Environmental performance of waste based construction materials. LCA study.

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ABSTRACT: Extractive industry generates large quantities of wastes from mining to finished product in spite of production yields improvements. However, the inertness of natural stone wastes allows them to be re-used as valuable raw materials towards more Sustainable Construction. This valorisation implies: i) relief of disposal sites and avoidance of related visual impacts, ii) promotion of suitable substitutes for natural aggregates, of which consumption is continuously increasing, and iii) decrease of these non-renewable resources depletion.

This paper presents an initial investigation on building materials incorporating ornamental stone sludge. In order to compare them with the natural stone-made, it is important to know not only their functional properties but also the environmental impacts over their whole lifetime. Consequently, good quality information about their burdens on the Environment should be generated and collected, using for its evaluation and interpretation the tool Life Cycle Assessment (LCA).

1 INTRODUCTION

Huge volumes of sludge from the processing operations are dumped at the facilities surroundings of most companies specialised in ornamental stones. This sludge is a consequence of the water used by cutting and finishing machines for cooling their abrasive tools and for collecting the emitted dust in a liquid phase. It is included in the European waste catalogue with the code 01 04 as “wastes from physical and chemical processing of non-metalliferous minerals” [2001/573/EC]. Although this waste is mainly constituted by water loaded with fine particles from the exploited rock, it can produce pollution, both to soil and in the phreatic layers.

This type of waste recycling means avoiding the need for landfill area and associated landscape damage [COM/2000/265/FINAL]. However, if they undergo further valorisation by converting them into marketable products, not only environmental but also economic advantages are obtained. Construction sector has the capacity of absorbing other industrial wastes and sub-products, so potential problems of disposal site shortage and pollution are reduced along with resources conservation.

2 OBJECTIVES

The subject of this paper is the evaluation of the environmental feasibility of certain kind of building materials containing limestone sludge that have been developed in a CARTIF project. This work expects to be a proper step in order to attain a technological solution to the problems caused by the indiscriminate waste disposal into the environment and the scarcity of continuously depleted natural resources used as raw material in construction.

A simplified comparative LCA between a natural stone slab and the laboratory made equivalent item, which could act as good replacement in particular purposes, especially for internal flooring, was carried out.

3 CONSIDERED SCENARIO

CARTIF Foundation is located in the centre of Castilla y León, Northwest region in Spain, which has a business structure basically formed by different companies devoted to six traditional economical sectors: agrofood, wood furniture, natural stone, textile, agricultural machinery and metal mechanic industry.

As can be observed in Figure 1, there are 91 varieties of natural stone in Castilla y León that are grouped, according to its geological and mineralogical constitution, in 7 families of rocks: sandstone, quartzite, gneiss, limestone, granite, marble and slate [García de los Ríos et al. 2002]. Some quarries are out-of-use but the most are currently worked, and close to both active and abandoned factories large quantities of generated wastes are stockpiled.

Figure 1. Location of natural stone exploitations in the region of Castilla y León (Northwest of Spain).

The chosen scenario for the CARTIF project was the marble and limestone sector because it constitutes 34% of the varieties range and calcium carbonate can be used as filling material of artificial stones. In particular, this work is focused on the reuse of limestone sludge.

About 23 different limestone types are distributed along 6 of the 9 provinces (except Ávila, Salamanca and Zamora). The exploitation subject of this research, Piedras Campaspero S.A., is located in Valladolid, border with Segovia. This company has been manufacturing the termed “moor limestone” since 1992 and, although it has advanced processing technology, no consumption and emission are registered so far.

In order to tackle a research useful to the company, a technical and economically feasible process of artificial stone manufacturing was designed. Through this process different types of cheap building materials are obtained simply by mould changes, and they can act as suitable substitutes for natural stone products. That is to say, the new materials are similar to the ones extracted from quarries, both in quality and visual aspects, but without the need for being submitted to the same processing activities as natural stone (cutting, polishing, etc.).

