Journal of Building Engineering 5 (2016) 24–33

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

# Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment

Nicolas Serres [a,*], Sandrine Braymand [b], Françoise Feugeas [a]

[a] ICube, INSA de Strasbourg, CNRS, 24 Boulevard de la Victoire, 67084 Strasbourg Cedex, France
[b] ICube, Université de Strasbourg, CNRS, 72 Route du Rhin, BP 10315, 67411 Illkirch Cedex, France

ARTICLE INFO

*Article history:*
Received 16 April 2015
Received in revised form
15 November 2015
Accepted 16 November 2015
Available online 18 November 2015

*Keywords:*
Waste
Life cycle assessment (LCA)
Recycled aggregate
Concrete
Recycling

ABSTRACT

Recycled concrete aggregates from demolition constitute one of the largest waste streams within the developed countries. These study aims to quantify environmental impacts associated with mixing compositions of concrete made of waste materials by using LCA. Environmental performances of natural, recycled and mixed 20-mm concrete samples, formulated with the same mechanical strength regarding the functional unit, were evaluated. Eight millimeter concrete samples, formulated with natural or recycled (concrete or terracotta brick) aggregates – with the same volume composition of the granular skeleton for apparent concrete application regarding the functional unit – were also studied. The LCA results are presented using various impact assessment methods, according to both EN 15804 and NF P 01–010 standards. Recycled samples present good environmental behavior, even if recycled materials (sand and aggregates) involve different operations (crushing against extraction, etc.). The terracotta 8-mm concrete sample presents low environmental impacts in comparison with the other 8-mm concrete samples. This sample exhibits a low aggregate density, which decreases transport impacts, and good mechanical strengths, which improves its lifetime.

## 1. Introduction

Building activity is requiring amounts of materials (such as gravel and sand) derived mainly from natural sources and is generating high quantity of wastes. The growing environmental concerns; the increasing footprint of landfills coupled with waste landfill costs; the quickly depletion sources of valuable natural aggregate in some developed countries, as well as waste storage limitation, inciting a reduction of the environmental footprint of waste treatments, are the driving forces promoting the recycling of concrete demolition wastes in new concrete. The recycling of these wastes and the solid waste stream are in this way considered important steps towards sustainable construction applications [1,2].

The abusive extraction of aggregates from natural resources has been highlighted at an international level, because of the depletion of quantity of primary resources in context of an awareness of the environmental protection [3]. The construction field is responsible for considerable waste flows within human society, as well as for the depletion of material and energy consumptions [4]. Recycled concrete aggregate used for construction can ease aggregate shortage problem and reduce both environmental pollution and ecological footprint [5].

It has been recognized that concrete manufactured using recycled concrete aggregate could have mechanical properties equal to the natural aggregate concrete provided that the parent concrete is of good quality [6,7]. However, manufacturing problems encountered limit their industrial use, mainly attributed to the high water absorption, the angular character of these aggregates, the particle size distribution of recycled sand [8] and to the substitution of natural sand by recycled sand [9].

During the last decade, there has been an increasing interest in assessing and measuring the environmental performances of cement and concrete [10–12]. Life cycle assessment (LCA), a standardized methodology (ISO 14040–14044), allows the evaluation of both material and energy flows, as well as environmental impact of products and processes over their lifecycle. LCA offers potential as a tool for qualitative and quantitative evaluation of the environmental advantages of a process, and for ranking processes according to cleanliness in the construction industry [13]. Papers which deal with environmental assessment of recycled concrete aggregate were published [14,15] and they were mainly focused on impacts of aggregate production *versus* waste treatment, without worrying about the nature and the origin of the aggregates. There is a published work in the specific area of environmental assessment of natural aggregate concrete and

---

[*] Corresponding author.
*E-mail address:* nicolas.serres@insa-strasbourg.fr (N. Serres).

http://dx.doi.org/10.1016/j.jobe.2015.11.004
2352-7102/

recycled aggregate concrete and their comparison [16,17]. It has been demonstrated (from Swiss data) that recycled concrete (RC) mixtures reduce the environmental impacts to about 70% of the conventional concrete samples impacts if co-products from the recycling process are not excluded from the scope, and cause similar global warming potential if additional cement and transport for RC are limited [16]. However, as it is often the case in the current literature, other LCA results (from Serbian LCI data) show that the impacts of cement and aggregate production phases are slightly larger for recycled aggregate concrete than for natural aggregate concrete, because a slightly larger amount of cement is required for recycled aggregate concrete in order to obtain the same compressive strength and same workability for both samples [17].

Thus, it seems interesting to evaluate the environmental impact of concrete materials with regards to the origin of aggregate content. Beyond materials, this is the global design of the construction structure which must be taken into account in order to appreciate its ecological behavior. Firstly, three 20-mm concrete samples have been studied: a traditional concrete, which was elaborated with natural aggregates; a recycled concrete, which was elaborated with recycled coarse aggregates and recycled sand; and a mixed concrete, which was elaborated with recycled coarse aggregates and natural sand. Secondly, 8-mm concrete samples which were manufactured with waste products (concrete or terracotta brick wastes) were compared to a natural aggregate concrete (gravel extraction).

## 2. Experimental procedure

### 2.1. Materials

Six concrete samples were studied (Table 1). They were manufactured using the EN 206–1 standard [18]. The recycled aggregates (coarse gravel and sand) come from recycling of demolition waste and they are produced in Alsace (France). The natural aggregates are silico-calcareous rolled rocks from a gravel pit based in Alsace. Three grading classes were delivered for natural aggregates: 0/4 mm, 4/8 mm and 8/16 mm, while one grading class (0/20 mm) was delivered for recycled aggregates, and grading selections have been completed to obtain the three following classes: 0/6.5 mm, 6.5/13.5 mm and 13.5/20 mm. Terracotta aggregates are issued from crushed waste bricks. From one grading class (0/20 mm), grading selections have been completed in order to obtain the following classes: 0/4 mm, 4/8 mm, 8/20 mm.

#### *2.1.1. 20-mm Concrete samples*

The constitution of the granular skeleton was established according to the Dreux–Gorisse method [19], with continuous grading curves. The densities of aggregates were considered for the formulation, with an identical volume of solid phase for all samples. Three 20-mm concrete samples were studied (Table 1). The composition is given in cube meter, with the aim to reach a concrete compressive strength class of C35/45. CEM I 52.5 N CE CP2 NF Portland cement was used for experimentation. The cement content was kept constant, *i.e.* 350 kg/m$^3$. The other parameters were fixed using the Dreux–Gorisse method and the Bolomey formula [20]. The traditional concrete will be considered as the referential concrete, consequently it was formulated without admixture. It is assumed that the water absorbed into the aggregate (recycled or not) will not affect the effective water.

For both recycled (RC) and mixed (MC) 20-mm concrete samples, a superplasticizer admixture (Sika® Viscocrete 5400 F) was used in order to increase the fluidity of the fresh concrete and thus to reach the desired workability (slump class S2). The admixture dosage, *i.e.* 0.75% of the cement mass for the MC sample and 3% of the cement mass for the RC sample, was found experimentally to reach a slump class S2 (50–90 mm of slump) according to the EN 206–1 standard.

#### *2.1.2. 8-mm Concrete samples*

Three other concrete samples, *i.e.* 8-mm concrete with a coarse aggregate size of 8 mm, were also studied (Table 1). The aimed application of these 8-mm concrete samples is apparent concrete, thus another formulation method was used, *i.e.* the volume composition of the natural aggregate concrete (NAC) was determined in order to reach a minimal concrete compressive strength class of C30/35, with a constant cement content (495 kg/m$^3$) and a fixed water content to reach a W/C rate of 0.5 (considering total water).

