Environmental life cycle assessment of concrete made with fine recycled concrete aggregates

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ABSTRACT: The majority of worldwide structures use concrete as its main material. This happens because concrete is economically feasible, due to its undemanding production technology and ease of use.

However, it is widely recognized that concrete production has a strong environmental impact in the planet. Natural aggregates use is one of the most important problems of concrete production nowadays, since they are obtained from limited, and in some countries scarce, resources. In Portugal, although there are enough stone quarries to cover coarse aggregates needs for several more years, supplies of fine aggregates are becoming scarcer, especially in the northern part of the country.

On the other hand, as concrete structures' life cycle comes to an end, an urgent need emerges to establish technically and economically viable solutions for demolition debris, other than for use as road base and quarry fill.

This paper presents a partial life cycle assessment (LCA) of concrete made with fine recycled concrete aggregates performed with *EcoConcrete* tool. *EcoConcrete* is a tailor-made, interactive, learning and communications tool promoted by the Joint Project Group (JPG) on the LCA of concrete, to qualify and quantify the overall environment impact of concrete products. It consists of an interactive Excel-spreadsheet in which several environmental inputs (material quantities, distances from origin to production site, production processes) and outputs (material, energy, emissions to air, water, soil or waste) are collected in a life cycle inventory, and are then processed to determine the environmental impact (assessment) of the analysed concrete, in terms of ozone layer depletion, smog or "greenhouse" effect.

1 INTRODUCTION

The construction industry is known as being environmentally inefficient. The intensive extraction of raw materials for the production of materials involved in buildings execution, the energy needed to perform heavy industrial processes and the resulting debris, both from new construction and demolition of old one, all contribute to a strong penalization of the environment.

One of the materials most used in the construction of structures is concrete because of its ease of production, low-demand technologies and easy-to-obtain materials needed in its production, leading to low production costs.

However, in order to produce concrete it is necessary to extract stone both for cement production and to be used as aggregates. Usually, concrete fine aggregates are obtained from the extraction of sand from river beds or maritime coats. However, this activity brings along severe environmental problems: the alteration of the water flow in rivers or of the tides in seas leads to the erosion of the margins, with direct consequences on the nearby infrastructures.

Even though in Portugal and particularly in the south of the country there are relevant amounts of natural sand for extraction, some recent studies (Dias, 2005) point out the need to implement more restrictive measures in terms of extraction, in order to invert the destructive process of the coasts that is being felt nowadays.

With the objective of checking the technical viability of replacing fine natural aggregates (FNA) with equivalent recycled aggregates (FRA) in concrete production, a research was endeavored at Instituto Superior Técnico aiming at evaluating the performance of concrete made with different ratios of replacement.

Notwithstanding the fact that the technical viability was proved by the results obtained (Evangelista & Brito, 2006, 2007), the economic and environmental viability needed to be checked. As a matter of fact it is not consensual nowadays that recycling is one of the paradigms in sustainability. Pereira (2004) refers clearly that in his view recycling is not a solution to the problem. Even though recognizing the benefits of this practice he states that "is not The solution". Even though recycling leads to a reduction in the use of abiotic materials, it is possible that waste treatment for future applications and/or the worst quality of the resulting products may jeopardize their reuse both in economic and environmental terms.

This paper presents a Life Cycle Assessment analysis performed on concrete with fine recycled concrete aggregates, in order to understand the real benefits brought by concrete recycling for the production of fine aggregates. This type of analysis corresponds to evaluating the various environmental impacts of each product, from its "cradle" to its "grave". The LCA analysis thus takes into account every resource and material consumed both directly (in its creation) and indirectly in all the accessory activities needed for its creation (extraction, transformation, etc.). This quantification allows the establishment of the environmental damage during its life cycle. According to the Environmental Protection Agency (EPA, 2006), the life cycle of a product is divided in four main stages:

- obtaining the raw materials - included are the resources consumed, as well as the materials and energy spent in the extractive and transport activities;
- production - included are the activities of raw materials transformation, product execution and its transport and conditioning to its destiny;
- use, reuse and maintenance - where the activities and consumptions resulting from the use and quality maintenance of the product are quantified;
- recycling and waste treatment - where the impact of the activities associated with destroying the product, as well as the impact of the resulting waste, are evaluated.

2 THE ECOCONCRETE TOOL

2.1 *General description of the software*

In order to perform LCA analyses the software Ecoconcrete, produced by the Joint Project Group (JPG), was used. This is a design tool that implements the LCA methodology specifically for the concrete production sector. Basically it is a spreadsheet within the MSExcel® platform in which data concerning production, transport, application, maintenance, and end-of-life cycle are inserted giving out the various environmental impacts felt.

