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Evaluation of the steel slag incorporation as coarse aggregate for road construction: technical requirements and environmental impact assessment

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ABSTRACT

This work analyses the environmental impact of using electric arc furnace slags as secondary raw material in pavement and its comparison with the traditional materials used in road construction. Chemical and technical evaluations of the main characteristics of the black slags as coarse aggregate were carefully developed.

The environmental analysis was carried out by using the Life Cycle Assessment methodology. The Life Cycle Inventory data was processed to obtain emissions grouped in terms of impact categories based on the Centre of Environmental Science of Leiden University baseline method at midpoint level. The results obtained revealed that some of the most relevant environmental impacts, such as carbon footprint, abiotic depletion, ozone layer depletion and photochemical oxidation, depend highly on the road construction processes, although, in the two scenarios analysed, the bitumen production was demonstrated to be the most contributing stage.

These indicators also concluded that important environmental benefits could be obtained from the use of black slag as course aggregate in road construction. Consequently, the results shown here could be added to the list of technical criteria for their inclusion into a multi-objective optimisation methodology.

1. Introduction

Steel industry is one of the major responsible of anthropogenic CO_2 emissions. But, in order to mitigate the climate change, the reduction of these emissions is not easy due to the high dependence on electricity and coal (Eloneva et al., 2010).

Nowadays, most steel is produced either via two main industrial routes: the integrated process, which uses coal as reducing agent and iron as raw material or the Electric Arc Furnace (EAF) route, where electricity is used to melt steel into the end product. The second route, also named secondary production since it uses steel scrap, is a less energy intensive process and it is shown as a promising alternative to be close to a theoretical zero CO_2 emission (Morfeldt et al., 2014).

Apart from the energy consumption associated to the production processes, the increase of steel consumption has also yield to an important growth of the volume of residues. Steelmaking residues are defined as by-products obtained from the conversion process of iron to steel. In particular, steel slag represents a significant proportion of these by-products (Proctor et al., 2000); for instance, the production of 3 tonnes of stainless steel is estimated to generate about 1 tonne of stainless steel slag. Consequently, a large amount of steel slag is yearly produced in the world (around fifty million tonnes per year).

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Nomenclature

ADTHv	average daily traffic of heavy vehicles
CML	Centre of Environmental Science of Leiden University
EAF	electric arc furnace
HF	concrete road surface
JCPDS	Joint Committee on Powder Diffraction Standards
LCA	life cycle assessment
LCI	life cycle inventory
LF	ladle furnace
LOI	loss on ignition
MB	bituminous mixtures
ZA	artificial gravel

The huge amount of generated slags and their environmental impact have prompted scientists and engineers to work on novel solutions, based on industrial more friendly concepts that allow using these residues as raw material for pavements (Rađenović et al., 2013). Steel slags can be used in road construction in order to replace natural aggregates, which reduces the environmental impact by reducing the consumption of natural and non-renewable aggregates and the quantity of slag deposited on landfill sites, both in asphalt (Mladenovič et al., 2015) and cement based roads (Saez-de-Guinoa Vilaplana et al., 2015). However, technical and environmental studies are required to determine the technical feasibility and the potential environmental benefits.

Two types of slag are produced in the EAF steelmaking process: EAF slag, also called black slag, and Ladle Furnace (LF) slag, also known as secondary refining slag or white slag (Rađenović et al., 2013). In this work, the scenarios analysed are focused on the slags obtained in EAF, where about 40% of the global steel production takes place (Muhmood et al., 2009).

Although, different kind of recycled materials can be used as aggregates in road construction, it is crucial to know the properties that such aggregates have in order to ensure that they meet the same quality standards as natural aggregates (Mladenovič et al., 2015). In particular, EAF slag has been frequently used as pavement aggregate due to their excellent mechanical properties, which make themselves suitable for asphalt layers with any kind of traffic load. For example, EAF slags-derived aggregates improve the skid resistance of the pavement and they also reduce the risk of aquaplaning due to their higher permeability (Liapis and Likoydis, 2012).

