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Environmental analysis for identifying challenges to recover used reinforced refractories in industrial furnaces

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ABSTRACT

Reinforced refractories have been demonstrated to be economically and technically useful in industrial furnaces to improve energy efficiency. Nevertheless, there is a lack of knowledge from the environmental point of view in which the end-of-life of these materials was analysed from a life cycle perspective.

This research examines the use of the Life Cycle Assessment (LCA) methodology to evaluate the environmental impact of alumina/ZrO_2 and MgO/ZrO_2 as reinforced refractories, considering the manufacturing and two different end-of-life scenarios, disposal in landfills and recycling.

The results indicated that the environmental performance of these reinforced refractories can be improved by means of promoting the reuse or recycling of the materials and reducing the amount of landfill waste within an integrated waste management system. Greater environmental benefits were obtained when the recycling efficiency was increased and the transport distance was decreased, especially in the case of alumina/ZrO_2. The research demonstrated that it was more sensible to use recycling. Consequently, efforts to consider these environmental results should be undertaken by the industrial sector to promote material recovery. In this sense, a matrix of additional actions is proposed to reduce the overall environmental impact of the system further.

1. Introduction

Refractories are heterogeneous materials with complex microstructures with different constituent properties. Traditionally, these materials are produced from abundant industrial minerals, such as SiO_2, Al_2O_3, MgO, dolomite and chromite, to be used as insulation or molten metal/slag containers (Kwong and Bennett, 2002). Because these materials are typically used in kilns, furnaces, incinerators and other applications, they have to meet different challenging specifications, such as mechanical strength, thermal stability, corrosion resistance, thermal expansion and other qualities to increase the service life. These properties are obtained in the refractory manufacturing process by means of the proper combination of chemical compounds and minerals (Koksal, 2009).

Recent tendencies in refractory materials have focused on improving the quality of these materials, and one of the main methods is to add reinforcement materials, such as zirconia, with the purpose of improving the fracture and the thermal shock resistance through microcrack toughening. For example, Wolf et al. (1995) evaluated the effect of mullite-zirconia additions on high-alumina refractories, and they concluded that the creep resistance was decreased with increasing mullite-zirconia aggregate content. Conversely, Zawrah (2007) also performed a study to analyse the effect of zircon additions with low and ultra-low cement alumina and bauxite castables. Considerably the reinforcement addition, different routes of introducing zirconia reinforcement to cement free alumina refractory castables were analysed by Rendtorff et al. (2012).

Additionally, there is a high worldwide consumption of these materials because the metal industry is one of the largest industries around the world, and refractory materials are the primary materials used as the internal lining of furnaces and transfer vessels. The steel and glass industries use considerable quantities of magnesite and zirconium aluminosilicate refractories (Othman and Nour, 2005), and the steel industry purchases approximately 50% by weight of the refractories produced annually (U.S Departament of Energy, 2001).

Landfilling is the most common method of disposing of the used refractories when furnace linings are found to be at the end of the

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Nomenclature

ALO	Agricultural Land Occupation Indicator
CC	Climate Change Indicator
D	Transport Distance
FD	Fossil Fuel Depletion Indicator
FE	Fresh Water Eutrophication Indicator
FEC	Fresh Water Ecotoxicity Indicator
HT	Human Toxicity Indicator
IR	Ionising Radiation Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MD	Mineral Depletion Indicator
ME	Marine Eutrophication Indicator
MEC	Marine Ecotoxicity Indicator
NLT	Natural Land Transformation Indicator
OD	Ozone Depletion Indicator
PMF	Particulate Matter Formation Indicator
POF	Photochemical Oxidant Formation Indicator
R	Recycling Efficiency
TEC	Terrestrial Ecotoxicity Indicator
ULO	Urban Land Occupation Indicator
WD	Fresh Water Depletion Indicator

working service lifetime (Nystrom et al., 2001). As a result, the disposal of refractories has become a great problem, considering the composition of these materials, which could contain hazardous components, and the current situation of overload in some landfills and even the environmental regulations. This situation has been aggravated in recent years due to the design of new refractories, such as reinforced refractories, to increase their performances (Donald et al., 1998).