To evaluate the concrete environmental impact Ecoconcrete resorts to one of three available analyses: CML, EDIP or Eco-indicator 99.

The CML methodology was developed at the Institute for Environmental Sciences of the Leiden University in Holland and proposes that the environmental impact of a product is made according to the negative effect that the different sub-products from its production have in eight different phenomena: abiotic depletion; acidification; global warming; ecotoxicity; eutrophication; human toxicity; production of photo-oxidant agents; destruction of the ozone layer. Additionally, the CML analysis predicts the concrete environmental impact by measuring the energy spent during its life cycle, as well as the chemical and non-chemical waste produced.

The EDIP (Environmental Design of Industrial Production) project, developed in partnership by various Danish entities, similarly to the CML methodology, aims at evaluating the impact during the life cycle by measuring the effects of a set of pre-established phenomena: global warming; destruction of the ozone layer; acidification; nutrients enrichment; eco-toxicity; human toxicity; photochemical ozone formation; waste gross production; toxic waste production; nuclear waste production; sludge slag and ash production.

The main difference between these two methodologies lies in the Life Cycle Inventory each one resorts to and specifically in the quantification of the impacts that the different activities cause.

Contrarily to the previous methodologies, that correspond to intermediate stages of the LCA analysis, needing post-interpretation taking into account the various parameters in question, and are therefore slow and complex (Goedkoop, 1995), Eco-indicator 99 is supposed to be a final analysis procedure, giving an environmental score to a product or process, with an easy and objective interpretation.

Eco-indicator 99 is obtained by evaluating the environmental damage in natural resources, public health and the ecosystems. The weight of each one was established through an enquiry to experts involved in a Swiss group of LCA (Baayen, 2000):

– damage to public health and the ecosystems have the same weight;
– damage to natural resources has a weight sensibly half of the previous ones.

2.2 *Limitations of Ecoconcrete*

Ecoconcrete is presently in its version 1.1. This tool is still under development and therefore there are still some factors that limit its use.

To begin with the software possesses only a limited database in what concerns elements to be evaluated. At the moment it is only possible to study four types of prefabricated concrete elements and four types of cast in situ concrete elements. Any other element that may involve different execution procedures or fabric processes is nor available yet.

Secondly the only environmental costs already inventoried from “birth” (raw materials extraction) to “gateway” (beginning of transport to destination) are those concerning three distinct types of cement (CEM I 52.5R, CEM II/A-L 32.5R and CEM III/A-42.5).

Finally, the software does not allow the direct prevision of recycled aggregates in concrete production. The only way to take into account this type of recycling is at the end of the life cycle of the product at its demolition.

3 ANALYSIS PERFORMED

3.1 *Adaptations implemented*

Because of the existing limitations of the software, adaptations were needed, both in terms of the composition of the concrete mixes under analysis and in the way the different component materials were taken into account.

The case study element selected was a 1 m^2 solid slab 0,25 m thick and with a reinforcement ratio of 70 kg/m^3.

To take into account the fact that the type of cement used in the experimental campaign (CEM I 42.5R) was not considered in the software, cement type CEM I 52.5R was used, because its chemical composition is the one that is most similar to the one of the cement used in the tests. However, this choice implies that a different strength class is considered which may affect energy consumption and gas emissions, since the difference in strength between two cements of the same type is directly related to the fineness module and the clinker burning process. However, since all the mixes analyzed have the same cement ratio, the error is going to be the same for all of them, thus allowing for acceptable comparative analyses.

To simulate the use of recycled aggregates, it was assumed at the end of the life cycle of the element under analysis that only part of it would be recycled (quantified in mass) in the production of a new slab. The remaining would be dumped. Therefore, knowing the content in fine recycled aggregates of each mix and the weight of the slab, it was possible to estimate the recycling ratio to be used as input in the software. It must also be stated that the transport distances, both for obtaining raw materials and dumping / recycling, were adapted: on the one hand, the use of recycled material on site reduces or even nullifies the distance needed to collect the fine aggregates; on the other hand, by using part of the recycled material on site, the quantity of material to be dumped is reduced (given the software limitations, this was considered by reducing the distance to the dumping site proportionally to the recycling ratio corresponding to each concrete mix). Table 1 presents the final estimate results.

