ENVIRONMENTAL IMPACT OF CONCRETE RECYCLING, COMING FROM CONSTRUCTION AND DEMOLITION WASTE (C&DW)

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ABSTRACT

This paper presents the results of a research study on the environmental impact produced by the recycling of concrete originating from construction and demolition waste (C&DW). The aim of the study was to implement a life cycle inventory (LCI) of the concrete recycling phases. It was carried out in Spain, with data collected from the various recycling processes involved in the mobile crushing plants operating in Catalonia. The values have been compared with the environmental impact produced during the extraction processes of natural resources (gravel and sand) from different European databases. The main emissions (CO_2, NO_x, SO_2, SO_x, and dust) with major influence on the greenhouse effect, acidification, and eutrophication were considered. The recycling waste processes generate lower environmental impact than the natural aggregate extraction. The amount of CO_2 emitted is approximately 3,000 g per ton of recycled aggregate, while this value varied from around 6,900 to 7,700 g per ton for the gravel and sand extraction processes considered.

INTRODUCTION

In the EU, the current annual production of construction and demolition waste (C&DW) is on the order of about 180 million tonnes, of which, about 28% is recycled (EU, 1999). Several countries have implemented Action Programmes to increment the amount of recycled material. (Lauritzen, 1997). These countries included Spain, where 25 to 30 % of C&DW was being recycled by the year 2000, and where the Environment Ministry has proposed an Action Programme (BOE, 2001) to increase these values, so as to recycle at least 40% by 2005, and 60% by the year 2006.

In the composition of conventional demolition waste, a high proportion of the weight is formed by concrete. Average values of 35% of the total C&DW were estimated in 1990, with predicted values of 40% by the year 2000. (D. Medio Ambiente, 1995). This means that at least 72 million of the EU´s yearly production of 180 million tonnes of C&DW comes from concrete waste. These figures illustrate the large weight and volume of concrete waste generated annually in the EU. To make a comparison with a parallel activity, in the year 2000, the automotive industry recycled more than 14 million tonnes of steel (Steel Recycling Institute, 2002) coming from discarded automobiles. This circumstance may reasonably be considered as one of the bases for the implementation of several steel recycling inventories originating in different sources. If we consider that the construction industry generates more recycled wastes than the motor industry, this brings home the importance of creating a life cycle inventory for the recycling of concrete.

The authors had access to the following databases: BUWAL 250 (PRé Consultants B.V. 1997), Data Archive (PRé Consultants B.V. 1997), y LCAiT (CIT Ekologik 2001). The amount of available data is limited due to the restricted-access policies often exercised by the industry. The greater part of the life cycle inventories (LCI) developed at present focus on obtaining raw materials, production, transport, and energies. A limitation of environmental information regarding recycling processes has been identified. The majority of recycling process inventories has been applied to materials having a short useful life, and which are consumed in great quantities, such as glass, paper, and plastic. Nevertheless, there does not yet appear to be awareness of the need for recycling inventories for construction materials, which have a longer lifetime. In this field, the relative scarcity of inventories is noticeable. Despite the important period of time which must elapse before a concrete structure becomes eligible for recycling, the expansive growth of demolition waste and modern policies regarding the desirability of recycling justify the interest of the environmental study of concrete recycling.

LIFE CYCLE ASSESSMENT AND THE SUBSYSTEM ARTICULATION

Environmental life cycle assessment (LCA) was developed from the idea of comprehensive environmental assessments of products, and was conceived in Europe and the USA in the late 1960s and early 1970s. Nevertheless, the application of this methodology grew mainly in North Europe in the early 1990s where, apart from technical feasibility and economic efficiency, environmental considerations play an increasingly important role in many industrial sectors.

Modern environmental policies with regulations, such as the European Directive on Integrated Pollution Prevention and Control, require the overall prevention and reduction of emissions and other impacts on the environment (IPPC, 1996).