**Table 1**
Mixture composition of the samples used in this paper.

20-mm concrete samples (*size of the grain: 20 mm*)

| **Concrete** | **Nomenclature** | **Natural sand**[a] **0/4 mm** kg/m$^3$ | **Recycled sand**[a] **0/6.3 mm** | **Natural coarse gravel**[a] **8/16 mm** | **Recycled coarse gravel**[a] **13/20 mm** | **Natural fine gravel**[a] **4/8 mm** | **Recycled fine gravel**[a] **6.5/13 mm** | **Cement** (CEM I) | **Total water** | **Admixture**[b] |
|---|---|---|---|---|---|---|---|---|---|---|
| Traditional | TC | 685 | 0 | 1065 | 0 | 111 | 0 | 350 | 194 | Without |
| Mixed | MC | 759 | 0 | 0 | 852 | 0 | 115 | 350 | 180 | 2.6 |
| Recycled | RC | 0 | 769 | 0 | 424 | 0 | 442 | 350 | 165 | 10.5 |

8-mm concrete samples (*size of the grain: 8 mm*)

| **Concrete** | **Nomenclature** | **Sand** 0/4 mm kg/m$^3$ | **Gravel** 4/8 mm | **Cement** (CEM II) | **Water** | **Admixture**[b] | **Aggregate density** g/cm$^3$ |
|---|---|---|---|---|---|---|---|
| Natural | NAC | 1100 | 742 | 495 | 247 | Without | 2.41 |
| Brick [c] | BAC | 1215 | | 495 | 247 | 24.7 | 1.60 |
| Recycled [d] | RAC | 1067 | 770 | 495 | 247 | 4.9 | 2.38 |

[a] Natural aggregate density: 2.60 g/cm$^3$; recycled aggregate density: 2.35 g/cm$^3$.

[b] The Sika® Viscocrete 5400 F superplasticizer agent, produced by the Sika Company, was used.

[c] The recycled brick aggregate concrete (BAC) sample was formulated with recycled terracotta tiles.

[d] The recycled concrete aggregate concrete (RAC) sample was formulated with recycled sand as well as recycled coarse gravel.

8-mm concrete samples were carried out with CEM II/A-L 32.5 R CE CP2 NF cement. These samples allow to develop a new waste stream for terracotta brick wastes and in this way one objective was to characterize only the influence of the substitution of the natural material by the recycled brick or the recycled concrete, maintaining the same volume proportions (same dosage for aggregates and cement). It is assumed that the environmental impacts of both CEM I and CEM II are not same due to different content of clinker. However, the samples are compared by groups.

The two other 8-mm concrete samples, *i.e.* the recycled concrete aggregate concrete sample (RAC) and the recycled brick aggregate concrete sample (BAC), were formulated with the same volume composition. Only the nature of the aggregate changes. Thus, the compositions in weight percent are different, because of the density values of the aggregates (Table 1). The same water quantity was used, even if absorption depends on aggregate type. This implementation problem due to the high water absorption of the terracotta bricks have been solved by the use of a superplasticizer admixture (Sika® Viscocrete 5400 F), allowing to increase the fluidity of the concrete paste. The admixture content was found experimentally to reach a slump class in the range of S1 (10–40 mm of slump)-S2 (50–90 mm of slump) according to the EN 206–1 standard. The admixture rate of the BAC sample is high, but it remains in accordance with the EN 934–2 standard [21].

### *2.2. Environmental comparisons of materials*

The LCA was based on international standards ISO 14040 [22], 14044 [23]: the limits of the study are presented in Fig. 1. Both 'use' and 'end of life' phases were not included in the system boundaries, because this work was focused on a cradle-to-gate assessment. The analyzed part of the life cycle includes production and transport of sand and gravels, cement, aggregates, and admixtures, as well as production of concrete. Short supply distances were retained and the assumption has been made that transportation distances from recycling centers correspond to road uses and are optimized for production of recycled aggregates for concrete production (Table 2). It was also assumed that the transport of all components was carried out by truck. The functional unit (F.U.) used as reference to compare the various samples was based on a reference flux model ($m^3$ of product) and it takes into account of all components useful for the implementation of samples, as well as dust production. Two sets of samples were compared (20-mm concrete and 8-mm concrete samples) and in all cases the F.U. follows a specific purpose, *i.e.* the three 20-mm concrete samples have been manufactured in such a way to have the same strength (Fig. 2) and the three 8-mm concrete samples have been manufactured in such a way to have the same volume composition with a minimal strength (in order to present the same aspect), according to the use of the same volume quantity of materials. In the first case, the same compressive strength does not always guarantee the same durability, but the typical lifetime is assumed to be equal to 100 years. In the second case, F.U. of $m^3$ has no sense, if the 8-mm concrete samples are assimilated as structural concrete samples. However, these samples aspire to be used as facing concrete: that is the esthetic aspect that is put forward (Fig. 3), which justifies the same aggregates volume composition, as well as large admixture rates, in order to obtain a good workability and thus the same aggregate quantity in all samples (Fig. 3). Thus a F.U. of $m^3$ is relevant in such application.

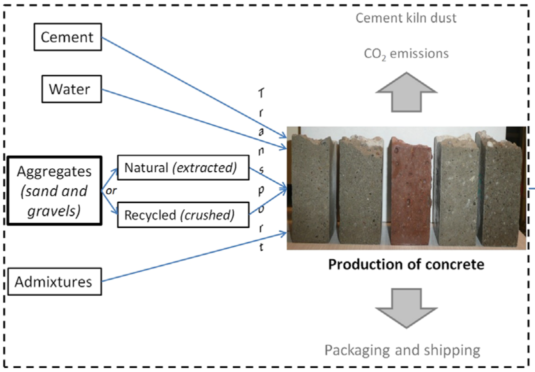

**Fig. 1.** Life cycle of concrete samples.

**Table 2**
Transport distances for aggregates, cements and admixture.

| **Component** | | **Distance (km)** |
|---|---|---|
| Cement | CEM I 52.5 N CE CP2 NF | 125 |
| | CEM II/A-L 32.5 R CE CP2 NF | 125 |
| Aggregate | Natural sand | 30 |
| | Recycled sand | 10 |
| | Natural coarse gravel | 30 |
| | Recycled coarse gravel | 10 |
| | Natural fine gravel | 30 |
| | Recycled fine gravel | 10 |
| | Recycled terracotta tiles | 10 |
| Superplasticizer admixture | | 165 |

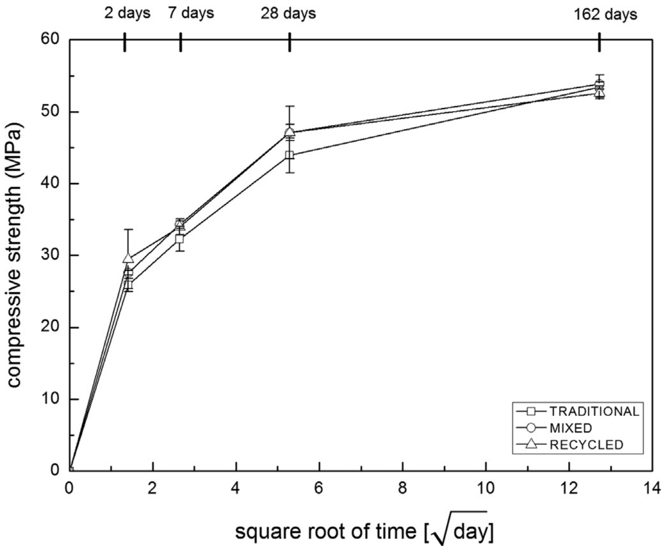

**Fig. 2.** Compressive strength values of the studied 20-mm concrete samples at several days of age.

The environmental comparisons were carried out with the SimaPro (7.2) software [24] by using various impact assessment methods. Some methods make it possible to characterize the environmental impact indicators according to the EN 15804 standard [25], as well as the NF P 01-010 standard [26], related to the environmental and health product declaration (Table 3).

