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A comparative Life Cycle Assessment between recycled aggregate and natural aggregate

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Abstract

The construction industry consumes many natural resources and generates a large amount of waste in the environment, in all phases of the life cycle. For this reason, the use of recycled material is increasingly being encouraged, instead of original raw material for the production of new materials that contribute to closing the materials cycle.
The objective of this study was to evaluate and compare the environmental impacts of obtaining natural aggregate and recycled aggregate, taking Spain as a case study. Life cycle assessment (LCA) and the IMPACT 2002+ method were used to calculate the environmental impacts. To carry out the inventory, primary information was obtained and subsequently complemented and compared with the Ecoinvent v2.2 database.
The results of this study show that the obtaining of natural aggregate has environmental impacts on all the evaluated categories. Recycled aggregate from reinforced concrete has impacts on the carcinogenic and non-carcinogenic effects category. However, it results in significant savings in the other categories. Recycling aggregate on the construction site resulted in higher savings in most categories than recycling aggregate at the plant.

Key Words: Natural aggregate, Recycled aggregate, Recycling, Environmental impact, Construction, Life Cycle Assessment, evaluation method, IMPACT 2002+, Ecoinvent.

Una comparación del Análisis de Ciclo de Vida entre el árido reciclado y el árido natural

Resumen

La industria de la construcción consume muchos recursos de la naturaleza y genera una gran cantidad de residuos al medio, en todas las fases del ciclo de vida. Por esta razón cada vez se

incentiva más el uso de material reciclado, en lugar de materia prima original para la producción de nuevos materiales que contribuyan a cerrar el ciclo de los materiales.
El objetivo este estudio consistió en evaluar y comparar los impactos medioambientales de la obtención de árido natural y de árido reciclado. Para el cálculo de los impactos medioambientales se siguió la metodología de Análisis de Ciclo de Vida (ACV) y se escogió como método de evaluación el IMPACT 2002+. Se empleó la base de datos Ecoinvent v2.2, sin embargo, estos datos fueron contrastados y comparados con datos obtenidos de fuentes primarias con el fin de que el inventario de ciclo de vida fuera representativo de España.
Los resultados de este estudio muestran que la obtención de árido natural presenta impactos en todas las categorías evaluadas, sin embargo el árido reciclado resulta beneficioso para la mayoría de estas categorías. El árido reciclado proveniente de hormigón armado, presenta impactos en la categoría efectos carcinogénicos y no carcinogénicos, debido al proceso de fundición durante el reciclaje del acero, y ahorros significativos en el resto de categorías estudiadas. Por último, el reciclaje del árido en la obra de construcción resultó en la mayoría de categorías, con ahorros más altos con respecto al reciclaje en planta.

Palabras clave: agregado natural, agregado reciclado, reciclaje, impacto medioambiental, construcción, Análisis de Ciclo de Vida, método de evaluación, IMPACT 2002+, Ecoinvent.

1. Introduction

The construction industry is responsible for many of the current environmental impacts. Global production of cement has grown very rapidly in recent years, and after fossil fuels and land-use change, it is the third-largest source of anthropogenic emissions of carbon dioxide (CO_2) Cumulative emissions from 1928 to 2018 were 38.3 ± 2.4 Gt CO_2, 71% of which have occurred since 1990 (Ardrew 2019).

Likewise, UN Environment (2017) reports that the construction industry consumes 36% of energy and emits 39% of CO_2 emissions worldwide.

Furthermore, Zabalza Bribián *et al*. (2011) state that worldwide, civil works and building construction consume 60% of raw materials extracted from the lithosphere. Hence, buildings represent 24% of global extractions. Tam *et al*., (2019) indicate that each year building construction around the world alone consumes about 40% of the raw stone, gravel and sand.

The consumption of raw material by the construction industry generates waste and energy is consumed to manage this waste. According to Solís-Guzmán *et al*. (2009), the construction industry generates 35% of the world's industrial waste and Illankoon *et al*., 2017, building construction contributes to about 26% of waste. The quantity of the construction and demolition waste generated in European Union exceeds 700 million tonnes per year (Iacoboaea *et al*., 2019) and approximately 333 million tonnes of CDW (excluding soils) (Menegaki *et al*., 2018). In Spain, 40 million tons of construction and demolition waste are produced per year, which represents 32% of the total volume of waste generated (Ortiz *et al*., 2010). This waste, called Construction and Demolition Waste (CDW), is not well-managed in most cases. A large part is dumped in landfills, occupying a volume that clearly exceeds that of household waste. Hence, it is increasingly important to find ways to reduce this waste by reincorporating it into the production of new materials through recycling.