4 METHODOLOGICAL APPROACH

4.1 *Life cycle assessment*

Life Cycle Assessment (henceforth LCA) methodology has been used to ascertain the new product environmental behaviour. This tool is an objective process for evaluating the environmental burdens associated with a product, process or activity, by identifying and quantifying both the materials and energy consumption and the wastes released to the environment. The “life cycle” or “cradle to grave” concept includes the extraction of raw materials, the processing and manufacturing of the product, the product distribution to the consumers and its use by them, and the disposal or recovery after the product useful life.

In accordance with the methodological framework described by the related International Standards [ISO 2006], the LCA procedure is divided into 4 stages which have been followed in this study and are briefly detailed in the following sections: goal and scope definition, inventory analysis, impact assessment and results interpretation.

4.2 *Goal and scope definition*

This LCA has the aim of carrying out a simplified comparative study of natural and artificial stone from an environmental point of view, taking into account all stages of their life cycle. They can only be compared on the basis of a similar functionality. So it was selected as main system function to floor a surface of 135 m^2 for 50 years. A technological characterisation of the developed material was realised as the last stage in the design process to check the material aptitude for construction use, discarding significant loss of properties and consequent reduction of lifetime or even diminished potential applications. In Figure 2 the functional performance of the two materials is shown.

	NATURAL STONE	ARTIFICIAL STONE
Porous systems Tests		
Absorption coeficient (%)	3.77	0.13
Apparent density (g/cm^3)	2.43	1.71
Mechanics and Dynamics Tests		
Compressive strength (MPa)	71.4	76.8
Flexural strength (MPa)	5.98	10.7
Drop height / impact resistance (cm)	31.25	50.0
Durability Tests		
Frost resistance coefficient (%)	0.04	0.06

Figure 2. Characterisation of natural and artificial stone.

The applicability studies were focused on a bush-hammered slab, in accordance with the corresponding technical norms that specify that the results obtained for every property are only valid for size and finishing identical to those of the assayed samples. It is worth mentioning that these specific tests were carried out according with the Spanish natural stone standards because this CARTIF project was previous to November 2005, when the agglomerated stone procedures were published in Spain.

Thus, the developed material accomplished the expected objectives, since it had reproduced the aesthetic appearance of the ornamental rock, even obtaining property improvement with respect to natural limestone. The resultant artificial stone is almost 30% lightweight, it has an important less absorption and higher compressive and flexural strength and impact and frost resistance.

Then, the chosen system function reflects a conservative assumption, as both products should at least have the same durability. The definied functional unit, to which input and output data are referred, is based on it: 750 units of bush-hammered slabs whose dimensions are 0.6 m long, 0.3 m wide and 0.03 m height for a paving-oriented application.

The new material was subjected to ultraviolet radiation, which is responsible for the oxidation processes that could lead to a yellowish colour. However, the correspondence between the hours of the accelerated ageing and the actual exposure to sunlight is not normalised yet, since long-term performance data are not available. In particular sectors, as for example the automotive industry, the tests use samples with actual ageing effects to compare with. Establishing equivalence from the utilised ultraviolet lamp, it was concluded that 53 months of natural radiation do not exert influence over the pieces. The material was also tested under atmospheric conditions (rain, wind, sun, etc.) for 10 months without occurring visual changes. Despite these results, this work centres on interior pavements, due to the lack of data about the behaviour of resin-agglomerated products laid outside.

4.3 *Life cycle inventory*

This stage consists of the compilation of an inventory of relevant inputs and outputs (energy, raw materials, air and water emissions and solid wastes).

The company under study provided most of the data used to this LCA. They were collected in 2004 and correspond to 2003. Different rules for allocations of flows to the functional unit were used (e.g. market price, mass, etc.). The adopted criteria for the establishment of the system boundaries were the availability of data referred to each unitary process and the impact significance.

Both natural and artificial stones require common input parameters during their life cycle, as is shown in Figure 3. Natural stone can be subjected to a recycling process at the end of its lifetime. It has been considered that 20% of used slabs are crushed in order to obtain aggregates and the rest is disposed in an inert landfill. Gravel is an avoided product related to the natural stone life cycle, so impacts associated with the quantity of gravel that is necessary to extract from pit, for getting the same quantity of aggregates, are saved. On the other hand, the end of life considered for the 100% of the artificial stone was landfilling, as it is a synthetic product whose recyclability, at the end of its service life, may be questioned.