In simple terms, the Life Cycle Assessment of products (LCA), or Life Cycle Analysis of products, is the evaluation of the contribution of all the processes involved in the manufacture of a product to a selected list of environmental effects. The basic concept of product LCA is that the entire life cycle is considered, including all of the environmental effects that result from each activity, ranging from the extraction of resources to the processing of final waste. This includes: identifying and quantifying energy and materials used, and waste released into the environment, assessing the environmental impact, and evaluating opportunities for improvement.

The LCA methodology can generally be used to support decisions about a purchase, guide the improvement of product processes, or to enable product approval and selection. Although the purpose of an LCA is to determine only the environmental impacts of a product, the aforementioned decisions or actions can be based on environmental, social, or economic aspects, or on any other similar considerations related to a product and its production.

Inventory analysis is the process of compiling the amount of natural resources and energy taken in by the system, and the amount of waste discharged to the environment from the system. This is the component of an LCA in which the product system is analyzed. A life cycle is made up of a range of processes; each with associated side effects, often termed environmental interventions. To summarize all of these, an inventory table, or Life Cycle Inventory (LCI), is needed. This is a list of all primary and other energy consumption values, emitted chemicals and chemical compounds, quantities of waste, amount of space used, etc.

To implement a Life Cycle Inventory, a clear definition of the boundaries and the functional unit is important, as it influences the outcome of an LCA study.