The EPD method[1], which is specific for the creation of Environmental Product Declarations, allows evaluating different category indicators, which are presented in Table 3, at the midpoint level. The CML method[2] groups the life cycle inventory results into midpoint categories, according to themes such as climate change or ecotoxicity. This method was used for calculation of specific impact indicators (Table 3). Both EDIP[3] (Environmental Design of Industrial Products) method and BEES[4] (Building for

---

[1] Swedish Environmental Management Council.
[2] Institute of Environmental Science of Leiden University, The Netherlands.
[3] Institute for Product Development Technical, University of Denmark.
[4] National Institute of Standards and Technology.

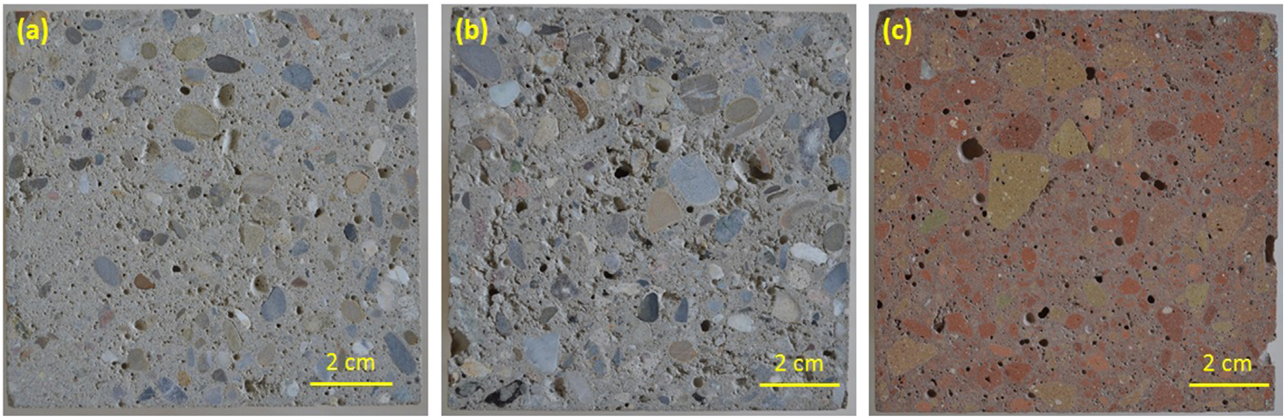

**Fig. 3.** Microscopic observations of (a) natural aggregate concrete (NAC); (b) recycled concrete aggregate concrete (RAC) and (c) recycled brick aggregate concrete (BAC) samples.

**Table 3**
Studied environmental impact indicators and assessment methods.

| Impact indicator | Unit | Standard | | Method | | | |
|---|---|---|---|---|---|---|---|
| | | NF P 01–010 | EN 15804 | EDP | CML | EDIP | BEES |
| Consumption of energetic resources | MJ | X | X | X | | | X |
| Abiotic depletion | kg Sb eq | X | X | | X | | |
| Water consumption | L | X | | | | | X |
| Global warming | kg $CO_2$ eq | X | X | X | X | X | X |
| Acidification | kg $SO_{2\ eq}$ | X | X | X | X | | |
| Eutrophication | kg $PO_4^{3-}$ eq | | X | X | X | | |
| Air pollution | $m^3$ | X | | | X | X | |
| Water pollution | $m^3$ | X | | | | X | |
| Ozone layer depletion | kg CFC–11 eq | X | X | X | X | X | X |
| Photochemical oxidation | kg $C_2H_4$ eq | X | X | X | X | | |

*Note:* the EDIP and BEES methods consider also other environmental impact indicators that do not fall within the legislative and regulatory framework of the EN 15804 and NF P 01-010 standards, and are therefore not included in this study.

**Table 4**
Eco-profile for 1 kg of superplasticizer according to the NF P 01-010 standard (data collected by the SYNAD).

| Raw material | Unit | Value |
|---|---|---|
| **Consumed** | | |
| Coal, brown (lignite) | g | 82 |
| Coal, hard | g | 51 |
| Oil, crude | kg | 0.16 |
| Gas, natural | $m^3$ | 0.22 |
| **Released to air** | | |
| $CO_2$ | kg | 0.72 |
| CO | g | 0.55 |
| $NO_x$ | g | 1.8 |
| $SO_x$ | g | 3.6 |
| $N_2O$ | mg | 67 |
| Methane | g | 1.2 |
| Butane | mg | 11 |
| Pentane | mg | 14 |
| Methanol | mg | 60 |
| Ethane | mg | 8.9 |
| Benzene | mg | 7.4 |
| NMVOC, non-methane volatile organic compounds | g | 0.29 |
| Hydrocarbons, aromatic, polycyclic | µg | 39 |
| Acetic acid | mg | 63 |
| Ammonia | g | 2.1 |
| Arsenic | µg | 58 |
| Chromium VI | µg | 16 |
| Mercury | µg | 94 |
| Nickel | mg | 0.46 |
| Vanadium | mg | 1.2 |
| Dioxins | ng | 43 |
| Methane, tetrachloro–, CFC–10 | µg | 2 |
| Ethane, 1,2–dichloro–1,1,2,2–tetrafluoro–, CFC–114 | µg | 1.8 |
| Methane, bromochlorodifluoro–, Halon 1211 | µg | 4.1 |
| Methane, bromotrifluoro–, Halon 1301 | µg | 5 |
| **Released to water** | | |
| COD, chemical oxygen demand | g | 2.6 |
| Hydrocarbons, aromatic, polycyclic | µg | 67 |
| Oils | g | 0.63 |
| Barite | mg | 51 |
| Nickel | mg | 3.9 |
| **Released to ground** | | |
| Chromium VI | mg | 0.22 |
| Oils | g | 0.66 |
| **Solid waste** | | |
| Waste, inert | g | 21 |
| Waste, toxic | g | 0.45 |
| **Total energy** | | |
| Total energy | MJ | 18.3 |

Environmental and Economic Sustainability) method, which evaluate category indicators – specified in Table 3 – at the mid-point level, have also been used to take into account water intake, air and water pollutions impact categories.

The impact categories considered by these four methods, but with a different unit, are not considered in this paper. For example, the CML method assimilates the water pollution as aquatic eco-toxicity in kg 1,4–DB eq. instead of $m^3$ in the NF P 01–010 standard.

SimaPro contains a number of impact assessment methods, and all the used methods are included in this software.

### 2.3. Life cycle inventory

In order to evaluate the environmental impact of samples, it is necessary to analyze all constituents, such as cement, water and admixture as well as fine and coarse aggregates and the processes of elaboration, which for cement or other components are well documented in the current literature: it was thus possible to collect environmental data. The sample manufacturing models describing material inputs (kilograms) and energy inputs (kWh), as well as emission outputs were based on the international standardization, such as RILEM [27] or BS–8500–2:2002 [28] and the authors' experience. Eco-profiles were also used to evaluate environmental damages of aggregates and superplasticizer admixture. For the raw and recycled aggregates, data have been collected by the French Aggregates Association (UNPG). Admixture data have been collected by the French National Union of Admixtures for Concrete and Mortar (SYNAD). The environmental data concerning natural and/or recycled aggregates could be accessed online [29], while the basic inputs and outputs for admixture are given in Table 4. Others data, such as concrete production, transport processes, cement or water, come from the ecoinvent database.