Several studies have been carried out on the subject of recycled aggregate in which its technical viability has been evaluated at laboratory and field level, (Vinayak *et al*., 2017, Kien *et al*., 2017, Mistri *et al*., 2019).

The durability of concrete containing recycled aggregate has been studied (Bravo *et al*., 2015; Ismail, *et al*., 2017; Thomas, *et al*., 2018), the absorption of water by immersion and capillarity (Bravo *et al*., 2015; Sicakova *et al*., 2017; Ismail, *et al*., 2017) and resistance to the penetration of chloride ions into concrete (Ferreira, 2013; Bravo *et al*., 2015; Sicakova *et al*., 2017). All these studies show that it is technically feasible to use recycled aggregate from construction and demolition waste to produce recycled concrete.

Despite studies on the physical, chemical and mechanical properties of these new recycled materials (Vinayak *et al*., 2017, Kien *et al*., 2017, Mistri *et al*., 2019). Subhasis *et al*., 2019 conclude that the combination of recycled coarse aggregate (RCA) and Particle Packing Method (PPM) mix design approach exhibits mínimum environmental impacts in comparation of conventional mix design method. However, the environmental impacts of this production and its comparison with the production of virgin materials have not been thoroughly evaluated. Consequently, this research assesses the environmental impacts of recycled aggregate compared to natural aggregate, to determine which is the most viable from an environmental perspective and thus to encourage the use of recycled material instead of original raw material.

The methodology used to calculate environmental impacts is life cycle assessment, which is defined as a technique to determine environmental aspects and potential impacts associated with a product (or service) through an inventory of the system's relevant inputs and outputs, evaluation of the potential environmental impacts associated with inputs and outputs and interpretation of the results of the inventory and impact phases in terms of the study objectives (ISO 14040).

This research is associated with the European Waste Directive, which foresees that in the year 2020, 70% of CDW must be properly valued. The objective of this directive is to achieve much higher levels of recycling by minimizing the extraction of additional natural resources. In addition, the development of construction materials that can reuse a high content of waste is an important line of research within the European Union's objectives (Pacheco-Torgal, 2014).

2. Life cycle assessment (LCA) methodology

2.1. Goal and scope definition

La fase experimental se llevó a cabo en la unidad de producción de Truchas Cocora, In this study, we evaluated the obtaining of natural aggregate and recycled aggregate from reinforced concrete in a fixed and a mobile plant.

The stages included in the primary production or process of obtaining natural aggregate are extraction and crushing.

We considered that the aggregate is extracted from the quarry using explosives and crushing is undertaken by crushers until a size of between 4 mm and 32 mm is obtained (Suárez, 2017).

In the process of obtaining recycled aggregate from concrete, we considered internal transport in the aggregate production mine. External transport was not included, since extraction mines are usually located very close to the aggregate crushing plant.

The stages or processes that were considered in secondary production depended on whether the recycling is carried out in a fixed or mobile recycling plant. If the recycling is carried out in a fixed plant, all the recycling plant infrastructure was considered. If the recycling is carried out in a mobile plant, only the mobile machinery infrastructure was taken into account.

Thus, if the recycling is carried out in a fixed plant, the process of transporting the waste from the generation site to the recycling plant was included. In the case of on-site recycling, the transportation of mobile machinery to the construction site was considered.

The scope of the study on the production of natural aggregate and recycled aggregate was Spain. For the purpose of distances and to obtain more specific data, Catalonia was taken as a basis and waste was considered to be generated in the centre of Barcelona, where the greatest quantity is produced. The recycling plants closest to the city centre of Barcelona (average distance 7 km) were also taken as a basis (Suárez *et al*., 2016). The alternatives were: natural aggregate (NA), recycled aggregate in plant (RAp) and recycled aggregate at the construction site (RAs).

2.2. Functional unit

The functional unit defined for this study was 1 kg of natural or recycled aggregate.