To address the mentioned above strategy, this work has been focused on technical analysis and environmental evaluations. On the one hand, in order to analyse if black slags meet the technical requirements to be introduced as coarse aggregate in hot bituminous mixture for different course layers associated to the heavy traffic categories, the results of a comprehensive chemical analysis were compared with the typical certain oxide ranges found in the literature (Sofilić et al., 2011), which have been reported as consequence of the quality of steel produced.

On the other hand, in order to estimate the environmental performance of the steelmaking black slag as secondary raw material for the road construction, the Life Cycle Assessment (LCA) methodology was applied.

The LCA is a methodology widely accepted to be used for analysing environmental impacts of products and processes (Society of Environmental Toxicology and Chemistry (SETAC), 1993). Previous works, such as Rebitzer et al. (2004), have technically and scientifically demonstrated the viability of using LCA to characterise the environmental implications of a wide range of industrial activities. In addition, its use is also strongly encouraged by European Union policies and regulation, i.e., the European Action Plan on Sustainable Consumption and Production and Sustainable Industrial Policy (COM(2008) 397), the ETAP action Plan (COM(2004) 38 final), etc.

Previously, the impacts of the road construction have been assessed using LCA methods but most of these studies have only analysed the environmental impact considering the use of waste such as fly ash (Birgisdóttir, 2005) and crushed concrete associated with traditional reinforced concrete and asphalt pavements (Rajendran and Gambatese, 2007).

However, there is a lack of studies about steelmaking black slag as a coarse aggregate in hot bituminous mixture quantifying the environmental performance using the LCA methodology. Only Mladenovič et al. (2015) address the environmental analysis of a road aggregate based on EAF slags and its comparison with natural aggregates but, in contrast to the analysis shown in the research, they do not take into account the chemical and physical characterisation of the slags.

Furthermore, to the authors' knowledge, there is no scientific literature focused on a particular environmental evaluation using Spanish conditions, consequently, this study represents a relevant contribution. The main objective is, therefore, to characterise the Spanish steelmaking black slag to study its environmental performance taking into account the technical specifications for road and bridge works, focussing on heavy vehicles requirements, according to technical specifications (UNE-EN 933-2, 1996).

2. Methodology

2.1. Steel black slag characterisation for road construction

2.1.1. Chemical characterisation of the steel black slag

The studied steel slag was characterised using X-ray fluorescence spectrometry to determine the chemical composition, while X-ray diffraction technique (XRD) was used to identify crystalline phases in it. To this end, diffraction patterns were measured in the 2Θ range of 5–80 using CuKα radiation.

2.1.2. Technical specifications of steel slag as coarse aggregate in hot bituminous mixture

The hot bituminous mixture is defined as a type of asphalt in which hydrocarbon ligand and aggregates (including mineral powders) are combined. The aggregate acts as the structural skeleton of the pavement whereas the hydrocarbon ligand covers homogeneously all particles of aggregates, acting as the glue of the mixture.

The use of the steel slag as coarse aggregate in the hot bituminous mixture was evaluated in this study by comparing the results obtained from tests with the specific technical requirements of coarse aggregate for road and bridge works in Spain (PG-3).

According to the standard classification of the geometrical properties of aggregates (UNE-EN 933-2, 1996), a coarse aggregate is defined as the fraction of the total amount of aggregate retained on the sieve of 2 mm. The specific requirements of the aggregates depend on the category of the road and the Average Daily Traffic of Heavy Vehicles (ADTHv), classified according Table 1. In particular, in base course layers for categories of heavy traffic denoted as T00 and T0, the coarse aggregate cannot be obtained by crushing gravel from granular deposits of limestone quarries and nature. By the contrary, in the case of base course layers corresponding to the T1 and T2 heavy traffic, material from crushing natural gravel can be used providing the particle size of the used coarse aggregate before its crushing was 6 times greater than the maximum size of the final aggregate.