For all life cycle stages, a statement of material and energy consumptions was carried out for all inputs and outputs of the system. Inputs are energy, water consumption and materials (extracted from ore or recycled) which are consumed for all stage of the life cycle. Outputs are water, air and/or ground emissions (*e.g.* cement dust), as well as wastes which are produced at all stages. These inputs and outputs are collected and pondered according to the functional unit, with a special attention to the other consumptions, linked to the transport, processes efficiency, etc.

Finally, the lifespan of the samples (20-mm concrete and 8-mm concrete) can be estimated in LCA considering mechanical properties. Compressive strength tests (according to the NF EN 12390–3 standard [30]) were carried out (Figs. 2 and 6). Cylindrical specimens (diameter 110 mm-height 220 mm) as well as cube specimens of 100 mm side were made. Once removed from their molds after 24 h, they were cured in an environmental chamber (T = 20 ± 2 °C; R.H. = 80 ± 5%) until to reach the test age. Three batches were made for each mix, and the results were considered to be the arithmetic mean of the three values obtained.

## 3. Environmental comparisons of the 20-mm concrete samples

LCA allows considering an environmental comparison of the different samples. This LCA compares environmental impact indicators of building materials, based on the same functions for the 20-mm concretes on the one hand, and the 8-mm concretes on the other hand.

The environmental impact indicators of the three 20-mm concrete samples (MC, RC and TC samples) are presented in Table 5 and Fig. 4, according to both EN 15804 and NF P 01–010 standards. The recycled 20-mm concrete sample (RC) presents the best environmental behavior: the majority of environmental indicator impacts is significantly inferior in comparison with the traditional 20-mm concrete sample (TC), which was evaluated as a reference and it is also slightly lower (except acidification) than the mixed 20-mm concrete sample (MC). The integration of both recycled sand and aggregates in the formulation of this 20-mm concrete seems advantageous concerning its environmental behavior.

**Table 5**
Environmental impact indicators of the 20-mm concrete samples.

| Impact categories | Unit | Mixed concrete MC | Recycled concrete RC | Traditional concrete TC |
|---|---|---|---|---|
| *Consumption of energetic resources* | *$10^3$ MJ* | *1.60* | *1.39* | *2.14* |
| *Abiotic depletion* | *kg Sb eq* | *1.19* | *0.87* | *1.64* |
| Water consumption | $10^5$ L | 6.67 | 5.85 | 7.80 |
| *Global warming* | *$10^2$ kg $CO_2$ eq* | *3.79* | *3.35* | *4.44* |
| *Acidification* | *kg $SO_2$ eq* | *1.08* | *1.22* | *0.86* |
| *Eutrophication* | *kg $PO_4{}^{3-}$ eq* | *0.17* | *0.13* | *0.22* |
| Air pollution | $10^5$ $m^3$ | 5.41 | 4.02 | 7.53 |
| Water pollution | $10^3$ $m^3$ | 2.72 | 2.22 | 3.38 |
| *Ozone layer depletion* | *$10^{-5}$ kg CFC–11 eq* | *2.10* | *2.01* | *2.87* |
| *Photochemical oxidation* | *kg $C_2H_4$ eq* | *0.10* | *0.07* | *0.13* |

*Note:* the italicized boxes represent the impact values considered by the EN 15804 standard.

The increase of the acidification environmental impact indicator may in part be explained by the presence of a superplasticizer admixture in the recycled and the mixed 20-mm concrete samples. Both RC and MC samples contain admixture in their chemical compositions (3% and 0.75% respectively), which can sensibly increase environmental impacts, especially as this impact indicator is more consequential for the RC sample which contains more admixture (Table 1). During the synthesis of a superplasticizer, substances with a high atmospheric acidification potential such as $NO_x$, $SO_x$, acids, etc. are released to the air.

For all categories, the differences between both RC and MC samples and the TC sample remain moderate because the use of recycled materials (sand and/or aggregates) induces more operations, *e.g.* riddling or crushing.

The climate change and air pollution indicators, quite big, may be linked to emissions of both organic substances and dust to air. If the MC and the RC samples have lower values for these impact indicators, this may be due to a reduction of transport operations (material quantities and distances), because these samples are formulated (or part thereof) with recycled sand and aggregates. Concerning this life cycle assessment, it is not necessary to consider the upstream transport of building material wastes to the recycling site. The upstream transport of building wastes (and not only transport, but the whole treatment process) is an allocation issue. It is the question how to allocate the impacts of waste treatment between the product which generates waste and product which receives waste. In this paper it is assumed that waste transport (whether to recycling site or to landfill) is allocated to product which generates waste, and the impacts of recycling are allocated to product which receives waste. Thus, this transport would take place to inert waste storage facilities, whatever happens. It is therefore not necessary to extract and transport raw materials from a quarry, which limits emissions of both organic substances and dust to air. Moreover, all samples contain the same amount of cement (CEM I), responsible of $CO_2$ emissions during its manufacture, which can increase these environmental impact indicators.

The water consumption environmental impact indicator, quite big too, highlights the best behavior of the recycled and the mixed 20-mm concrete samples (both samples contained less water in their formulations) in comparison with the traditional 20-mm concrete sample. The recycled aggregates present various compactness considering that they are formed by coarse gravel and sand, whereas the natural aggregates are rolled rocks from gravel pit. In other words, there are less granular materials (in kg) per cube meter of concrete: there is a dilution effect.

## 4. Environmental comparisons of the 8-mm concrete samples

The environmental impact indicators of the 8-mm concrete samples are presented in Table 6 and Fig. 5, according to both EN 15804 and NF P 01-010 standards. The recycled concrete aggregate 8-mm concrete sample (RAC), formulated with both recycled sand and aggregates, presents a good environmental behavior in comparison with the natural aggregate 8-mm concrete sample (NAC). All impact categories related to the EN 15804 standard are lower (or equivalent for acidification) than the NAC sample. This specific comparison between the RAC and the NAC samples is in accordance with the earlier comparison between the RC and the TC 20-mm concrete samples in the previous section. The Table 6 reveals also that the recycled brick aggregate 8-mm concrete sample (BAC) presents low environmental indicator impacts, closer to the RAC sample than the NAC sample.