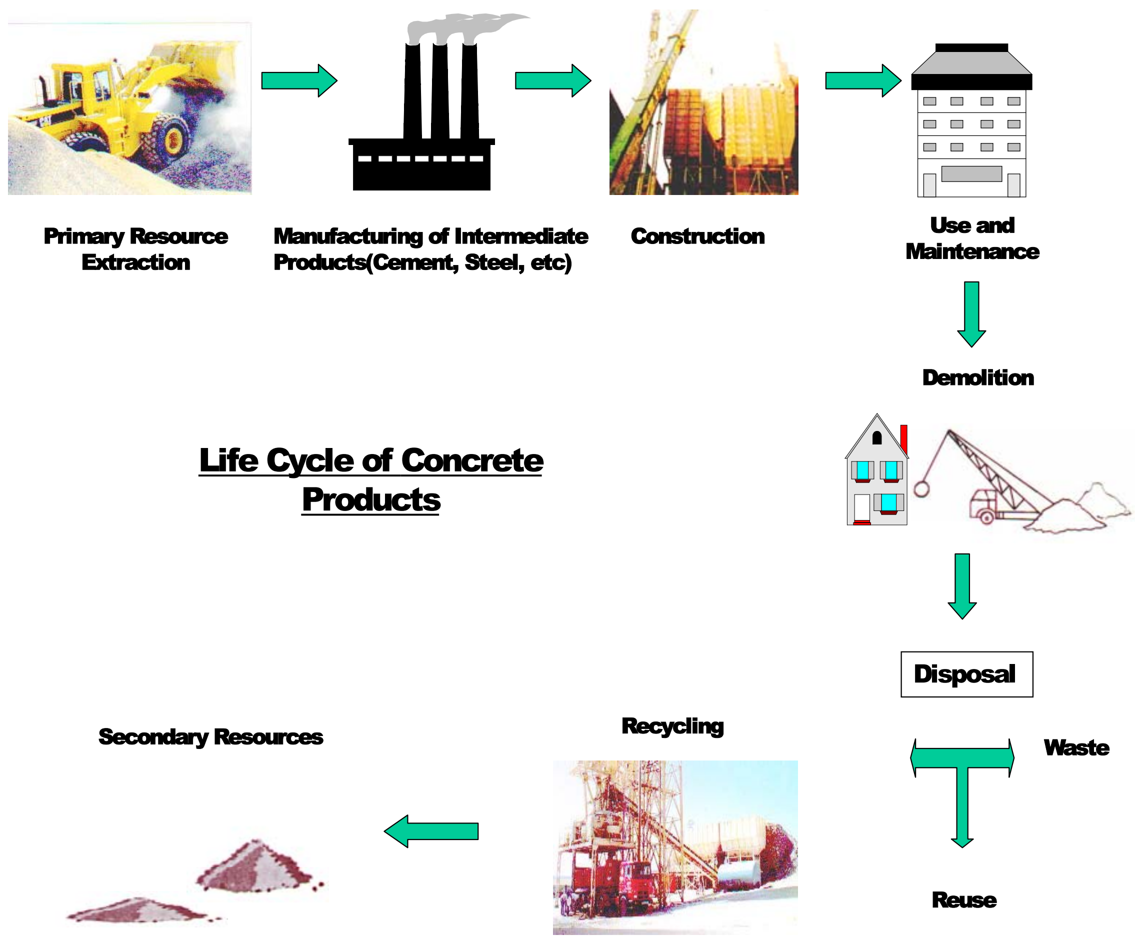

Fig. 1 – Complete Life Cycle of Concrete Products

Figure 1 shows the complete LCA (from cradle to grave) of any concrete product. This system, as shown in Figure 1, can be defined as being composed of various subsystems existing in sequential order, where the output of each subsystem makes up the input of the next one, each being linked by a transport system. Thus, a concrete recycling subsystem uses the outgoing materials from the preceding demolition process as input of materials, and it produces the recycled aggregates as output. The sum of all subsystems makes up the total system. The complete life cycle described in Figure1 begins with the extraction of aggregates from natural quarries (primary aggregates), and culminates in the production of aggregates from the recycling process (secondary aggregates). Both types of aggregates are applicable to making concrete.

The system boundaries determine the extent to which the inventory takes into account parameters from the supporting product systems and from the environment. In Figure1, the specific context of the subsystem in concrete recycling is defined.

Figure 2 illustrates this subsystem, in which there are some inputs, some processes, and some outgoings.

Its boundaries may present different configurations. For instance, it may include only concrete recycling processes, or it may also include the obtaining of material via the demolition processes, and/or the transport system linking subsystems, and/or the final transport of aggregates.

The subsystem defined here can be classified as the *gate to gate* type, because it only includes the recycling processes relative to concrete.

Inputs of the Subsystem
The resources (materials) come from the preceding demolition subsystem it in the linear chain of the Life Cycle set out in Fig. 1. So as to adhere to the defined boundaries, the energy resources considered shall be only those involved in the subsystem's own processes, and shall not include the energy involved in previous processes of demolition or transport.

