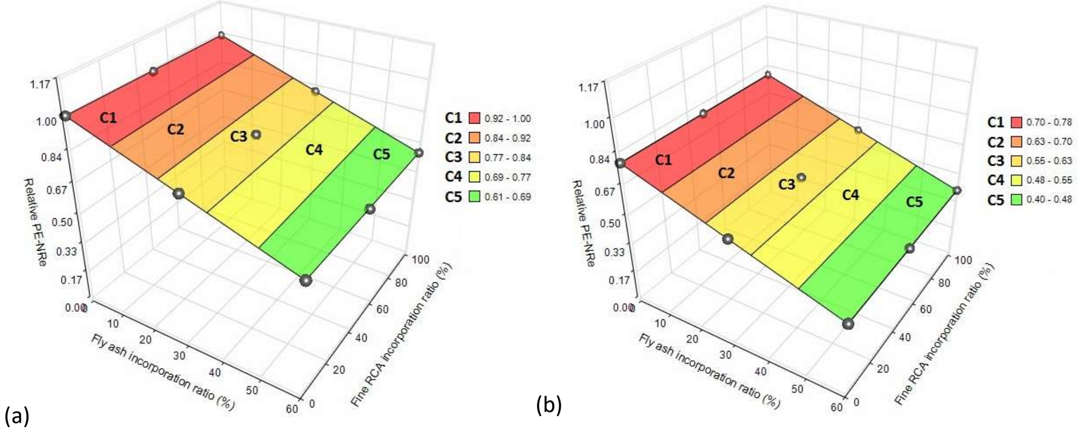


Figure 6 - Relative PE-NRe of mixes with various amounts of FA and fine RCA (a) without and (b) with 100% of replacing coarse NA with coarse RCA. Black dots - relative results; shades - qualitative levels of GWP - green being the best. Figures (a and b) are relative to the conventional concrete (M1)

As for other EI categories, in terms of the joint effects of both RCA and FA amount with or without SP, the energy consumption linearly changed with the individual effect. In addition, by using SP in all concrete mixes with or without fine RCA and/or FA, the PE-NRe increased up to 2%.

5 Conclusions

In this study, the EI were considered for 1 m^3 of concrete from “cradle to gate” for different environmental categories. According to the sensitive analysis carried out for the transportation distances, the most probable base scenario for the centre of Portugal was considered as an adequate case study. The NativeLCA method was adopted to pick the most appropriate environmental datasets to be employed as generic data. The following conclusions can be drawn.

Broadly speaking, the EI slightly increased when SP was used (up to 4%). Furthermore, the incorporation ratio of fine RCA did not change the results for most of the EI categories. Contrary to the "incorporation ratio of fine RCA and the use of SP", and despite the long transportation distance between the coal power plant and the concrete plant considered in the case study, the EI significantly decreased (32-60%) in most categories with increasing incorporation ratios of FA. Similarly to the incorporation ratio of FA, the EI of most of the categories decreased (1-46%) when coarse NA was fully replaced with coarse RCA. Concerning the combined effects of the mentioned materials, namely incorporating both FA and RCA with or without SP, similarly to the individual effect, the EI in most of the cases changed linearly (Figure 7).