This BAC sample is formulated with a material that have minor

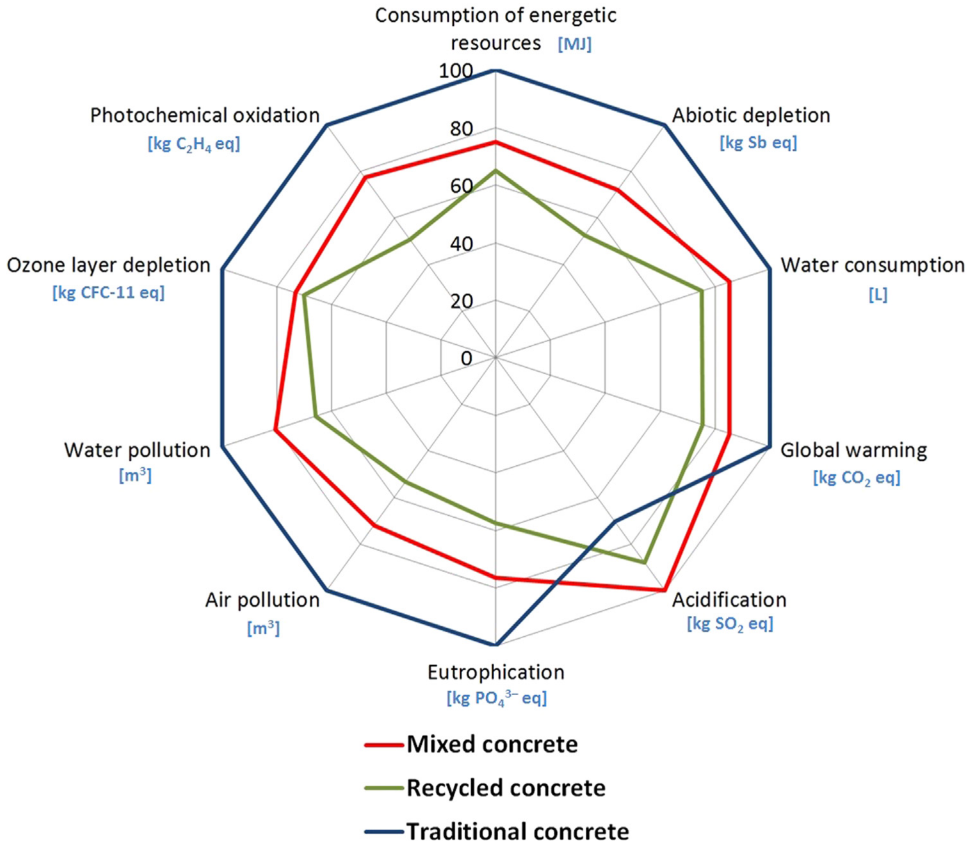

**Fig. 4.** Environmental assessment of the 20-mm concrete samples according to both the EN 15804 and the NF P 01-010 standards.

**Table 6**
Environmental impact indicators of the 8-mm concrete samples.

| **Impact categories** | **Unit** | **Recycled brick aggregate concrete BAC** | **Natural aggregate concrete NAC** | **Recycled concrete aggregate concrete RAC** |
|---|---|---|---|---|
| *Consumption of energetic resources* | *$10^3$ MJ* | *1.87* | *2.22* | *1.29* |
| *Abiotic depletion* | *kg Sb eq* | *0.99* | *1.70* | *0.90* |
| Water consumption | $10^5$ L | 6.37 | 8.45 | 6.66 |
| *Global warming* | *$10^2$ kg $CO_2$ eq* | *3.66* | *4.69* | *3.57* |
| *Acidification* | *kg $SO_2$ eq* | *0.98* | *0.75* | *0.90* |
| *Eutrophication* | *kg $PO_4^{3-}$ eq* | *0.15* | *0.23* | *0.13* |
| Air pollution | $10^5$ m$^3$ | 6.44 | 8.77 | 4.76 |
| Water pollution | $10^3$ m$^3$ | 2.52 | 3.56 | 2.39 |
| *Ozone layer depletion* | *$10^{-5}$ kg CFC−11 eq* | *2.67* | *2.96* | *1.65* |
| *Photochemical oxidation* | *kg $C_2H_4$ eq* | *0.06* | *0.14* | *0.07* |

*Note:* the italicized boxes represent the impact values considered by the EN 15804 standard.

impact (terracotta bricks) [31]. The reasoning is conducted on the density of samples. Then, the formulation of the BAC sample allows using fewer resources, which is confirmed by the results where the environmental indicator impacts ‘abiotic depletion’ and ‘resource consumption’ are low in comparison with the NAC sample (Table 6). The density of the BAC sample is equal to 1.6 g/cm$^3$, against 2.41 g/cm$^3$ for the NAC sample and 2.38 g/cm$^3$ for the RAC sample. However, a high part of admixture (5%) is used to manufacture the BAC sample, which can increase its environmental behavior. The BAC sample exhibits a low aggregate density, which could slightly decrease environmental impacts related to the transport operations. As a consequence, the ‘global warming’ environmental indicator impact is low in comparison with the NAC sample. However, the reduction of the environmental impact of the BAC sample should not only be related to the environmental behavior of the terracotta bricks. The lifetime of the 8-mm concrete samples was also considered. Compressive strengths measurements have been implemented (Fig. 6) and the samples formulated with terracotta bricks have high mechanical strengths, improving their lifetime and like so their environmental impact, in comparison with the natural and the recycled 8-mm concrete samples. The results of BAC compressive strength are surprisingly well. However, the BAC sample was formulated with waste aggregates from factory, which are clean, without contaminants that may decrease the mechanical resistance. The high mechanical strengths could be also explained by the formulation method (same volume composition for all components for all samples), in particular as regards the water dosage, because formulations were made with constant total water rate. During mixing operation, much of the water absorbed by the aggregates is released into the concrete, but a part of this water stay in aggregate. This amount of water is not experimentally definable and because the 8-mm concrete samples are supposed to be used as facing/apparent concrete, it seems better to work at a constant total water rate [32].

For the three 8-mm concrete samples, the difference between the environmental indicator impacts, *i.e.* the global result, is more pronounced in comparison with the three concrete samples (Tables 5 and 6). This could be attributed to the specific formulation, *i.e.* the three 8-mm concrete samples have the same volume composition. The proportions by weight are therefore different. There is also a contribution of the cement (CEM II), inducing

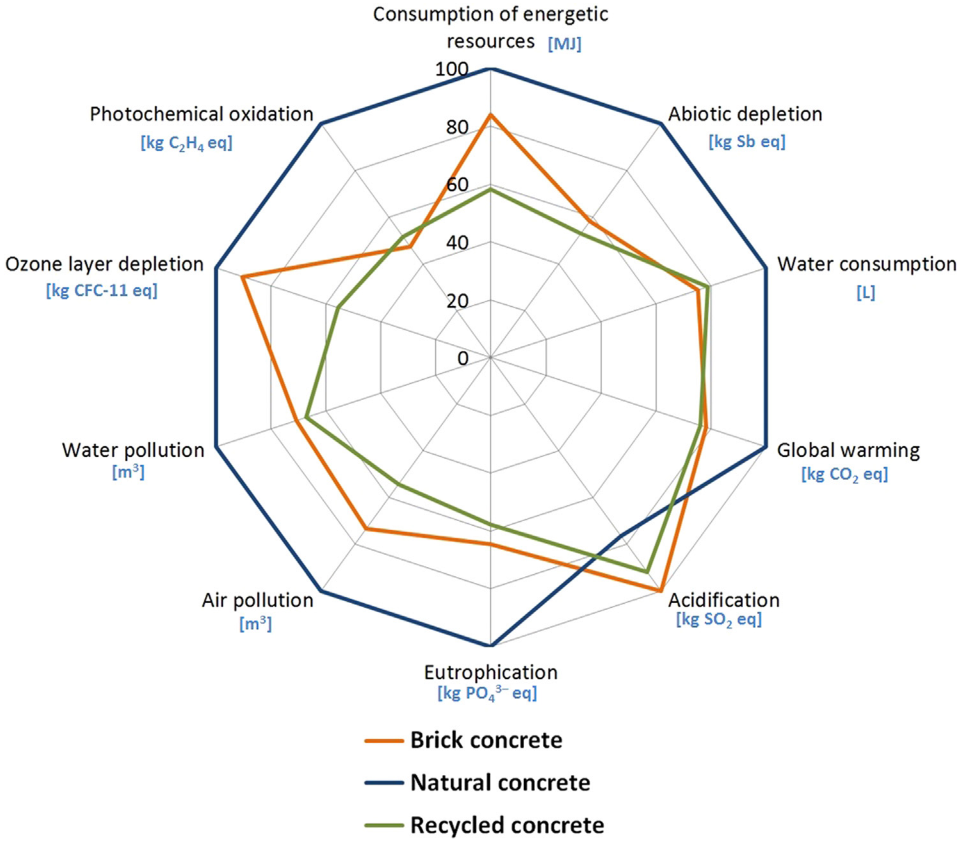

**Fig. 5.** Environmental assessment of the 8-mm concrete samples according to both the EN 15804 and the NF P 01-010 standards.