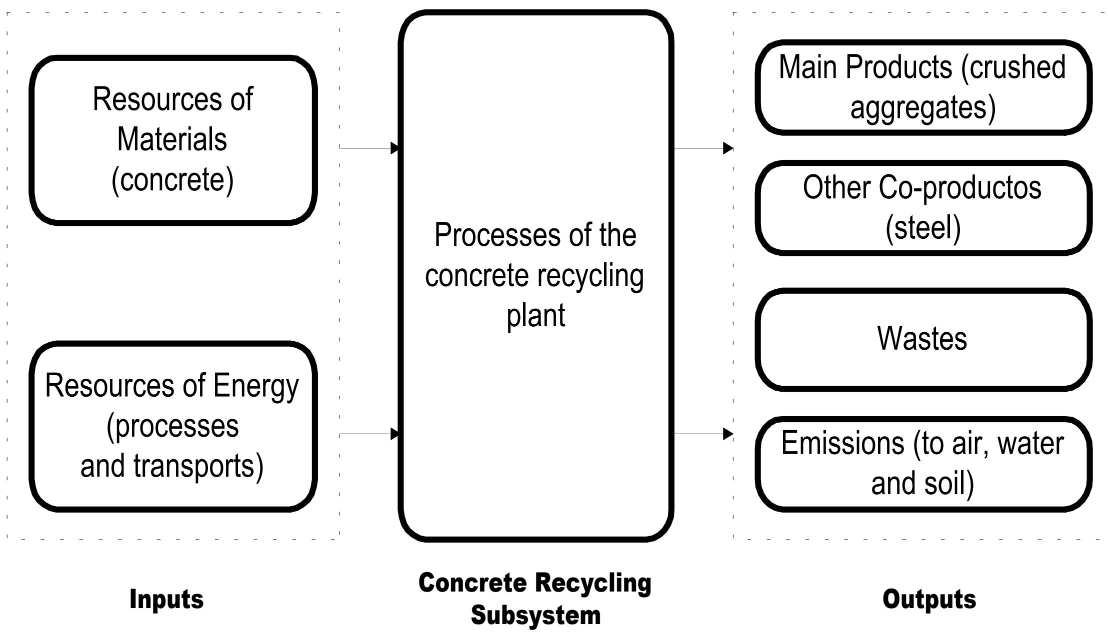

***Fig. 2** – Concrete Recycling Subsystem*

The Subsystem Processes
The processes of the subsystem are those which make possible the obtaining of a product (secondary aggregates) from concrete waste. Concrete recycling plants carry out various processes, such as classification and separation of materials, crushing of concrete waste, and internal transport.

The Outputs of the Subsystem
The outputs consist of the principal products, the secondary products, the emissions and the residues or waste. The principal products consist in aggregates of varying gauges. Secondary products are all those which, while forming part of C&DW, do not belong to the group of petreous materials but are still capable of being recycled and re-used. Principal among these are the different types of materials derived from the classification and selection processes, such as plastic, glass, metals, etc. Reinforced steel, which has not been possible

to separate from the concrete in the separation process, and is later removed by an electromagnet in the crushing process, is considered a secondary product. Other outputs taken into account are the emissions to the environment (the ground and water) and, in some cases, the production of solid wastes.

The flow of input and output to the subsystem implies that generation of environmental burdens originates in the different processes. These must comply with a law of the equilibrium of burdens, in order to ensure the equilibrium of the system. The equilibrium of burdens, E_i, may be expressed as in equation [1]:

$$\Sigma E_i \text{ (inputs)} + \Sigma E_i \text{ (processes)} = \Sigma E_i \text{ (products)} + \Sigma E_i \text{ (wastes)} \qquad \text{equation [1]}$$

INVENTORY

The methodology applied in implementing the inventory is comprised of the stages recommended by the International Organisation for Standardisation (ISO) 14041:1998. Data presented has been compiled from that available in the four recycling plants located in Catalonia. To determine the quantity of emissions corresponding to energy consumption of the different phases of the recycling subsystem, the calculations have been supported by the SimaPro 4.0 program, determining the pollutant emissions derived from the consumption of 1 Kg. of fuel oil (calculated according to data from INDEMAT 96).

Main characteristics of the inventory subsystem

According to the subsystem articulation presented above, the system boundaries respond to the *gate to gate* type, as defined in the description of the subsystem articulation. The functional unit is defined as the recycling of one tonne of concrete proceeding from C&DW. The prime materials are concrete waste not containing any other mixture of material, contaminated fractions (plaster, glass, etc.), or other inert fractions (brick, tiles, etc.).

The subsystem processes

The subsystem processes have been defined through fieldwork, consisting of data collected in the four recycling plants in Catalonia. Three of these plants produce mixed aggregates derived from concrete waste, while one plant produces aggregates for concrete with purity close to 100%. This company has been used as a reference in this work. It has a mobile crusher plant, and the internal transport is carried out by means of front-loading shovels.

The outputs of the subsystem

<u>The main products</u> are aggregates of three gauges: fractions > 45 mm (rank aggregates 1), fractions of 20-45 mm. (rank aggregate 2), and fractions of 0-20 mm. (rank aggregate 3).

<u>The secondary products</u> are the fractions of steel reinforcing removed from concrete waste by electromagnet at the mobile crushing plant. In some cases, prior to the recycling processes, small amounts of metal fractions can be taken out of the waste by manual separation (see grey option in Fig. 3).

<u>The waste</u> is composed of materials that lack commercial value and cannot be recycled as new products. Nevertheless, in the process of concrete recycling, all of the outputs (aggregates and steel) have positive economic value, and no waste is generated.

Emissions: Calculation of the environmental emissions originating in the subsystem is based on the law of equilibrium of environmental burdens, expressed in equation (1).