Table 1. Estimate data used as input for Ecoconcrete

	Composition		
	BC	B30R	B100R
Fine aggregates content (kg/m^3)	664	610	488
Fine recycled aggregates (FRA) content (kg/m^3)	0	148	488
Distance from natural aggregates production headquarters (km)	100	70	0
Recycling ratio (%)	0	6,2	21,4
Distance from dumping ground (km)	50	46,9	39,3

3.2 *Results obtained*

Ecoconcrete quantifies the environmental impacts of the different stages of the element's life as well as the use of the various raw materials throughout the whole period, estimated as 50 years for practical terms. However and since in principle each mix will have a different service life due to its durability-related characteristics, the environmental impacts were estimated in terms of each year of the life cycle of the element. To do that the expected service life of each concrete mix was estimated based on its chloride diffusion coefficient. Since the concentration of chlorides at a given age t and depth x is given by equation (1) (BREU, 1993), it follows that service life (i.e. the time needed for a given chloride concentration (D_c) to occur at the reinforcement level) is inversely proportional to the chloride diffusion coefficient (D_{nssm}).

$$C(x,t)=C_0\left\{1-\text{erf}\left(\frac{x}{2\sqrt{D_c.t}}\right)\right\} \quad (1)$$

Therefore the estimated service life of each mix, admitting 50 years that the reference concrete BC (without recycled aggregates), is given in Table 2.

Table 2. Estimated service life for the different concrete mixes

	BC	B30R	B100R
D_{nssm} (cm^2/s)	$1{,}8\times10^{-11}$	$2{,}0\times10^{-11}$	$2{,}4\times10^{-11}$
Service life (years)	50	44,7	37,4

3.2.1 *Analysis using the CML methodology*

The analysis of the CML parameters of energy consumption and waste emission (both chemical and non-chemical) shows that there is a significant reduction of these values when FRA are included in the mix. However, if the lower durability of these mixes is taken into account, it is concluded that yearly environmental costs increase with FRA inclusion, indicating that gains obtained with recycling do not compensate the lower longevity of the material. Nonetheless, these results may be justified by the present limitation of the software that led to the consideration of unrealistically low replacement ratios (only 21% for the concrete mix with integral replacement of FNA with FRA, B100R).

In terms of the environmental parameters specified by CML, Table 3 shows that there is a linear decrease of total impacts with the replacement ratio (around 7% for B30R and 20% for B100R). However, when taking into account the lower durability of mixes with FRA, the trends are inverted and the reference concrete (BC) becomes the "cleanest" and B100R the "dirtiest".

3.2.2 *Analysis using the EDIP methodology*

The comparative analysis of the various results obtained for each of the concrete mixes analyzed is shown in Table 4. The variations of each of the parameters are within the same range as those presented in the CML methodology. This is was expected since these methodologies determine the impacts through linear combinations of the various impacts included in the LCA and the difference in absolute values is only due to the different life cycle inventories (LCI) used.

Taking into account the expected service life of each of the mixes, the benefits brought by the incorporation of FRA seem to be insufficient to compensate for the losses due to their lower durability. Again this is probably a misleading result because of the artificially low replacement ratios inserted as data because of the limitations of the software.

Table 3. Relative changes of the environmental parameters of the CML methodology

Impact parameter	BC	B30R	B100R
Destruction of the ozone layer	-	-6.4%	-19.1%
Global warming	-	-6.9%	-21.0%
Human toxicity	-	-6.9%	-20.6%
Acidification	-	-7.2%	-21.7%
Eutrophication	-	-7.6%	-23.0%
Production of photo-oxidant agents	-	-6.7%	-20.3%
Aquatic toxicity (fresh water)	-	-6.8%	-20.4%
Aquatic toxicity sediments (fresh water)	-	-6.7%	-20.1%
Ground eco-toxicity	-	-6.8%	-20.7%
Abiotic depletion	-	-6.6%	-19.7%

Table 4. Relative changes of the environmental parameters of the EDIP methodology

Impact parameter	BC	B30R	B100R
Destruction of the ozone layer	-	-6,4	-19,1
Aerial human toxicity	-	-7,5	-22,3
Global warming	-	-6,9	-21,0
Acidification	-	-7,3	-21,8
Nutrients enrichment	-	-7,4	-22,2
Chronic aquatic toxicity	-	-4,7	-15,1
Acute aquatic toxicity	-	-4,7	-15,1
Chronic ground eco-toxicity	-	-7,2	-23,2
Acute ground eco-toxicity	-	-7,5	-22,3
Aquatic human toxicity	-	-6,9	-21,5
Ground human toxicity	-	-7,6	-22,5
Production of photo-oxidant agents	-	-6,9	-20,7
Overall waste	-	-8,3	-27,1
Toxic waste	-	-5,2	-16,8
Nuclear waste	-	-3,3	-10,6
Sludge slag and ashes	-	-7,0	-22,7

3.2.3 *Analysis using Eco-indicator 99*

As referred before, Eco-indicator 99 classifies a product by giving it an environmental rating. Even though this rating is technically hard to interpret, it is an efficient way of establishing comparisons between various alternatives and pointing out the most environmentally efficient. It is clearly tailored to inform the final consumer as opposed to being analyzed by the entities associated with the production. Results are summarized in Table 5.

