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Utilization of Ladle Furnace slag from a steelwork for laboratory scale production of Portland cement

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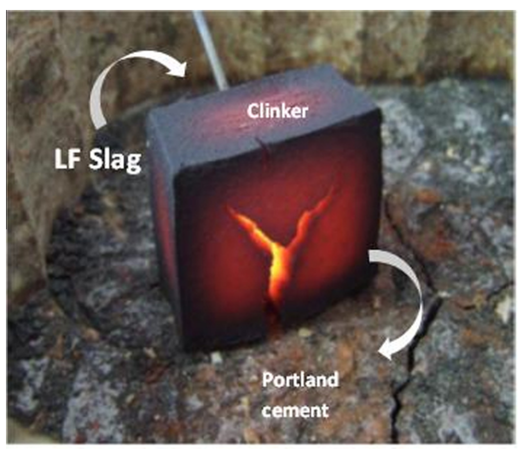
HIGHLIGHTS

- LF slag from the secondary metallurgy process is a potential option as raw material.
- Energy and CO_2 emissions can be reduced by using clinker based on LF slag.
- Mechanical properties of Portland cement improved by incorporating LF slag.
- Cement's mineralogical characteristics were not affected by LF slag.

GRAPHICAL ABSTRACT



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ABSTRACT

Ladle Furnace slag from the secondary metallurgy process can potentially be used as a raw material. To supplement the limited number of studies of Ladle Furnace slag that have been performed, this work investigates the incorporation of Ladle Furnace slag into the raw meal for Portland cement production. Clinker and cement were manufactured at the laboratory scale from various meal compositions, and high Alite cement was obtained by adjusting the lime saturation factor (LSF) as well as the alumina and silica ratios (AR and SR, respectively). The results of chemical and mineralogical analyses showed that using Ladle Furnace slag to produce Portland cement did not negatively affect the mineralogical characteristics. In addition, mechanical properties, such as compressive strength and volume expansion, were positively affected by incorporating 39.2 wt.% slag into the raw meal. However, a slightly higher initial setting time was required for samples containing slag; this result can be attributed to the amount of MgO in the cement. In general, our results suggest that Ladle Furnace slag can be used as a raw material in the manufacture of Portland cement to reduce the intensive consumption of natural raw materials, energy and CO_2 emissions by the cement industry.

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1. Introduction

The technical, economic, and environmental effects of using alternative fuels and raw materials in clinker manufacturing have received considerable attention in recent years [1–3]. In particular, the use of waste or by-products as raw material substitutes during its manufacturing has been studied heavily because these substitutes can lead to significant savings of natural resources [2,4].

Portland cement (often referred to as OPC, Ordinary Portland Cement) is the most common type of cement used around the world for a wide range of applications, including general civil engineering, construction, and smaller projects. The main compound in Portland cement is tricalcium silicate ($3CaO{\cdot}SiO_2$), also called Alite. This compound gives Portland cement the properties of a hydraulic material [1]. The manufacture of Portland cement is accompanied by high carbon dioxide emissions and high energy demand during the firing of the raw meal and the grinding of the final clinker [1].

Steel slag is a waste material considered as a by-product of the steel-making process [5]. An enormous amount of steel slag is generated in the word, and only in Europe every year nearly 20 million tons of steel slag is generated [6,7]. Therefore, this waste material has been studied as an additive component in construction material. Examples of these studies are the evaluation of steel slag as a coarse aggregate on the properties of asphalt for road construction [8] and recycling steel slag as a component to meet the compositional requirement for being successfully used into lightweight aggregates and brick-like product [9]. However, a significant amount of slag is sent to landfills every year, and using steel slag in cement may reduce the amount of slag that is wasted. In addition, using steel slag may reduce energy consumption, carbon dioxide emissions, and the consumption of natural raw materials [10]. The composition of steel slag is also an important reason why it is a promising raw material substitute for cement manufacturing. Although the composition of steel slag depends heavily on the raw materials and processes used in its manufacture [11,12], steel slag is typically composed of silicates ($3CaO{\cdot}SiO_2$ and $2CaO{\cdot}SiO_2$ phase), oxides (CaO–FeO–MnO–MgO solid solution), free CaO, and periclase (MgO) [13].