The environmental burdens, corresponding to the inputs and processes of the subsystem, are a direct consequence of the energy consumption associated with these. According to the boundaries established, input energies are considered to be those associated with each one of the processes carried out in the recycling plant. Consequently, it has been necessary to determine and quantify the types of energy used in each process. Fossil fuel (fuel oil) is the energy source for the mobile crushing plant and the front-loading shovels. Aggregate production is between 80 and 100 tonnes per hour, and the average consumption of fuel is about 25 lt per hour for the crushing, and about 20 lt per hour for the front-loading shovels. These values have been validated by visiting different companies in Catalonia.

In calculating the emissions, the environmental burdens associated with the subsystem processes were obtained from Table 1, which shows consumption per litre and per MJ of fuel oil for each of the phases of the subprocess, by reference to the functional unit.

Using the values in this table and using the inventory of emissions corresponding to the consumption of 1 Kg. of fuel oil (SimaPró 4.0) as a reference, the environmental burdens associated with the processes of the subsystem have been calculated. Based upon these values and by application of equation (1), the environmental loads associated with the output elements may be determined. An allocation method must be taken into account, because this is a multi-output system. First, considering that the subsystem produces main products (aggregates), plus a secondary one (steel), and does not produce waste, equation [1] takes the form:

$$\Sigma\ E_i\ (\text{inputs}) + \Sigma\ E_i\ (\text{processes}) = \Sigma\ E_i\ (\text{rank aggregates1}) + \Sigma\ E_i\ (\text{rank aggregates2}) + \Sigma\ E_i\ (\text{rank aggregates3}) + \Sigma\ E_i\ (\text{steel}) \quad [1]$$

Phases of the concrete recycling subsystem	Fuel	Average consumption	Power (MJ/t.concrete)
Transport	fuel oil	0.25	9.635
Crushing	fuel oil	0.37	14.26
Internal transport	fuel oil	0.25	9.635

Table 1*- Energetic Resources of the different phases defined in the concrete recycling subsystem*

The next step is to apply an allocation criterion. If allocation cannot be avoided, then an appropriate method has to be chosen to allocate the burdens in a multiple-function system. Most of the approaches proposed allocate burdens in proportion to some physical property or economic value. Physical properties used as a basis for allocation may include mass, energy or exergy content, volume, and molecular mass. In this application, an allocation method in proportion to mass has been applied. According to (Ekvall, 2000), (Azapagic, 1998), (Huppes, 1994) (ISO 14041: 1998), a multiproduct allocation model for LCA is feasible only if it is a linear homogeneous model to describe system behaviour. This approach assumes that changes in the burdens, and the resulting environmental impacts, are directly proportional to changes in functional outputs. In such a linear homogeneous model applied to the system, the total environmental burdens, E_i, are related to the functional outputs, m_j, by a set of equations of the form:

$$E_i (m_1\ m_2\ \ldots\ldots\ m_n) = \Sigma A_{ij}\ m_j \qquad [2]$$

The subsystem under consideration fits reasonably well under a linear homogeneous behaviour model and the hypotheses of physical causality since, if the mass of the products is increased, more energy will be required and consequently the environmental burden will be increased. This means that changes in the burdens are directly proportional to changes in functional outputs. On this basis, equation [2] could be applied for the calculation of results.

ΣE_i (inputs) $+\Sigma E_i$ (processes) $= \Sigma A_{ij}\ m_j = \Sigma E_i$ (rank aggregates1) $+\Sigma E_i$ (rank aggregates2) $+ \Sigma E_i$ (rank aggregates3) $+\Sigma E_i$ (steel) eq.[1a]

In matrix form, eq. [1a] can be written as:

$$\begin{bmatrix} E1 \\ E2 \\ . \\ Ei \end{bmatrix} = \begin{bmatrix} a11 & a12 & . & a1j \\ a21 & a22 & . & a2j \\ . & . & . & . \\ ai1 & ai2 & . & aij \end{bmatrix} * \begin{bmatrix} m1 \\ m2 \\ . \\ mj \end{bmatrix} \qquad [1b]$$