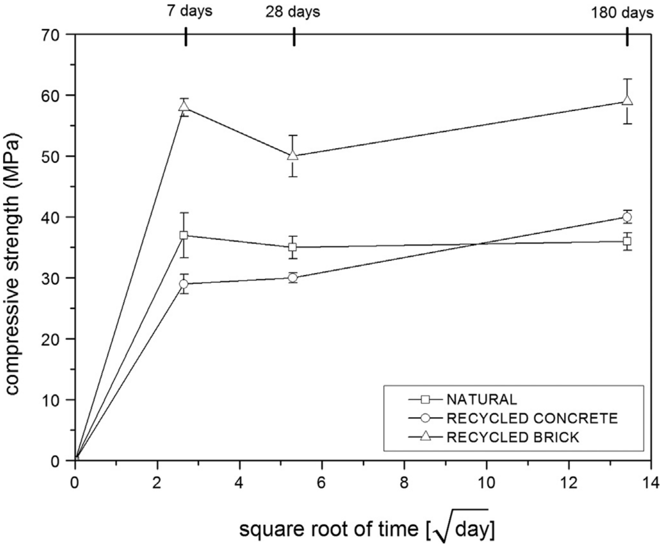

**Fig. 6.** Compressive strength values of the studied 8-mm concrete samples at several days of age.

emissions of $CO_2$. The amount of cement used to manufacture the 8-mm concrete samples is proportionally higher for these samples than the concrete samples (495 kg/$m^3$ against 350 kg/$m^3$), which can change the result of the LCA.

## 5. Discussion

The results obtained for the three 20-mm concrete can be directly compared because their functions, *i.e.* identical mechanical strengths, are equal. The general reduction of the environmental indicator impacts of the recycled 20-mm concrete sample (and also the mixed 20-mm concrete sample) remains moderate in comparison with the traditional 20-mm concrete sample because the utilization of recycled materials (sand or gravel) involves more operations, such as crushing, conditioning, cleaning, etc. In addition, the utilization of recycled materials induces conversion of land or occupation of land. For the 8-mm concrete samples, the esthetic aspect is put forward. However if a structural implementation would be expected as function for this material, it would be obvious to analyze a m² of wall, and therefore less material would be used in the case of the BAC sample. But, if the wall thickness is defined by an architectural criterion, it would reduce the amount of cement, or an extra quantity of water would be added, with few admixtures to obtain the same strength that natural concrete. In any case, this would lead to reduce the environmental impacts, and then the BAC sample would be even better.

In the 20-mm concrete samples case, similar compressive strength (durability) and workability should provide the same function with regard to functional unit. However, this objective is obtained by retaining the same cement amount and changing the water and admixture amounts, which is not the only possible way. For example, it could be possible to manufacture ‘traditional’ concrete with a similar amount of admixture as used in recycled concrete. In that case, the water content could be decreased and consequently the cement content would be smaller for the same workability and compressive strength. As a result, all the impacts of traditional concrete related to $CO_2$ emissions would be smaller. Although this paper was dealing with the only influence of the substitution of aggregates, considering environmental aspects without low cost consideration. Other mix design (with same objectives) could lead to different conclusions, regarding same

**Table 7**
Contribution (%) of each phase (aggregate, cement and concrete production and transport) to each calculated impact indicator.

| Environmental impact indicator | Unit | Sample | Aggregate production | Cement production | Concrete production | Transport |
|---|---|---|---|---|---|---|
| Consumption of energetic resources | MJ | MC | 8.9 | 79.6 | 1.0 | 10.5 |
| | | RC | 6.3 | 86.3 | 0.8 | 6.6 |
| | | TC | 5.9 | 77.5 | 1.1 | 15.3 |
| | | BAC | 1.3 | 92.8 | 0.5 | 5.3 |
| | | NAC | 4.8 | 79.4 | 0.9 | 14.8 |
| | | RAC | 6.6 | 83.8 | 0.8 | 9.6 |
| Abiotic depletion | kg Sb eq | MC | 7.1 | 79.5 | 1.1 | 12.3 |
| | | RC | 6.0 | 83.9 | 1.0 | 9.1 |
| | | TC | 4.2 | 78.1 | 1.1 | 16.5 |
| | | BAC | 2.2 | 88.6 | 0.7 | 8.5 |
| | | NAC | 3.5 | 79.5 | 0.9 | 16.1 |
| | | RAC | 5.5 | 82.8 | 0.9 | 11.7 |
| Water consumption | L | MC | 3.4 | 91.9 | 1.9 | 2.6 |
| | | RC | 3.5 | 92.4 | 1.9 | 2.1 |
| | | TC | 7.7 | 87.0 | 1.8 | 3.2 |
| | | BAC | 0.2 | 95.9 | 1.6 | 2.2 |
| | | NAC | 6.3 | 89.0 | 1.5 | 3.1 |
| | | RAC | 3.8 | 92.2 | 1.5 | 2.3 |
| Global warming | kg $CO_2$ eq | MC | 1.5 | 92.9 | 1.4 | 4.1 |
| | | RC | 1.4 | 93.9 | 1.4 | 3.2 |
| | | TC | 1.4 | 91.8 | 1.3 | 5.3 |
| | | BAC | 0.9 | 94.8 | 1.0 | 3.2 |
| | | NAC | 1.2 | 92.4 | 1.1 | 5.2 |
| | | RAC | 1.3 | 93.5 | 1.2 | 4.0 |
| Acidification | kg $SO_2$ eq | MC | 6.2 | 81.3 | 5.1 | 7.3 |
| | | RC | 5.0 | 84.9 | 4.8 | 5.1 |
| | | TC | 5.6 | 79.3 | 5.0 | 9.9 |
| | | BAC | 3.1 | 88.6 | 3.6 | 4.5 |
| | | NAC | 4.6 | 81.4 | 4.2 | 9.7 |
| | | RAC | 5.1 | 79.6 | 4.2 | 11.1 |
| Eutrophication | kg $PO_4{}^{3-}$ eq | MC | 6.4 | 83.6 | 1.7 | 8.3 |
| | | RC | 5.7 | 86.5 | 1.4 | 6.3 |
| | | TC | 7.1 | 80.4 | 1.7 | 10.7 |
| | | BAC | 3.7 | 89.2 | 1.0 | 6.1 |
| | | NAC | 5.9 | 82.1 | 1.4 | 10.6 |
| | | RAC | 5.7 | 80.4 | 1.3 | 12.6 |
| Air pollution | $m^3$ | MC | 2.6 | 90.8 | 1.5 | 5.0 |
| | | RC | 2.4 | 92.2 | 1.5 | 3.9 |
| | | TC | 2.8 | 89.1 | 1.5 | 6.5 |
| | | BAC | 1.9 | 93.1 | 1.2 | 3.9 |
| | | NAC | 2.3 | 90.0 | 1.3 | 6.4 |
| | | RAC | 2.3 | 90.5 | 1.3 | 6.1 |
| Water pollution | $m^3$ | MC | 9.5 | 71.2 | 3.2 | 16.0 |
| | | RC | 9.3 | 74.0 | 3.3 | 13.3 |
| | | TC | 9.6 | 67.3 | 3.0 | 19.7 |
| | | BAC | 2.3 | 80.6 | 2.8 | 14.2 |
| | | NAC | 7.8 | 70.5 | 2.5 | 19.1 |
| | | RAC | 8.4 | 74.9 | 2.6 | 14.5 |
| Ozone layer depletion | kg CFC – 11 eq | MC | 1.6 | 81.9 | 0.7 | 15.7 |
| | | RC | 1.0 | 90.3 | 0.5 | 8.2 |
| | | TC | 4.4 | 71.3 | 0.8 | 23.3 |
| | | BAC | 1.2 | 92.8 | 0.3 | 5.7 |
| | | NAC | 3.6 | 73.3 | 0.7 | 22.4 |
| | | RAC | 1.7 | 85.4 | 0.5 | 12.6 |
| Photochemical oxidation | kg $C_2H_4$ eq | MC | 3.6 | 80.4 | 0.4 | 15.5 |
| | | RC | 3.5 | 83.9 | 0.4 | 12.1 |
| | | TC | 6.5 | 74.0 | 0.4 | 19.0 |
| | | BAC | 5.4 | 82.9 | 0.3 | 11.3 |
| | | NAC | 5.3 | 75.8 | 0.3 | 18.4 |
| | | RAC | 3.8 | 80.2 | 0.3 | 15.6 |