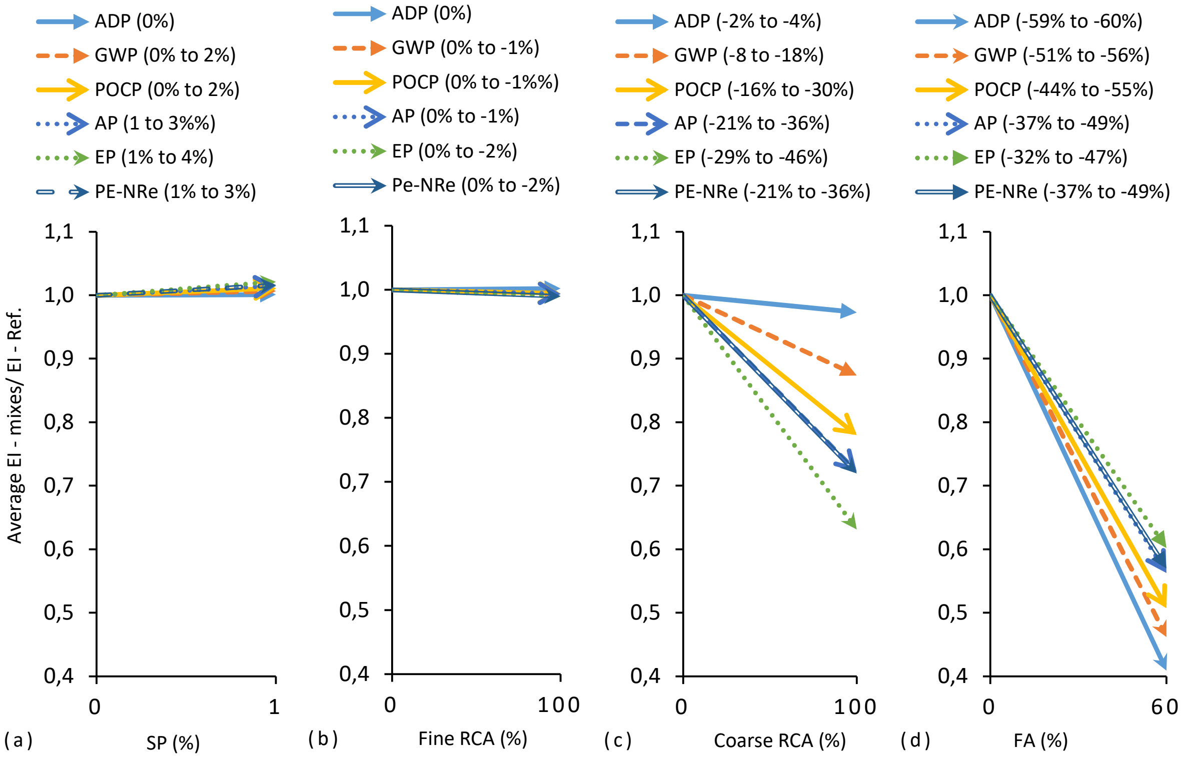


Figure 7 - Influence of incorporating SP, fine RCA, coarse RCA and FA on EI and cost of 1 m^3 of concrete for the most current scenario in the centre of Portugal. Solid lines represent decrement and dashed lines represent increment in EI relative to reference concrete "M1"

Abiotic Depletion Potential (ADP)

The ADP does not change with increasing incorporation ratio of fine RCA. However, it slightly decreased when 100% of coarse RCA were incorporated in the concrete mix. Moreover, it decreased about 30% and 60% when incorporating 30% and 60% of FA, respectively. As for fine RCA, SP does not affect the ADP. Concerning the combined effects of incorporating both FA and RCA with or without SP, the ADP linearly changed with the summation of each individual effect. As expected from the literature, cement corresponds to almost 100% of the impacts of ADP. Thus, only the incorporation of FA is efficient to decrease the total ADB of concrete.

Global warming potential (GWP)

Because the GWP is mainly affected by cement content, it significantly decreases with the incorporation ratio of FA. In fact, cement is the largest contributor to the GWP (87 - 96%). The GWP of concrete mixes seems not to be affected by the incorporation of fine RCA. However, it slightly decreased when 100% of coarse RCA incorporated in the concrete mix. Similarly to fine RCA, the use of SP did not influence the GWP of mixes as much. Furthermore, the GWP of concrete mix increased up to 1% when 1% SP was introduced. In fact, the difference between the GWP of NA and RCA concrete, with or without SP, mainly depends on the transportation distance of these aggregates rather than on their incorporation ratios. Moreover, for mixes made with both RCA and FA, the GWP linearly changed with the summation of each individual effect.

Photochemical ozone creation (POCP) potential

As for GWP, the POCP significantly decreased when FA was incorporated in the concrete mix. The impacts in this category decreased about 16% when coarse NA were fully replaced with coarse RCA, being however less affected by the incorporation of fine RCA. These trends were also found for mixes with SP. The same factors mentioned concerning the effect of incorporation of RCA, FA and the use of SP on GWP of concrete mixes can be invoked for POCP. As for incorporating fine RCA, the use of SP did not influence the POCP of mixes as much. Furthermore, the results show that by using 100% of coarse RCA and 30% or 60% of FA either with or without SP, the POCP is lower than that of the reference concrete.

Acidification potential (AP) and eutrophication potential (EP)

Similar to GWP, the AP to produce fine NA concrete is slightly lower than that of fine RCA concrete, namely due to a different transport distance. In addition, the AP decreased up to 21% when coarse NA were fully replaced by coarse RCA. As for coarse RCA incorporation ratio, the transport distance between the coal power plant “FA producer” and concrete plant was 2.7 times longer than the distance between the cement plant and the concrete plant. However, the AP decreased about 20% by incorporating 30% of FA, and the AP linearly decreased with an increasing incorporation ratio of FA. In addition, the AP of all concrete mixes slightly increased when SP was used. Broadly speaking, the percentage of changes in EP of the concrete mixes due to the incorporation ratio of FA and RCA, either without or with SP, is very close to the one found for AP. Moreover, the same conclusions that were mentioned for AP can be adapted to EP. In addition, relative to other used materials, the contribution of coarse aggregates and cement to the total EP is significant.

Consumption of primary energy, non-renewable (PE-NRe)

Although the energy consumption to produce fine NA is lower than that for fine RCA, this EI is almost the same in concrete made with them because the NRe is highly dependent on the transport distance.

Therefore, the PE-NRe of concrete slightly changed with the incorporation ratios of fine RCA. Moreover, relatively to the incorporation ratios of fine RCA, PE-NRe significantly decreased with the incorporation ratio of coarse RCA. This is due to the energy consumption required to produce coarse NA that is significantly higher (5 times) than that of coarse RCA, and because of the transport distance. Although the selected distance between the FA plant and the concrete plant is 2.7 times longer than that of the cement plant, the PE-NRe of concrete significantly decreased with the incorporation ratio of FA. As for other EI categories, in terms of the joint effects of both FA and RCA amount, with or without SP, the energy consumption linearly changed with the individual effect. In addition, by using SP in all concrete mixes with or without fine RCA and/or FA, the PE-NRe slightly increased.

Lastly, the generalization of the above conclusions, namely the almost proportional relationship between the total EI of the mixes and some of the components' content, must be viewed with some caution. In fact, it depends on the assumed scenarios and other approaches in life cycle inventory modelling.

6 Acknowledgments

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