Concrete mixes with FRA show a better rating than the reference concrete and the more so the greater the replacement ratio. These results agree with those of the two other methodologies. Similarly to those methods, their lower durability leads to a yearly worse performance (Table 6). Again this has to do with the way the problem was stated and the limitations of the software.

4 CONCLUSIONS

The Life Cycle Assessment analyses are an excellent way of quantifying the real impact that a given product has over the environment, from the onset of the raw materials extraction to its destruction and post-processing. To be valid, these analyses must be based on ample and reliable data bases (Life cycle inventories).

Ecoconcrete uses two of the existent LCI's: CML and EDIP. Their differences basically have to do with the value attributed to the damage caused by the activities and products inventoried.

Since Ecoconcrete is still under development some of the data concerning the problems under analysis had to be introduced indirectly with some detriment to the analysis presented. As a consequence, the results under-evaluate the benefits brought by the incorporation of recycled aggregates, in particular at the end of the life cycle of the structure, where it was necessary to state lower recycling ratios than those actually existing.

Table 5. Absolute results of the Eco-indicator 99 analysis for all concrete mixes analyzed

	BC	B30R	B100R
Cement	3,810	3,810	3,810
Aggregates	0,100	0,097	0,090
Admixtures	0,106	0,106	0,106
Reinforcement	1,463	1,463	1,463
Water	0,000	0,000	0,000
Transport constituents	0,930	0,831	0,653
Fabrication	0,104	0,104	0,104
2, Transport to site	0,000	0,000	0,000
3, Construction	0,104	0,104	0,104
4, Maintenance	0,000	0,000	0,000
5, Demolition	0,806	0,787	0,745
6, End of life scenario	0,894	0,826	0,676
Total	8,316	8,128	7,750
Δ	-	-2,26	-6,81

Table 6. Eco-indicator 99 results taking into account the different service lives

	BC	B30R	B100R
EI99	8.316	8.128	7.75
EI99 / ano	0.166	0.182	0.207
Δ (%)		9.33	24.59

A determining factor in the impact of concrete with FRA is the lower use of natural aggregates, with a consequent decrease of the impacts from their extraction. This was not quantified in the present version of the software since the input does not allow a decrease in the amount of natural aggregates without repercussions in the overall composition of the mix.

Nevertheless, the LCA analyses performed pointed consistently to an environmental benefit resulting from the replacement of FNA with FRA, even though overbalanced by the lower service lives of concrete mixes with FRA. For the reasons given above due to the present limitation of the Ecoconcrete software, it is believed that this last trend may be reversed.

5 REFERENCES

Baayen, H., 2000, *Eco-indicator 99: a damage oriented method for Life Cycle Impact Assessment, Manual for designers*: Dutch Environmental Ministry

BREU P3091, 1993, *Assessment of performance and optimal strategies for inspection and maintenance of concrete structures using reliability based expert systems*, Final technical report.

Dias, J., 2005, *Evolution of the Portuguese coastal area: autotrophic and natural impediments*, Scientific Meetings Journal, V. 1, pp. 7-27 (in Portuguese).

EPA, 2006, *Life cycle assessment: principles and practice*, Report EPA/600/R-06/060.

Evangelista, L. & Brito, J., *Carbonation and chloride penetration in concrete made with fine recycled concrete aggregates*, SIABE 06 - Iberian-American Symposium “Concrete in Structures”, Rio de Janeiro.

Evangelista, L. & Brito, J., *Mechanical behavior of concrete made with fine recycled concrete aggregates*, Cement and Concrete Composites, V. 29, n. 5, pp. 397-401.

Goedkoop, M., *The Eco-indicator 95: weighting method for environmental effects that damage ecosystems or human health on a European scale*, Final report, PRE Consultants B.V.

Goedkoop, M. & Spriensma, R., *The Eco-indicator 99: a damage oriented method for Life Cycle Impact Assessment*, Methodology Report, 3rd Ed., PRE Consultants B.V.

Pereira, F., *Illusions and paradoxes of recycling: the way to dematerialization of the economy*, , Waters & Waste Journal, n. 5/6 (in Portuguese).