MC: 20-mm mixed concrete; RC: 20-mm recycled concrete; TC: 20-mm traditional concrete; BAC: 8-mm recycled brick aggregate concrete; NAC: 8-mm natural aggregate concrete; RAC: 8-mm recycled concrete aggregate concrete.

environmental impacts. The cost of concretes will not be the same, as it is most likely that the cost differences are larger with the used methodology since the admixtures are the most expensive concrete constituent. So, the conclusions for the 20-mm concrete samples are valid only for the presented methodology.

For the 8-mm concrete samples, the reduction of the environmental damages is important for the BAC and RAC samples, because of the utilization of recycled materials too, which allows to reduce associate transports to supply the manufacture of the samples. Once again, according to authors' assumption, the upstream transport of building material wastes to the recycling site has no direct impact on this life cycle assessment, because this specific transport would take place to inert waste storage facilities, whatever happens. There are therefore less emissions of greenhouse gas, as well as fewer emissions of organic substances and dust to air. Moreover, the high mechanical strengths obtained for the recycled terracotta aggregate 8-mm concrete sample can be explained by the presence of fine elements of terracotta in the cement paste and also by the use of the same total water content [9]. If mechanical properties of this sample are better, its lifetime will be improved, which can also explain a good environmental behavior. The durability of these samples will have to confirm the typical lifetime, which is assumed to be equal to 100 years.

Concerning the ‘global warming’, ‘air pollution’ or ‘ozone layer depletion’, the predictions are that the current emissions will create considerable damages in the coming decades [33]. Epidemiological data on respiratory effects from environmental pollution are summarized in the current literature [34]. An explanation to justify the decrease of these environmental impact categories for the samples which contain recycled materials (RC, MC, RAC and BAC samples) may be the reduction of transports (material quantities and distances), because these samples are formulated (completely or partially) with both recycled sand and aggregates. Thus, it is not necessary to extract and transport raw materials from ore or stone quarry, which limits emissions of organic substances and emissions of dust to air.

For all samples, a part of the ‘global warming’ indicator can be attributed to the cement (CEM I or CEM II), because of the generation of $CO_2$ during cement manufacturing process which produces millions of tons of the waste product cement kiln dust, contributing to respiratory and pollution health risks [10]. Carbon dioxide comes from two complementary sources: the energy expenditure needed to achieve high temperatures to realize the physico-chemical process to manufacture the material; and the phenomenon of transformation of the limestone ($CaCO_3$) under the effect of heat out of lime (CaO) and $CO_2$. More than 60% of the $CO_2$ emissions during manufacture of cement come from this carbonation [35].

In order to have an overall reading of the results, it is possible to implement a damage assessment step, *i.e.* endpoint level in ISO terminology, evaluating three damage categories: human health, ecosystem quality and resources. This means that the impact category indicator results are grouped to form damage categories. The environmental impact indicators ‘global warming’, ‘ozone layer depletion’, ‘photochemical oxidation’, ‘air pollution’ and ‘water pollution’ can be related to the human health damages. Under these considerations, it seems that the samples which contain recycled materials have a better behavior than traditional or natural concrete samples (TC and NAC). The environmental impact indicators ‘abiotic depletion’, ‘consumption of energetic resources’ and ‘water consumption’ can be related to the resources damage category. Once again, the samples which contain recycled materials have the better environmental behavior. The environmental impact indicators ‘acidification’ and ‘eutrophication’ can be related to the ecosystem quality damage category. In this case, the results are worse for the samples that contain recycled materials. The RC, MC, RAC and BAC samples require admixture in their formulation, which increase the acidification environmental indicator.

Table 7 presents the contribution to total impacts of each phase (aggregate, cement and concrete production as well as transport) in the concrete production process, for all types of concrete and calculated environmental impact indicators. The contribution of the cement production phase is ranging from 67 to almost 96%, according to the environmental impact indicator and the sample. The largest contribution of cement production is for the BAC sample and in general for the recycled samples (RC and RAC), while the lowest is for TC and NAC samples even if the same amount of cement was used. Indeed, the contribution of transport (the second source of impacts) for TC and NAC samples is significantly larger in comparison with other 8-mm or 20-mm concrete samples. The contribution of the concrete production phase is small and ranging from 0.3 to 5.1% according to the environmental impact indicators (Table 7).

For all environmental indicators and concrete samples, the contribution of the aggregate production phase is smaller than the cement production and ranging from 0.2% to 9.6% (Table 7). This contribution appears very low for the terracotta aggregates. However, this contribution remains higher for the samples formulated with other recycled aggregates (20-mm RC sample and 8-mm RAC sample) than for concretes with natural aggregates (20-mm TC sample and 8-mm NAC sample), because of additional operations. More energy is consumed for the production of recycled concrete aggregates than for natural aggregates and the LCI data include also transport of mobile plant to demolition site and landfilling of recycling waste [36] in addition to recycling.

Finally, according to the presented results, it seems that the utilization of recycled sand or recycled gravel could be really useful in order to reduce the environmental impacts of the concrete samples.

## 6. Conclusions

The use of alternative aggregate established from waste materials could be a step towards solving part of the depletion of natural aggregate. This paper was dealing with environmental aspects only, so the conclusions for the samples are valid only for the used methodology, *i.e.* the samples have been manufactured in such a way to have the same strength (20-mm concrete) or the same volume composition with a minimal strength (in order to present the same aspect), according to the use of the same volume quantity of materials (8-mm concrete). Different mix design (with same objectives) can lead to different conclusions, regarding same environmental impacts. This paper suggests that the environmental behavior of these materials remains acceptable. Regarding the three studied 20-mm concrete samples, the recycled concrete sample (RC) presents the best environmental behavior: a majority of the studied environmental impact indicators are significantly inferior in comparison with the traditional concrete sample (TC) and closer than the mixed concrete sample (MC), even if both samples were formulated with admixture and the utilization of recycled materials (sand or aggregates) involves more operations, such as crushing, etc. Similar results were obtained with the 8-mm concrete samples, with the same assessment methods (CML, EDP, EDIP and BEES), according to both NF P 01–010 and EN 15804 standards. The impact category ‘acidification’, due to admixture utilization for the mixed and the recycled 20-mm concrete samples as well as the recycled concrete aggregate and the recycled brick aggregate 8-mm concrete samples, are at the advantage of the reference samples. According to the use of recycled materials, the reduction for both mixed and recycled 20-mm concrete samples, as well as recycled or brick 8-mm concrete samples could be attributed to a better enhancement of the chemical composition of these samples, integrating recycled raw materials and thus reducing either conversion or occupation of land. The development of concrete formulated with recycled aggregates can be interesting to limit the storage of construction wastes, in order to reduce the waste storage areas and the environmental footprint of these sites. The recycled brick aggregate concrete sample (BAC) presents lower environmental indicator impacts than the two other 8-mm concrete samples, as this sample exhibits a low aggregate density, which could slightly decrease environmental impacts related to the transport operations, *i.e.* the formulation of the BAC sample allows to use fewer resources.

