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Effect of stainless steel slag waste as a replacement for cement in mortars. Mechanical and statistical study

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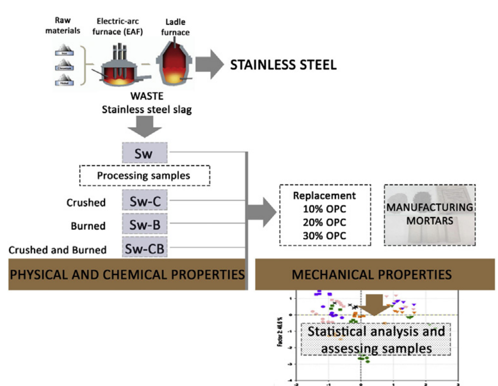
HIGHLIGHTS

- Different treatments of stainless steel slag waste (SW) were performed to improve it.
- Chemical properties of SW showed a positive cementitious capacity.
- SW processed showed an increase in mechanical strength results.
- SW processed through simple treatments can be used as a substitute for cement.

GRAPHICAL ABSTRACT



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ABSTRACT

This document studies replacing cement by stainless steel slag waste and improving the mechanical properties of the slag waste by using different types of treatments.

The application of stainless steel slag waste reduces the use of raw materials for manufacturing cement and provides a profit from the large amount of waste generated.

This study analyses the cementation and pozzolanic reaction characteristics of stainless steel slag waste to evaluate its strength activity index and its environmental impact. The cement was replaced with different substitution percentages of untreated stainless steel slag waste and slag waste that was processed through crushing, burning and both treatment to determine the optimum replacement ratio according to its mechanical properties. A study based on multivariate factor analysis was developed to compare these processed wastes according to their mechanical behaviour. The decision mechanism consists of a feature extraction method to evaluate the wastes used as a cement substitute.

1. Introduction

Stainless steel production is currently one of the most dynamic sectors of the manufacturing industry due to a large increase of the use of this product in the construction and industrial sectors; considerable amounts of waste are generated from these factories [1,2]. These high amount of waste generated is not only a quantity crisis but also an environmental problem [3–6]. For every three tons of stainless steel produced, approximately one ton of slag waste is generated [1].

Steel slag is a by-product of the steelmaking and steel refining processes. Different types of steel slag are generated from basic-oxygen-furnace (BOF) steelmaking, electric-arc-furnace (EAF)

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steelmaking and ladle-furnace steel refining processes [7]. In the first process stage (BOF or EAF), steel slag is a by-product of the aggregate [8,9]. However, in the second stage of manufacturing stainless steel (ladle-furnace steel refining), stainless steel slag is generated as dust. The dusts are the most important by-product of stainless steelmaking and refining operations. It is understood as dust, the particles with mean diameter of 3 μm. Approximately 1–2% (mass fraction) of raw materials charged in the smelting furnaces enters into the exhaust gases and is then converted into dust [10]. This slag dust requires more storage space and has less market value than the aggregate slag used in the construction sector [11].

Currently, both slags are generally treated as waste and dumped in landfills. Alternative uses for these stainless steel slags could be applied. There are several previous studies for the application of steel slags [12]. Stainless slag can be used as landfill liner materials or for cement adhesives and roadbed materials after undergoing a stabilization/solidification process or other methods [12,4]. In practice, compared with blast furnace slag, the application scope of steelmaking slag is limited to the production of aggregates for road pavement or concrete [13–15].

Previous papers have studied the cementitious properties of steel slag [16]. According to these studies, this type of waste could be used in the manufacture of cement. The cement industry is researching possible revisions in the manufacturing process and in the selection of raw materials [17]. Currently, 0.97 tons of CO_2 are produced for each ton of clinker [18]. The goal of the cement industry is to reduce CO_2 emissions by 50% in 2050 [17]. One of the primary paths toward reaching this goal is reducing the clinker content in cement. The use of stainless steel slag waste as a supplementary cementitious material can be of great interest in this context [16].

The amount of waste produced from the stainless steel industry must be considered as along with the toxic waste, such as nickel, lead, chromium or cadmium, generated by landfill storage of this waste [2,9]. These toxic elements can cause environmental damage. The presence of minor constituents in any substance or product, whether natural or artificial, plays an important role in their properties. It is necessary to detect the nature and concentration of these elements. Among the minor constituents of Portland cement that deserves special attention is chromium, which affects both cement properties (varying the short-term and long-term mechanical strength, changing the colour of white cements, controlling the corrosion of concrete reinforcement etc.) and its toxic-polluting consequences [19].