		NATURAL STONE		ARTIFICIAL STONE	
PRODUCTION	MATERIALS	Quarry and factory	Limestone Water Diesel Abrasive & cut stone spare parts (diamond blades and wires, chains, bush-hammering heads, etc.)	Mixture	Limestone sludge Polyester resin Styrene Co octoate MEKP Anti-UV additive
				Mould	Silicone rubber Hardener Particle board Plasticine Wax
	ENERGY (Electricity consumption)	Extraction	Compressor Quarry chain saw	Filler conditioning	Filter press Heater Crusher Sifting machine
		Cutting and superficial treatment	Bridge cutter Multiblade gangsaw Bush-hammering machine	Mixing	Agitator
		Internal transport	Bridge crane	Mould preparation	Vacuum chamber Heater
		Depuration	Pump Decanter Valves	Casting and hardening	Vibration table Heater
	TRANSPORT	From quarry to factory	Lorry 16 t	--	
PACK.	MATERIALS	EUR-flat pallet LDPE covering Polypropylene packing band			
DIST.	TRANSPORT	Lorry 16 t from factory to client			
USE	MATERIALS	Laying materials: Cement, sand, hydraulic lime, Kraft paper bags, water Water for cleaning & maintenance			
	ENERGY (Electricity consumption)	Mortar kneading			
END OF LIFE	TRANSPORT	Lorry 21 t for waste collection of kraft paper bags, packaging plastics, used slabs, etc.			
	DISPOSAL SCENARIO	Inert landfill		Landfill	

Figure 3. Input parameters of natural and artificial life cycles.

The emissions of styrene were estimated based on studies about the volatility of polyester resins [Neira et al. 2005]. Some output flows could not been considered for example, vibration and noise produced during the processing of natural stone have not been measured and were accordingly neglected. This study did not take into account other unquantifiable parameters, like visual impacts or social nuisance.

4.4 *Impact evaluation*

Unavailable data have been estimated from theoretical models or databases, as for example Ecoinvent [Ecoinvent Centre 2003]. All inventory data linked to the functional unit have been imported into the LCA software package SimaPro 7.0 [PRé Consultants B.V. 2004]. The Eco-Indicator 99, egalitarian version, was utilised as assessment method. [Goedkoop & Spriensma 2000]. This archetype reflects a moderately optimistic point of view, consisting of a scenario in which all possible effects are considered, even in very long term and problems can lead to catastrophe.

In this paper, eleven impact categories, grouped in three damage categories, have been evaluated:

– Damages to Human Health, expressed in DALYs (Disability Adjusted Life Years). The following impact categories are included: carcinogens (Carc), respiratory organics (RO), respiratory inorganics (RI), climate change (CC), radiation (Rad) and ozone layer depletion (OD).

- Damages to Ecosystem Quality, expressed in PDF·m^2·year (PDF: Potentially Disappeared Fraction). These damages include ecotoxicity (Ecotox), acidification/eutrophication (A/E) and land use (Land).
- Damages to Resources, expressed in MJ. These damages are caused by the depletion of minerals (MD) and fossil fuels (FF).

The characterisation was carried out to obtain the environmental profile of the two products. In this phase, the results of the inventory table are multiplied by the characterisation factors of the substances for each impact category.

In order to compare the importance of the damage categories, these were normalised and then weighted for obtaining a single score, following the Eco-Indicator 99 E/A (A: average weighting set). In this method, the damage categories are normalised at European level, taking the damage caused by 1 European per year. It is considered as 64.7 DALY, $1.95 \cdot 10^{-4}$ PDF·m^2·year and $1.68 \cdot 10^{-4}$ MJ, with data of 1993 and updates for the most significant emissions. In addition the weights assigned by the egalitarian version are 30% to human health damage, 50% to ecosystem quality and 20% to resources consumption.

The interpretation from the characterisation and weighting results will be discussed below.