## References

[1] R.-U.-D. Nassar, P. Soroushian, Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement, Constr. Build. Mater. 29 (2012) 368–377.

[2] V.W.Y. Tam, K. Wang, C.M. Tam, Assessing relationships among properties of demolished concrete, recycled aggregate and recycled aggregate concrete using regression analysis, J. Hazard. Mater. 152 (2008) 703–714.

[3] M.C. Limbachiya, A. Koulouris, J.J. Roberts, A.N. Fried, Performance of recycled aggregate concrete, in: N. Kashino, Y. Ohama (Eds.), Proceedings of the RILEM International Symposium on Environment-Conscious Materials and Systems for Sustainable Development, RILEM Publications SARL, Koriyama, Japan, 2004, pp. 127–136.

[4] D. Krajnc, P. Glavič, A model for integrated assessment of sustainable development, Resour. Conserv. Recycl. 43 (2005) 189–208.

[5] C.-H. Lee, J.-C. Du, D.-H. Shen, Evaluation of pre-coated recycled concrete aggregate for hot mix asphalt, Constr. Build. Mater. 28 (2012) 66–71.

[6] F. Debieb, L. Courard, S. Kenai, R. Degeimbre, Mechanical and durability properties of concrete using contaminated recycled aggregates, Cem. Concr. Compos. 32 (2010) 421–426.

[7] J. Xiao, Y. Huang, J. Yang, C. Zhang, Mechanical properties of confined recycled aggregate concrete under axial compression, Constr. Build. Mater. 26 (2012) 591–603.

[8] M.N. Soutsos, K. Tang, S.G. Millard, Concrete building blocks made with recycled demolition aggregate, Constr. Build. Mater. 25 (2011) 726–735.

[9] S. Braymand, P. François, F. Feugeas, C. Fond, Rheological properties of recycled aggregate concrete using superplasticizers, J. Civ. Eng. Arch. (2015) (in press), http://dx.doi.org/10.17265/1934-7359/2015.05.011.

[10] D.N. Huntzinger, T.D. Eatmon, A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies, J. Clean. Prod. 17 (2009) 668–675.

[11] A. Josa, A. Aguado, A. Heino, E. Byars, A. Cardim, Comparative analysis of available life cycle inventories of cement in the EU, Cem. Concr. Res. 34 (2004) 1313–1320.

[12] P. Van den Heede, N. De Belie, Environmental impact and life cycle assessment (LCA) of traditional and 'green' concretes: literature review and theoretical calculations, Cem. Concr. Comp. 34 (2012) 431–442.

[13] O. Ortiz, F. Castells, G. Sonnemann, Sustainability in the construction industry: a review of recent developments based on LCA, Constr. Build. Mater. 23 (2009) 28–39.

[14] G.A. Blengini, E. Garbarino, S. Šolar, D.J. Shields, T. Hámor, R. Vinai, Z. Agioutantis, Life cycle assessment guidelines for the sustainable production and recycling of aggregates: the sustainable aggregates resource management project (SARMa), J. Clean. Prod. 27 (2012) 177–181.

[15] A. Jullien, C. Proust, T. Martaud, E. Rayssac, C. Ropert, Variability in the environmental impacts of aggregate production, Resour. Conserv. Recycl. 62 (2012) 1–13.

[16] C. Knoeri, E. Sanyé-Mengual, H.-J. Althaus, Comparative LCA of recycled and conventional concrete for structural applications, Int. J. Life Cycle Assess. 18 (2013) 909–918.

[17] S. Marinković, V. Radonjanin, M. Malešev, I. Ignjatović, Comparative environmental assessment of natural and recycled aggregate concrete, Waste Manag. 30 (2010) 2255–2264.

[18] CEN/TC 104, "Concrete and related products". EN 206-1 Concrete – Part 1: Specification, Performance, Production and Conformity, 2004.

[19] J.P. Ollivier, J. Baron, Les bétons: Bases et données pour leur formulation, in French, Eyrolles, Paris, 1997.

[20] J. Bolomey, Determination de la résistance à la compression des mortiers et bétons (Determination of compressive strength of mortar and concrete), Bull. Tech. Suisse Rom. 51 (1925) (126–133 and 169–173).

[21] NF EN 934-2+A1, Admixtures for concrete, mortar and grout-Part 2: concrete admixtures – definitions, requirements, conformity, marking and labelling, 2012.

[22] ISO 14040:2006, Environmental management – life cycle assessment – principles and framework, 2006.

[23] ISO 14044:2006, Environmental management – life cycle assessment – requirements and guidelines, 2006.

[24] Pre-sustainability, Homepage SimaPro-Software, ⟨http://www.pre-sustainability.com/simapro⟩ (accessed 27.06.15).

[25] European Committee for Standardization, EN 15804, Sustainability of construction works, Environmental product declarations, Core rules for the product category of construction products, 2012.

[26] AFNOR, French Standard, NF P 01-010, Environmental quality of construction products, Environmental and health declaration of construction products, 2004.

[27] E.K. Lauritzen, Demolition and reuse of concrete and masonry, in: Proceedings of the Third International RILEM Symposium held in Odense, Denmark, Organized by RILEM TC 121-DRG and the Danish Building Research Institute, E & FN Spon, London, 1994.

[28] BS 8500-2, Concrete, Complementary British Standard to BS EN 206-1, Specification for constituent materials and concrete, 2002.

[29] UNPG, Life cycle assessment of aggregates: ⟨http://www.unpg.fr/dossiers/environnement/analyse_de_cycle_de_vie_des_granulats⟩ (accessed 27.06.15).

[30] NF EN 12390-3, Testing hardened concrete-Part 3: compressive strength of test specimens, 2012.

[31] G. Bianchini, E. Marrocchino, R. Tassinari, C. Vaccaro, Recycling of construction and demolition waste materials: a chemical–mineralogical appraisal, Waste Manag. 25 (2005) 149–159.

[32] S. Braymand, Study of rheological and mechanical properties of recycled brick aggregate concrete, in: Proceedings of the Waste Material in Construction – WASCON, Swedish Geotechnical Institute (Eds.), ISCOWA, Göteborg, Sweden, 2012.

[33] J.M. Harris, B. Roach, The Economics of Global Climate Change, Global Development and Environment Institute, Tufts University, 2009.

[34] S. Baldacci, G. Viegi, Respiratory effects of environmental pollution: epidemiological data, Monaldi Arch. Chest Dis. 57 (2002) 156–160.

[35] M. Nisbet, M. Marceau, M. VanGeem, Environmental Life Cycle Inventory of Portland Cement Concrete, PCA R&D Serial No. 2137a, A Report on Concrete: Sustainability and Life Cycle, PCA CD033, 2003.

[36] S.B. Marinković, M. Malešev, I. Ignjatović, Life cycle assessment (LCA) of concrete made using recycled concrete or natural aggregates, in: F. Pacheco-Torgal, L.F. Cabeza, J. Labrincha, A. de Magalhães (Eds.), Eco-Efficient Construction and Building Materials, Woodhead Publishing Limited, Cambridge, UK, 2014, pp. 239–266.