2.3. Life cycle inventory

The data required to study the impacts included primary information collected through consultation with organizations and associations in Spain, such as the Ministry of Industry, Energy and Tourism, the Association of Aggregate Manufacturers of La Rioja (ANEFA) and the Gremi d'Àrids de Catalunya. Manufacturers of construction materials in Spain were also directly consulted and visits were undertaken to CDW recycling plants in Catalonia belonging to Gestora de Runes de Catalunya, which treat a very high percentage of waste. Thus, a total of seventeen companies, agencies and recycling plants were directly consulted (Suárez, 2017).

The data obtained from primary sources were completed and/or compared with the Ecoinvent v2.2 database and other secondary sources. In all cases, crushing machinery was considered that has a useful life of 50 years and a production capacity of 400,000 t/year. It was estimated for the purpose of comparing the systems for obtaining the aggregate with an operating time of the machinery of one year (Suárez, 2017).

2.3.1 Natural aggregate

The main input processes considered to obtain the natural aggregate are shown in Table 1.

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Table 1. Input processes in the natural aggregate (NA)

Process	Unit	Quantity	Source
Extraction with explosives	kg	1.36E-04	Ministry of Industry, Energy and Tourism, (2013); AFA (2010); Gremi d'Àrids de Catalunya (2015) and Spanish companies (2013)
Diesel used in machinery	MJ	1.40E-02	Ministry of Industry, Energy and Tourism, (2013); Gremi d'Àrids de Catalunya (2015)
Electricity	kWh	1.80E-03	Ministry of Industry, Energy and Tourism, (2013); Gremi d'Àrids de Catalunya (2015)

Air emissions due to the use of explosives in the extraction of aggregate and air emissions due to the crushing process of 1 kg of natural aggregate (Table 2) were considered as outputs. In addition, the waste generated in the process of obtaining natural aggregate was considered as an output. This is basically a mixture of several types of solid waste, similar to municipal waste (according to Ecoinvent v2.2, this equals 2.12E-06 kg per kg of aggregate obtained).

Table 2. Emissions to the air due to the crushing of 1 kg of aggregate (Ecoinvent v2.2)

Process	Unit	Quantity
Heat	MJ	3.26E-02
Emission of particles < 2.5 µm	kg	8.71E-07
Emission of particles > 10 µm	kg	8.72E-06
Emission of particles > 2.5 µm y < 10 µm	kg	7.84E-06

2.3.2 Recycled aggregate

The inputs used in both the recycled aggregate produced in the plant and the in situ recycled aggregate are detailed in Tables 3 and 4 respectively.

Table 3. Input the production process of the recycled aggregate in plant (RAp)

Process	Unit	Quantity	Source
Concrete waste	Kg	1.04E+00	Ecoinvent v2.2
Waste transport	Tkm	7.00E-03	(ACR, 2015); Recycling plants visited (2014)
Infrastructure of the recycling plant	p	5.00E-11	Ecoinvent v2.2
Diesel used in machinery	MJ	1.50E-02	Recycling plants of Catalonia (2013)
Electricity	kWh	2.00E-03	Mercante *et al*. (2010) and Recycling plants in Spain (2013)

Table 4. Input of the process for obtaining recycled aggregate at the construction site (RAs)

Process	Unit	Quantity	Source
Concrete waste	kg	1.04E+00	Ecoinvent v2.2
Conveyer belt	m	4.75E-08	Ecoinvent v2.2
Machinery	kg	9.51E-05	Ecoinvent v2.2
Diesel used in machinery	MJ	1.50E-02	Recycling plants of Catalonia (2013)
Lubricant oil	kg	2.50E-06	Ecoinvent v2.2

As outputs, we considered air emissions from the aggregate crushing process. In this case, we used the same air emissions as those the crushing process of natural aggregate, since the process and the machinery used to crush the aggregate is the same in both cases (Table 2).

The amount of steel waste per kg of recycled aggregate was calculated from a study by Zazurca (2012) in a single-family house in Barcelona, in which 1 kg of concrete required 0.04 kg of steel as a quantity to obtain reinforced concrete.

This value was also compared with the BEDEC database of the ITEC, where it was found that structural elements of concrete, including walls, pillars, beams, hoops, slabs and reinforced concrete slabs, need an amount of steel that ranges from 0.02-0.07 kg steel per kg of reinforced concrete. Steel waste management is included in this process, i.e. steel casting to produce secondary steel. Figure 1 shows the limits of the system in the production of aggregate.