There are several process stages in steel production during which various types of slags, each one with different properties, are generated. These stages include the Blast Furnace (BF), Basic Oxygen Furnace (BOF), Electric Arc Furnace (EAF) and Stainless Steel (SS-EAF and SS-AOD) stages. As mentioned above, a high amount of steelmaking slags are produced in the world [14] and more than 40% of global steel production takes place in EAFs.

Two types of slag are produced in the electric arc furnace steelmaking process: EAF slag and Ladle Furnace (LF) slag [15]. This latter is known as basic slag, reducing slag or white slag [15,16]. LF slag is produced in the secondary metallurgy or refining process, which generates high-grade steels. In this process, liquid steel first undergoes an acid dephosphorylation process in the EAF (oxygen blowing). Then, the steel is discharged into a ladle furnace, where it is deoxidized, desulfured and alloyed under the protection of a basic slag.

The chemical compositions of both EAF slag and LF slag can vary between batches because scrap melting is carried out in batches. In addition, local conditions, varying manufacturing practices, and scrap metal variations can also affect the chemical composition of the slag that is produced [17,18].

Typically, calcium and magnesium oxides constitute more than 60% of the LF slag by weight [19]. Calcium oxide is the main component, as it is required to maintain the basicity of the process. The role of magnesium oxide is to protect the ladle furnace's refectory walls. Silicon, aluminium and ferric oxides make up less than 40% of the total weight. Other compounds, including manganese and titanium oxides, sulphurs from the steel desulphuration process and calcium fluoride, are present in minor amounts.

Although LF slag is produced at lower volumes compared to EAF slag, the utilization of LF slag is very significant in the steel industry. Current industries that utilize LF slag include agriculture to correct soil acidity, environmental engineering to fix ions in water depuration [5], aquiculture to develop fishing blocks [20] and steel factories [21].

However, steel slag has not been used extensively in cement production. In fact, according to statistic data from EUROSLAG in 2010 [22], only 6% of European steel slag was used for cement production, which indicates that global use of LF slag is far below 6%. Such low usage can be partially attributed to how the steel slag is classified, as the slag can be considered either a product or waste. Fluctuations in slag composition and availability may also contribute to the low usage [23]. Therefore, the use of steel slag in cement applications has been the topic of several studies, such as shown in the Chen et al.'s work [24]. They used combined physical pre-treatments; such as grinding, sieving, and magnetic separation for the recovery of iron rich materials and to use the remainder of the waste slag, from an integrated steel mill for the clinker production. Other works have investigated steel slag as a raw material in cement manufacturing refer to slags produced in blast furnace [25] or EAFs in the melting stage or primary steelmaking operations (EAF slag) [1,6,11,26–28]; studies of LF slag in cement manufacturing, especially Portland cement manufacturing, are scarce.

In 2002, Altun and Yılmaz [29] used LF slag with high MgO as an additive in Portland cement, reporting that 30% slag should be added to it to obtain adequate physical and mechanical properties. However, this percentage would only satisfy Turkish standards. Setién et al. [30] explored LF slag properties and capabilities via chemical and mineralogical characterizations. Setién et al. suggested that LF slag could develop certain hydraulic properties and could therefore be recycled for construction and civil engineering applications. This conclusion has been supported by other authors [31–34], who suggest using LF slag in the manufacture of mortars.

The works discussed above have focused on the cementitious properties of LF slag or the use of LF slag as an additive or partial replacement for sand and cement in mortar manufacturing. Thus, further knowledge of the technical properties of produced cement, using LF slag as a raw material is still required for the its use in the construction industry.

Unlike recently published works, this work addresses the possibility of manufacturing Portland cement from clinker produced by incorporating a significant quantity of LF slag into the raw material. A clinker was produced with a Lime Saturation Factor (LSF) of 98% to ensure a high Alite content in the cement and low CO_2 emissions. The LSF is kept below 100% to avoid emitting a high amount of CO_2 during the calcination process [35].

X-ray florescence spectrometry was used to determine the chemical composition of the cement, and X-ray diffraction was used to identify typical crystalline phases in it. In addition, several of its mechanical properties were measured, including compressive strength, setting time and dimensional stability, and these properties were compared to those of conventional Portland cement.

2. Materials and methods

Clinker meal was prepared from four raw materials: limestone, shale, LF Slag (henceforth LFS) and Mill Sludge (MS) being two latter from an ArcelorMittal steelworks in Spain. Table 1 shows the composition of raw materials in which can be observed that LFS