In matrix A_{ij}, the dimension, i (rows), is the total of contaminating substances emitted into the air, water, and ground by the processes. The j dimension (Columns) is the total amount of outputs delivered by the process. The dimension of vector m_j, which also coincides with the number of outputs or products of the subsystem and its elements, corresponds to the different proportions of mass of each product. In the case under consideration, the definition of vector m_j involves establishing the following values:

- m_1, mass proportion of fraction > 45mm. (aggregates grade 1)
- m_2, mass proportion of fraction 20-45 mm (aggregates grade 2)
- m_3, mass proportion of fraction 0-20 mm. (aggregates grade3)
- m_4, mass proportion of steel fraction

When an equilibrium of masses is met, the sum of all these values must be equal to the functional unit, which is one tonne of mass, or $\Sigma\ m_j = 1$. These values may vary according to market demands, which determine the volume of production in the different grades. Generally speaking, the aggregates that find the greatest commercial application are the coarser grades. In Catalonia, production of these fractions is usually around 75% of the total. In the recycling plant adopted as reference for this study, the average values of the aggregate mass produced by one tonne of recycled concrete are:

- mass proportion of fraction > 45mm. (rank ag.1)… = 35%
- mass proportion of fraction 20-45 mm (rank ag. 2)…=40%
- mass proportion of fraction 0-20 mm. (rank ag. 3)… =25%

In order to determine the steel mass that is produced as a by-product of the subsystem, the partial results of a study generated by the Junta de Residus (Waste Management Board, part of the Catalan regional government) has been taken into account. The study is part of the

Guide of application of decree 201/94 (Junta de Residus, 1995), and includes a comparative evaluation of concrete and steel mass in demolition waste from different origins. From this study an average value of 22 Kg. of delivered steel per tonne of recycled concrete has been determined.

On the basis of these values, the mass coefficients of the vector m_j are as follows:

$m_j = (0.342 \quad 0.391 \quad 0.245 \quad 0.022)$

With the vector m_j determined above, and the application of eq. [1b], the environmental burdens allocated to the different outputs of the subsystem have been determined.

Analysis of Results

The aim of this study is to analyse and validate the results obtained from the Life Cycle Inventory developed, and to compare them with those obtained from other references. Since no other concrete- recycling inventory was available for a comparison of results, the analysis was based on a comparison of the extraction processes of primary resources (sand and gravel). The specific inventories available for the study are provided by SimaPro 4.0 (Pré Consultants, 1997), and correspond to the denomination, *Gravel I* and *Sand I* . The unit of comparison is the production of 1 tonne of aggregates (primary and secondary) useful for concrete production. SimaPró inventories treat data in two sub-systems, the transport and the quarrying and processing of primary aggregates.

For the comparison, it must be taken into account that the energetic resources of the different inventories considered came from different sources. While SimaPró inventories consume electric energy for the quarrying and crushing of primary aggregates, and fuel oil for transport, the concrete-recycling inventory consumes only fossil fuel in all of the processes.

Output Data Analysis

The analysis considers the emissions with the highest percentages in the categories of environmental impact:

- CO_2, due to its major influence on the greenhouse effect and induced climatic change on a global level.
- NOx, due to its contribution to acidification and eutrophication on a regional level.
- SO_2, due to its contribution to acidification on a regional level.
- Dust, due to its important visual and direct impact on the image and health of the environment and its inhabitants on a local scale.

Table 2 shows the amount of the emissions described above for the different inventories under comparison.