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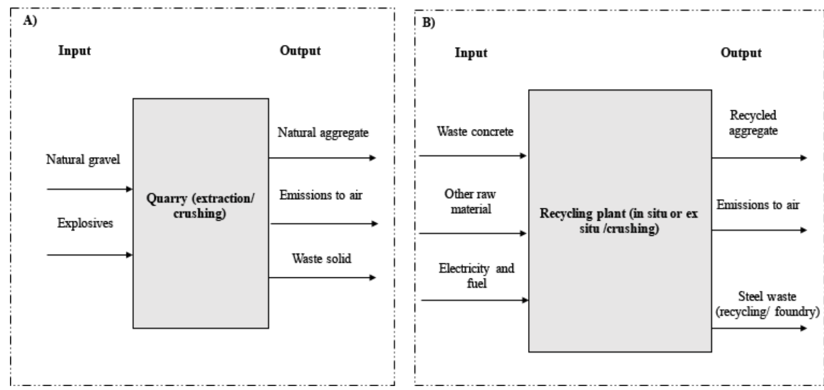
Figure 1. Limits of the system. A) Natural aggregate, B) Recycled aggregate.



2.4. Life cycle impact assessment

The impact categories to be evaluated were chosen considering existing scientific consensus, expressed in recommendations on LCA studies in buildings according to CEN/TC350.

The chosen categories were: global warming (GW) (kg CO_2 eq); ozone depletion (OLD) (kg CFC-11 eq); acidification (A) (kg SO_2 eq); eutrophication (E) (kg PO_4 p-lim); respiratory organic effects (RO) (kg C_2H_4 eq); carcinogenic effects (C) (kg C_2H_3Cl eq); and non-carcinogenic effects (NC) (kg C_2H_3Cl eq); non-renewable energy (NRE) (MJ primary); respiratory inorganics (RI) (kg PM 2.5 eq); mineral extraction (ME) and land occupation (LO) (m2org.arable).

To characterize the selected impact categories, we used Simapro 7.3.3 software. To evaluate the impacts, we applied the IMPACT 2002+ method, since it best adapts to all the chosen impact categories and can be used to evaluate all these categories without the need for another evaluation method. This method has been assessed by other authors, including García O. (2008), Raluy (2009) and Colombani (2014).

3. Results and discussion

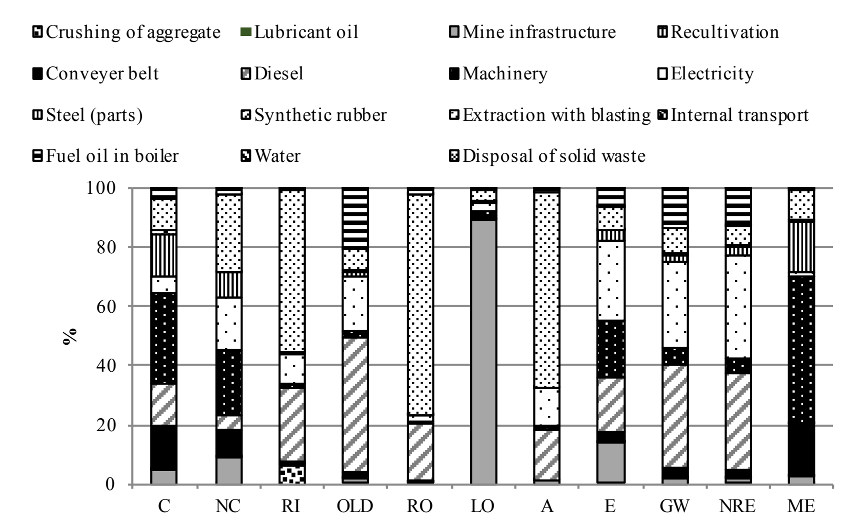
3.1. Natural aggregate

In the assessment of obtaining the natural aggregate, the extraction process with blasting had considerable impacts in all categories (Figure 2). The greatest impacts due to this process were found in the respiratory organic category (74%), acidification (66%), respiratory inorganics (54%) and non-carcinogenic effects (24%). This is because extraction with blasting emits substances into the environment such as nitrogen oxides (NO_x) and volatile organic compounds, which cause respiratory problems due to the formation of photochemical smog and the emission of particles, affecting human health (Wallington *et al*., 2014; Kulkarni *et al*., 2011). The emission of ammonia and NOx from the blasting process also affects the acidification category (Roy *et al*., 2014).