It must be considered the amount of waste produced from stainless steel industry, as well as waste generated by storage in dump, such as nickel, lead, chromium or cadmium [2,9]. These elements can present environmental damages. This study through the analysis of the leaching of heavy metals proves that the material shows high values of Cr but this metal is presented as Cr (III). The presence of chromium in cements (20–160 ppm) is due mainly to the raw materials used in cement manufacture [20] that contain chromium as an impurity. The use of stainless steel slag waste (Sw) in cement manufacturing involves analysing the presence of chromium VI because there this toxic element is limited according to the current Spanish legislation for the manufacture of cement. Chromium content was evaluated according to UNE-EN 196-10, and it was shown that it is not detrimental to the environment or human health. The values of Cr (VI) decreased when the waste is presented inside the cementitious matrix, and this material did not exceed the levels required by the standards for cement. Previous works corroborate this reduction of Cr VI [2]. These studies demonstrated through different treatments that the presence of heavy metals in stainless steel slag waste could be reduced. In addition, to evaluate the environmental impact of the presence of Cr VI in the cement matrix manufactured with Sw, this study aims to calculate the cementitious properties of Sw. Other studies previously demonstrated that these wastes exhibit cementitious properties under the influence of chemical activators [21]. According to its microstructural morphology, chemical composition and X-ray diffraction spectrum, Sw is typically composed mainly of calcium oxide, silica, magnesium and aluminium oxides. The potential value and the fineness of the waste suggest that these wastes can be used as a supplementary cementitious material [22,23]. According to the physical characteristics of other residues studied, it was observed that the fineness of the particles and the composition of the waste can provide cementitious properties in cement materials [24].

Recent studies have discussed the application of stainless steel slag in cement material but with only 10% cement replacement [25]. It is also possible to use Sw as part of the sand and cement in mortar manufacturing for the construction industry, replacing up to 30% of cement [26]. To increase the final concrete strength, researchers have suggested several ways of processing the raw material such as re-melting [23], use of activators [27] or crushing and screening [28,29]. It should be noted that the presence of free lime and magnesia could cause problems in restrained structural members due to delayed expansion phenomena [30].

Crushing and burning Sw can improve the reactivity and strength of the cementitious components [31,32]. Previous studies showed that some slag has better properties for use as a cement additive when subjected to simple processes, suggesting Sw processing to obtain a higher strength in manufactured cement. In this study, the possibility of using Sw as a partial replacement of cement was analysed; this material was processed through crushing, burning and both.

In the present study, the physical and chemical properties of unprocessed stainless steel slag waste, crushed slag waste and burned slag waste were studied for comparison. The environmental effects applying leaching test and mechanical behaviour of this type of waste were studied to assess the possibility of using stainless steel slag as hydraulic binders to replace cement. Different percentages of non-processed (Sw-N), crushed (Sw-C), burned (Sw-B) and crushed and burned (Sw-CB) Sw were applied in the manufacture of cement mortars to determine the optimal replacement rate to increase the economic value of this waste and to determine the influence of waste processing in the mechanical behaviour of mortars. To evaluate the use of stainless steel slag waste in cement mortars and to classify it according to its durability, mechanical behaviour and its environmental impact, a multivariate analysis was applied to the cement mortars studied.

2. Materials

The present study evaluated four stainless steel slag wastes processed including unprocessed (Sw-N), crushed (Sw-C), burned (Sw-B), and a combination of both crushed and burned (Sw-CB) Sw. In addition, to evaluate the influence of Sw as a partial replacement of cement, the properties of the cement manufactured with Sw were compared to cement without additions (Control-OPC) and with a common addition (Control-FA). Therefore, both materials were also studied.

2.1. Cement – ordinary Portland cement (OPC)

In this work, CEM I 52,5R was used; this cement does not contain mineral additions. Therefore, the behaviour of the mortar with the addition of stainless steel slag waste is not conditioned by the components present in the cement. The water used was potable water, and CEN Standard Sand (NS) was used; these materials