5 DISCUSSION

5.1 *Characterisation*

In an LCA, it is important to verify used data for getting an idea of what reliability the results have. As far as this work is concerned, a sensibility analysis was carried out. The chosen sensibility factors were data of doubtful origin.

In the case of natural stone, the quantity of dust generated during the processing of ornamental limestone is not known for certain. If it is considered the water supply to the cooling system, the wastage is 30% of the block. This scenario will be referred as NS-30. On the contrary, if it is considered the dairy collection of sludge, which has nearly 65% water content, the wastage increases up to 60%. Similarly, this situation will constitute the scenario named as NS-60. For the artificial stone the sensibility is related to the energy consumption, since the manufacture process is not yet implemented and consequently the consumption could not be estimated according machinery effective powers. AS-max corresponds to a scenario in which the energy consumption of a theoretical process without filter press has been oversized in a percentage of 30%. In the last scenario, AS-min, it is assumed the installation of the drying system and 30% undersized energy consumption. Their relative contributions to impact are reflected in Figure 4.

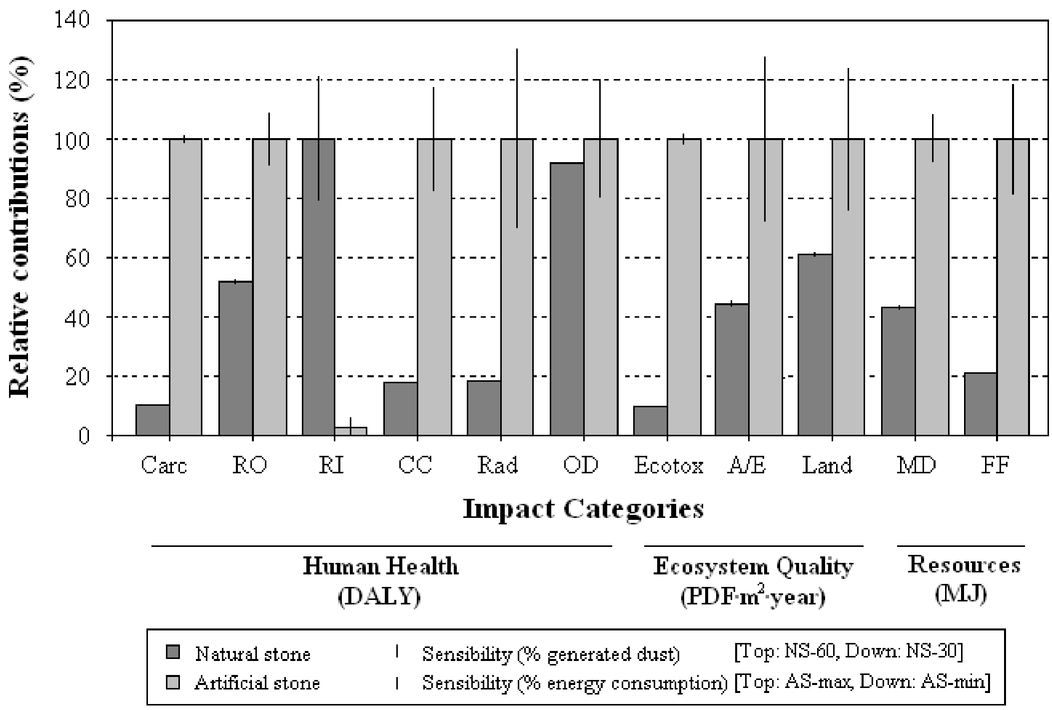

Figure 4. Comparative characterisation with sensibility analysis (Eco-Indicator 99).

Based on the available data and using the Eco-indicator 99 E/A method with the associated limitations, the AS-max scenario has worse environmental properties than NS-30 for all impact categories, except Respiratory Inorganics. The sensitivity analysis shows that critical assumptions do not have a great influence in the results except in the Ozone Layer Depletion category, in which the best scenario of AS (AS-min) has a lower contribution than the two scenarios of NS, while AS-max impact is higher than both of them. However, it has to be kept in mind that this category does not represent a meaningful contribution to either natural or artificial stone whole impact.