The infrastructure of the extraction mine has great impacts on the land occupation category (89%) and the machinery process affected mineral extraction (50%) and had carcinogenic effects (31%) (Figure 2). The conveyer belt process also affected mineral extraction and had carcinogenic effects.

Another process whose impact was significant is diesel consumption in machinery. The greatest impact due to the use of diesel was found in the categories of ozone depletion (46%), global warming (35%) and non-renewable energy (32%). This is due to the fact that CO_2 emissions and chlorine-containing emissions are generated in the diesel combustion process, which reduces the ozone layer (Bolaji and Huan, 2013). Lastly, electricity had the greatest impact on the non-renewable energy category (35%) and global warming (29%).

Figure 2. Characterized results of the natural aggregate.



3.2. Recycled aggregate

- **Recycled aggregate in plant**

Figure 3 indicates that the production of secondary steel has the greatest impact on carcinogenic and non-carcinogenic effects, because the smelting process emits substances such as dioxins associated with human health problems (Krishnaraj, 2015). However, Figure 3 shows that the secondary production of steel leads to great savings in the other categories evaluated.

The considerable savings in most categories evaluated for recycled aggregate in plant (Figure 3) are due to the fact that the recycling of steel avoids the extraction of natural mineral, saves energy and therefore reduces CO_2 emissions that, according to Dombrowski and Ernst (2014) and Truelove and Parks (2012), are responsible for global warming. In addition, steel recycling avoids impacts due to the production of steel from original raw material. These results are in agreement with several authors: Yellishetty *et al*. (2011), Zabalza Bribián *et al*. (2011) and Sodsai and Rachdawong (2012), who mention that the manufacture of steel in an electric arc furnace (used in steel recycling) consumes less energy and generates less CO2 emissions than a basic oxygen furnace used in the production of steel from original raw material.

In a study by Turk *et al*. (2015), significant savings were also evidenced when steel was recovered by recycling concrete waste.

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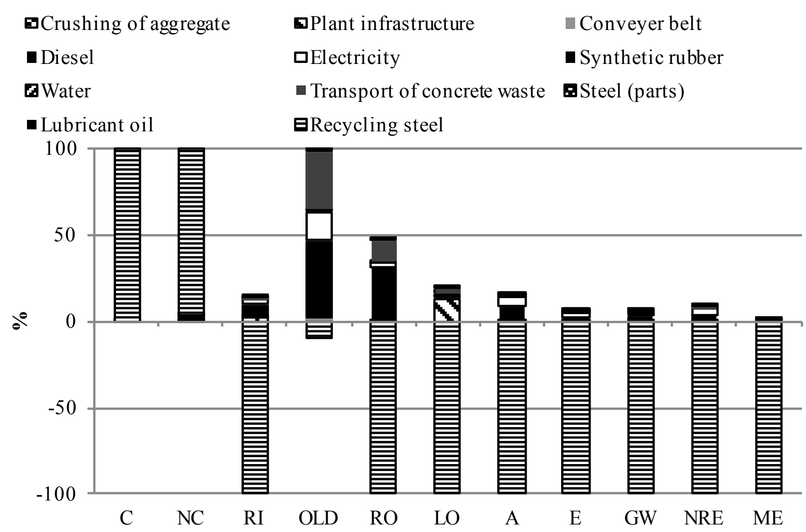
Figure 3. Characterized results for recycled aggregate in plant.



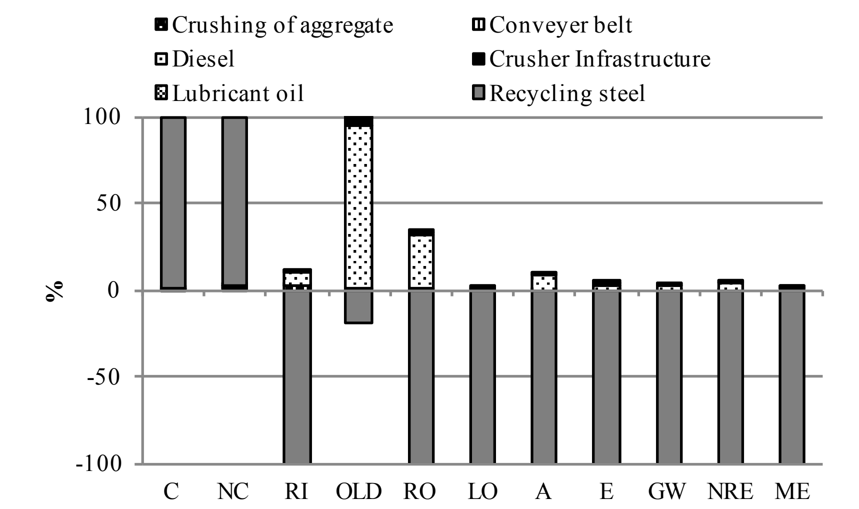
Another process that affects the production of RAp is the consumption of diesel fuel in machinery. This has the greatest impact on the categories of ozone depletion (45%), respiratory organic effects (31%), acidification (8%) and respiratory inorganics (8%). These categories are affected because the diesel combustion process results in the emission of CO_2, NO_X, volatile organic compounds, ammonia, emission of particles and emissions containing chlorine (Ferrís and Tortajada *et al*., 2003).