Therefore, alternative options have to be studied to reduce landfilling disposal as is supported by Aranda Usón et al. (2012) who developed a new methodology to estimate the energy content of the residual fraction refused by mechanical–biological treatment to be reused or by Menikpura et al. (2013) who proposed a low-cost locally adapted integrated solid waste management system to enhance climate co-benefits. One of the important issues, from the standpoint of waste minimisation, is the recycling of materials to be used in other applications, such as additives for cement production (Aranda Usón et al., 2013) or as raw material in refractory manufacturing processes (Lule-Gonzalez et al., 2005). The latter is the most valuable option. Several studies have been conducted on related subjects, such as the recycling of MgO–C refractories from electric arc furnaces performed by Lule-Gonzalez et al. (2005), the recovery and recycling of scrap refractories studied by Valoref (1998) or even the steel industry and the recycling of refractories as researched by Nakamura et al. (1999). However, the quantities and composition have to be analysed considering the technical and quality requirements of the new materials, as is reported by Gencel et al. (2013) in a recent study examining the influence of zeolite and ferrochromium slag addition in new clay bricks fabrication.

Conversely, several studies have been aligned to the recycling process. Fang et al. (1999) focused on the spent refractory waste recycling through the quantification of these wastes and the analysis of the feasible recycling and reusing technologies in the United States. Additionally, Hanagiri et al. (2008) analysed the current state of the recycling technologies for refractories in Japan, as well as the recycling process stages. In this research, several tentative findings regarding the best conditions and processes are given for refractory recycling. However, these studies are not focused on an environmental analysis of these materials considering their whole life cycle (including final disposal).

Therefore, as described previously, although several studies have been developed during the last decades, most have considered technical and chemical aspects related to the performance and recycling viability of the reinforced refractories. Nevertheless, there is a lack of knowledge concerning the environmental analysis of these materials, especially from the Life Cycle Assessment (LCA) point of view, including the end-of-life of these materials.

Consequently, this research evaluates the environmental impact associated with two specific base refractories, alumina and magnesium oxide, which are reinforced using zirconia (alumina/ZrO_2 and MgO/ZrO_2). This study is performed considering the manufacturing process and the different end-of-life scenarios, disposal in landfilling and recycling materials using LCA methodology.

2. Methodology

This research proposes an environmental analysis based on the LCA methodology to study the performance of new reinforced refractories considering a recycling process alternatively to the landfilling. The LCA methodology has been fully proven, both technically and scientifically (López-Sabirón et al., 2014), and proposed by the standard ISO 14040 (Guinee et al., 2001). According to some researchers, such as Rebitzer et al. (2004) and Aranda-Usón et al. (2013), this methodology is synthesised in four interrelated phases: goal and scope definition, inventory analysis, impact evaluation and interpretation, where the old data will be replaced with new, leading to a more realistic evaluation.

The inputs and outputs of each management stage were defined, and the inventory emissions were calculated using SIMAPRO v7.3.2 (PRé Consultants, 2007) and data provided by the Ecoinvent v2.2 database (Ecoinvent Centre, 2007). In this study, the midpoint approach is used to evaluate the environmental impact. To this end, the RECIPE method (Goedkoop et al., 2009) was selected for quantifying the life cycle impact category indicators because it is one of the most recent and harmonised indicator approaches. This method calculates eighteen midpoint indicators: ozone depletion (OD), human toxicity (HT), ionising radiation (IR), photochemical oxidant formation (POF), particulate matter formation (PMF), climate change (CC), terrestrial ecotoxicity (TEC), agricultural land occupation, urban land occupation (ULO), natural land transformation (NLT), marine ecotoxicity (MEC), marine eutrophication (ME), fresh water eutrophication (FE), fresh water ecotoxicity (FEC), fossil fuel depletion (FD), mineral depletion (MD), and fresh water depletion (WD). These indicator scores express the relative severity on an environmental impact category.

2.1. Scope of the analysis and functional unit

Because the consumption of refractory materials is intensive in melting industrial furnaces and considering their short lifetime during the use phase, this study analyses their environmental impact, including the end-of-life alternatives for these materials to improve performance. Therefore, it is necessary to provide a reference to which the process inputs and outputs are correlated. In