Approximately 90% of the natural stone total impact is due to the category of Respiratory Inorganics, while the category of Fossil Fuels is responsible for almost 50% of the artificial stone total impact, followed by the category of Ecotoxicity and Carcinogens, in decreasing order of importance.

The impact in the category of Respiratory Inorganics of the natural stone scenarios is mainly caused by the raw materials extraction stage, associated with the limestone consumption. Regarding the pollutants, most of the impact of the natural stone in this category is because of the air emission of particles 2.5 to 10 µm in diameter. The contribution of particles 2.5 µm in diameter or smaller means almost the rest of this impact. The end of life stage in inert landfill corresponding to the 80% of the slabs is responsible for practically the rest of the natural stone impact. The avoidance of gravel extraction is a consequence of the recycling of the remaining 20% of the slabs. Although impacts associated with the quantity of gravel that is necessary to extract from pit, for getting the same quantity of aggregates, are saved, its relative contribution to the natural stone total impact is small.

Slightly over half of the natural stone total impact in the category of Fossil Fuels is produced by the distribution stage. The second more impacting stage of the natural stone life cycle is the energy consumption.

Concerning the artificial stone, this impact is totally due to the production stage, in which fossil fuels are necessary as raw material of the petroleum-derived products (resin, styrene, chemicals, etc.) and for generating the required energy in the slabs manufacturing.

5.2 *Weighting*

In order to achieve straightforward conclusions and to decide which alternative is environmentally preferable, a normalisation and weighting step was performed. Hereinafter, aiming at comparing the best natural stone scenario with the worst artificial stone scenario, only the NS-30 and AS-max scenarios will be considered.

The use of natural stone sludge in the artificial stone manufacturing entails an impact saving in the category of Respiratory Inorganics. Therefore, the single score of the production stage is reduced.

Figure 5 shows the single score environmental assessment of NS-30 and AS-max. It can be observed that, even comparing these scenarios, an artificial stone slab performs environmentally better than its natural stone homologous (Eco-Indicator 99 E/A).

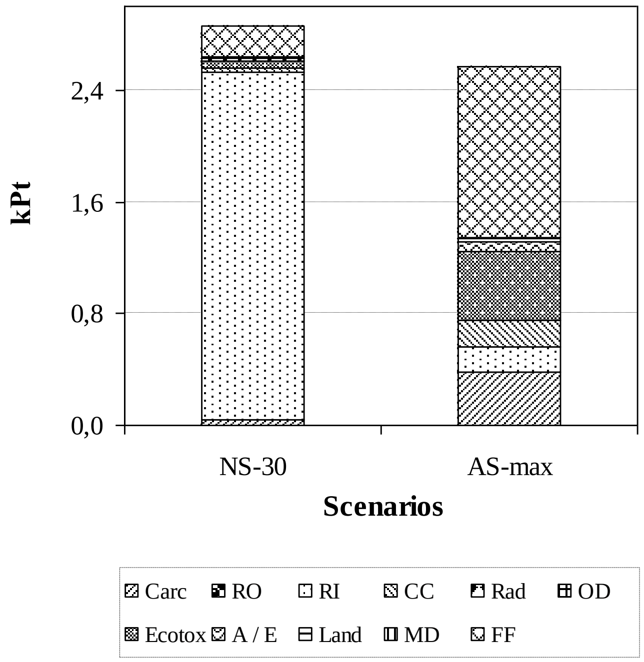

Figure 5. Comparative single score (NS-30 versus AS-max).

Regarding the natural stone, we can notice that the greater number of ecopoints is due to the impact in the Human Health damage category while impact in Resources is responsible for the most of the ecopoints of the artificial stone.

It can be highlighted that this result, favourable for the developed material, is obtained despite that a weight of 30% for the impact in the damage category of Human Health is considered by the egalitarian version of the Eco-Indicator 99. Figure 6 shows the mixing triangle, which plots between 0 and 100% the weights for the three damage categories [Hofstetter et al. 2000]. It is divided in two areas by the line of indifference, representing weighting sets of the same single score. In other words along this line the possible selected sets correspond to those that make both products equally damaging to the Environment, so whether artificial stone is environmentally preferable than natural stone or not, is clearly dependent on the set applied.