Finally, unlike the natural aggregate, the process of obtaining concrete aggregate in plant includes the transport of concrete waste from where it is generated to the recycling plant, which corresponds to the process of exploitation of aggregate in a quarry. The transport of this waste from the centre of Barcelona to the recycling plant mainly affects the ozone depletion (34%) and respiratory organic (12%) categories, due to the emission of nitrogen oxides, volatile organic compounds and emissions that deteriorate the ozone layer.

- **Recycled aggregate on the construction site**

This aggregate production alternative is similar to RAp, since the same type of waste is treated. However, in this case, the recycling is carried out on the construction site (Figure 4).

Figure 4. Characterized results for recycled aggregate on the construction site.



The amount of steel waste generated when the concrete is removed from steel is equal to the alternative RAp. Therefore, the results of impacts due to the recycling of steel waste generated in the RAs (Figure 4) show similar behaviour to the production of concrete aggregate in the plant (Figure 3).

The recycling of steel has very significant impacts on the categories of carcinogenic effects (100%) and non-carcinogenic effects on human health (98%), as well as savings in the category of ozone depletion (-20%) and in the rest of the evaluated categories (-100%). These results are due to the impacts avoided by secondary steel production. The secondary production of steel also avoids impacts due to the disposal of landfill waste.

Another process that affects the production of RAs is the consumption of diesel fuel in machinery. This has the greatest impact on the categories of ozone depletion (95%), respiratory organic effects (31%), acidification (9%) and respiratory inorganics (8%).

The impact of the rest of the processes is considered insignificant, including the transport of machinery to the site and its return. This is not a relevant process, even though it is included in the crusher infrastructure process. The same can be said of aggregate trituration and lubricant oil.

3.3. Comparison of results (comparative analysis)

Figure 5 and Table 5 show that the obtaining of natural aggregate affects all the categories evaluated. However, these impacts tend to be almost null in the carcinogenic and non-carcinogenic effects categories compared to the impacts of the recycled aggregate alternatives in these two categories. The great impacts of the production of recycled aggregate are due to the melting process in the secondary production of steel (steel recycling) resulting from reinforced concrete. During the process of steel smelting, emissions are generated that can affect human health, such as the emission of particles and dioxins (Krishnaraj, 2015).

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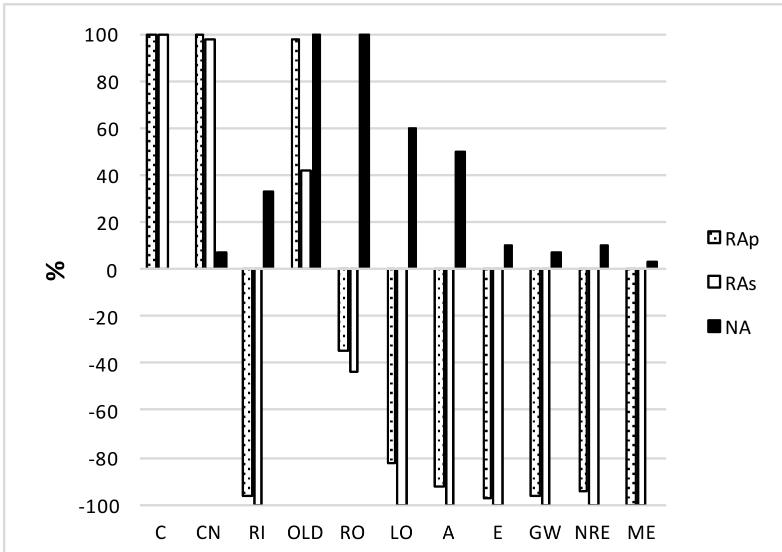
The alternative production of recycled aggregate leads to savings in the categories of organic and inorganic respiratory effects, soil occupation, acidification, eutrophication, global warming, non-renewable energy and mineral extraction. The lower impacts are due to the lower energy consumption and CO_2 emissions in the process of obtaining the recycled aggregate compared with the process of obtaining natural aggregate, as reported by Limbachiya *et al*. (2012). In addition, according to Alves *et al*. (2014), the recycled aggregate also leads to savings in the use of natural resources.