Emissions to Air (g/ton.)	Inventory of concrete recycling		Inventories of SimaPró 4.0			
			Gravel I (g/t)		Sand I (g/t)	
	Transport	Crushing	Transport	Electricity	Transport	Electricity
CO_2	1704.44	1261.3	4920	2820	4920	1950
NO_x	26.36	19.5	94.2	5.36	94.2	5.49
SO_2	1.62	1.2	12	0.419	12	11.2
Dust	0.17	0.126	0.49	0.0371	0.49	0.873

Table 2 *– Emissions to air from extraction processes of primary aggregates and from production of secondary aggregates.*

From a comparative analysis of the results, the following conclusions have been drawn:

CO_2 Emissions

The main CO_2 emissions are a result of the transport processes in all of the inventories. In the primary (natural) aggregates, the CO_2 values due to transportation processes are about 63% of the total for gravel, and about 71% of the total for sand; while in secondary (recycled) aggregates, the CO_2 values due to transportation processes represent about 57% of the total. This important difference between the rate of CO_2 values due to transportation processes by primary and secondary aggregates should be attributed to the different amount of fuel consumed. Regarding the crushing processes, the quantity of CO2 emitted due to crushing is 1261 g per tonne for recycled concrete; whereas in primary aggregates, it reaches approximately 1950 g and 2820 g per tonne for sand and gravel, respectively. This leads to the conclusion that the difference in CO_2 emissions could be attributed to the number of processes included in the subsystem dealing with natural sand and gravel, which include quarrying as well as grinding or crushing, with an increase in the amount of energy required.

NO_x Emissions

The total NO_x emissions due to recycling of concrete are 45.86 g per tonne. This value represents approximately 50% of the total emissions due to quarrying and processing of primary aggregates (about 99 g per tonne). These NO_x emissions are mainly an output of the utilization of fossil fuel. Thus, primary aggregates produce 94.2 g of NO_x per tonne due to transport processes, while only 5.36 and 5.49 g of NO_x per tonne are due to electricity consumption for gravel and sand, respectively. On the other hand, secondary aggregates produce 26.36 g of NO_x per tonne due to transport processes, and 19.5 g of NO_x per tonne in the crushing process.

SO_2 Emissions

The emissions of SO_2 produced in the processing of recycled aggregates reaches 2.784 g per tonne, which represents 22.4% and 12%, respectively, of the emissions produced in the production of natural gravel and sand. The quarrying and grinding processes for sand generate twice the amount of SO_2 emissions than those for gravel. This is explained by the kind of energy resource utilized in each case.

Dust Emissions

The numerical estimation of dust levels takes into account the amount of electrical energy and fossil fuel consumed in the processes. It uses the typical dust emissions from each country´s power-generation plants, and the emissions corresponding to each type of fossil fuel used in the production of thermal energy. The emissions of mechanical actions (the action of the crushing plant, the sand grinders, etc.) must be included to provide more realistic results.

CONCLUSIONS

- The processes of quarrying, crushing, and grinding of natural aggregates produces a greater environmental burden than the processes of crushing and recycling of concrete, especially concerning CO_2. This is probably due to the fact that, in all processes of producing natural aggregates, the extraction processes must also be considered, with the consumption of energy implicit in these.

- The importance of reducing the consumption of fossil energy is emphasized in order to reduce potential impacts on the environment.

- The major part of the environmental burdens produced in the different systems is the result of transport. These processes are responsible for the most energy usage and emissions of gases and particulates. These involve emission of the principal gases responsible for the greenhouse effect (CO_2), with higher values in the production processes of primary (natural) aggregates than in recycling processes. The transport distances play an important role in the results. The distances considered in the inventories of production processes of primary aggregates are bigger than those considered in the recycling processes.

- Within the context of this study, it could be stated that the building industry could contribute to a sustainable development by reducing the emissions of CO_2, if they were to consider recycling as the better option over production of primary aggregates.

- Nevertheless, comparative analysis of the inventories for the production of primary aggregates (SimaPró) and the inventory for concrete recycling show limitations. The system boundaries of the different inventories are not homogeneous. This makes analysis difficult.

- The data used in the implementation of concrete recycling inventory is representative of Spain, while the inventories of SimaPro have been made with data from another geographical region. Thus, the data that have been compared above came from different sources, which makes the extrapolation difficult.

- The quantity of information available in databases existing in the market, and included in this study, is limited. This is due partially to the lack of specific inventories in this area, and partially to difficulty in accessing and obtaining existing information.

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