All points within the light grey area in Figure 6 can be seen as selections of weighting sets for which artificial stone is more environmentally friendly.

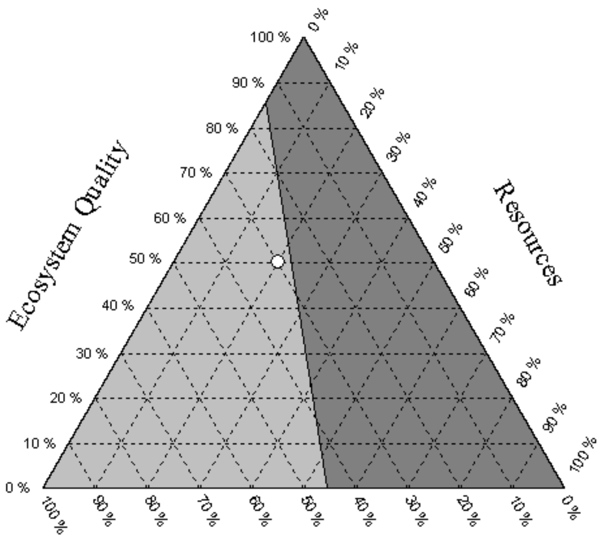

Figure 6. Weighting triangle representing NS-30 and AS-max scenarios (the weithting set of the egalitarian version is marked).

6 IMPROVEMENT ACTIONS

One of the main problems that arise when a LCA is carried out is to achieve a good quality of inventory data. Inputs and outputs of the productive process of natural stone exploitations are not referenced to date. Therefore, the need for consumptions and emissions records by each manufactured product family is obvious. Only in this way the assumptions, which take away reliability from the results, might be avoided.

With respect to the procedure developed for artificial stone manufacturing, in the laboratory tests there was high process sensibility with the analysed parameters (grain size distribution and filler humidity, temperatures and durations of curing and postcuring processes). Hence it is considered necessary to apply Taguchi Methodology to the experiment design in order to optimise the process with as few experiments as possible.

In this work, within the scope of a simplified LCA accompanying a research project, lab scale results have been theoretically extended. In the laboratory tests the performance and influence magnitude of all relevant parameters have been determined.

However, in order to guarantee the equity of the comparison of the environmental profiles of two products assessed by LCA, one of which is result of an actual industrial process, the other should try to approach to the maximum to industrial scale, by at least the pilot plant implementation, highest level of development phase. A detailed analysis of generated information in this plant could lead to the process parameter optimisation, which is required for the upscalling to production plant.

And even in these conditions, several effects take place that can not be ignored. These are, among others, effects inherent to processes (yield changes due to production plant reorganisation and redesign, emission level changes due to the introduction of measures for reducing the concentrations up to legal limits, for instance, filter and gases cleaning systems, inclusion of an end of life management for wastes, etc.), synergy effects or effects from the optimisation of the production capacity [Shibasaki et al. 2006].

Although it would be convenient to carry out an actual data inventory, directly from processes under comparison, this preliminary study is the necessary first step towards creating an environmental concern on the ornamental sector behaviour.

In addition, further work is planned on the topic of leachates analysis and the inclusion of other system parameters in future LCA of these products.

7 CONCLUSIONS

Nowadays processing sludge represents a severe problem for ornamental rocks industry since its recycling potential currently remains to be exploited. [EIPPCB 2004].

A technically and economically feasible manufacture procedure for SMEs belonged to the limestone exploitation sector has been assessed from an environmental point of view in this paper. The resulting artificial stone not only complies with functional requirements for its application as interior pavement but also it has environmental advantages compared to the equivalent natural stone, due to the saving of the impact associated with the sludge disposal. In addition, the ornamental rocks exploitations would access to new markets by producing certain articles at a lower cost than in natural stone.

The present study creates possibilities for a further development mainly focussed on the methodology optimisation for using sludge as filler in artificial stone.

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