In the category of respiratory organic effects, the production of natural aggregate has the greatest impact (100%). However, the greatest savings occur in the production of RAs (-44%) and RAp (-35%). The impact of natural aggregate on this category is due to the use of blasting to extract aggregate from a quarry.

Figure 5. Characterized results of the alternatives for obtaining aggregate.



The production of RAs lead to the greatest savings (-100%) in the categories of respiratory inorganic effects, soil occupation, acidification, eutrophication, global warming and non-renewable energy.

The RAp alternative brings about savings of between -82% and -100% in the respiratory inorganic categories, soil occupation, acidification, eutrophication, global warming, non-renewable energy and mineral extraction. The lowest savings occur in the land occupation category, and the highest in mineral extraction. In this last category, all the alternatives of production of recycled aggregate have the greatest savings, since the extraction of virgin material is avoided.

The recycling of aggregate on the construction site (RAs) leads to greater savings than plant recycling (RAp) in most of the categories evaluated (Figure 5). These results are in agreement with Vossberg *et al*. (2014), who found that on-site recycling has advantages over recycling at the plant in the global warming category. This is because of lower energy consumption when recycling is carried out on site than when it is carried out in a fixed recycling plant.

The great savings due to the RAs are also due to the fact that the production of this type of aggregate avoids the impacts of transporting waste to the recycling plant.

Although machinery must be transported to and from the construction site, the impact of this process is insignificant.

Table 5. Results for aggregate production alternatives.

Categories	Unit	NA	Rap	RAs
C	kg C_2H_3Cl eq	4.56E-05	1.10E-02	1.10E-02
NC	kg C_2H_3Cl eq	6.14E-05	8.38E-04	8.22E-04
RI	kg PM 2.5 eq	1.41E-05	-4.11E-05	-4.30E-05
OLD	kg CFC-11 eq	3.32E-10	3.26E-10	1.40E-10
RO	kg C_2H_4 eq	6.71E-06	-2.33E-06	-2.98E-06
LO	m2org.arable	1.28E-04	-1.75E-04	-2.14E-04
A	kg SO_2 eq	7.27E-05	-1.35E-04	-1.46E-04
E	kg PO_4 p-lim	6.70E-07	-6.36E-06	-6.54E-06
GW	kg CO_2 eq	3.44E-03	-4.45E-02	-4.62E-02
NRE	MJ primary	5.51E-02	-5.20E-01	-5.53E-01
ME	MJ surplus	2.60E-04	-9.12E-03	-9.08E-03

4. Conclusions

The main conclusions of this study are listed below:

- The obtaining of natural aggregate impacts all the evaluated categories. However, in the carcinogenic and non-carcinogenic effects categories, it has almost no impact compared with the obtaining of recycled aggregate.
- The production of recycled aggregate has great impacts in the carcinogenic and non-carcinogenic category and leads to savings in the organic and inorganic categories of respiration, soil occupation, acidification, eutrophication, global warming, non-renewable energy and mineral extraction.
- The steel waste generated in the recycling of reinforced concrete, which is recycled or reincorporated for the secondary production of steel, leads to significant savings in the respiratory organic and inorganic categories, soil occupation, acidification, eutrophication, global warming, non-renewable energy and extraction of minerals. However, in the carcinogenic and non-carcinogenic effects categories, the production of secondary steel has an impact due to the steel smelting process.
  These impacts are linked to either primary or secondary (recycling) steel production. When the two types of production are compared, the recycled steel has environmental advantages as it reduces the extraction of original raw material and avoids the impact of the recycling of steel scrap.

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- In most of the categories that were evaluated, the recycling of aggregate in the construction site (RAs) provides greater savings than plant recycling (RAp).
- Although it is included in the crusher infrastructure process, the transport of machinery to the construction site and its return is not relevant in the process of recycling aggregates on site.

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