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Study and analysis by means of surface response to fracture behavior in lime-cement mortars fabricated with steelmaking slags

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HIGHLIGHTS

- The fracture properties were examined by Response Surface Methodology (RSM).
- The effects of slag content and age on fracture energy were analyzed using CCD.
- The process for determining the response surfaces is similar for traditional mortars.
- Mortars those are prepared with black slag reach high mechanical strengths under.

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ABSTRACT

The objective of this work is to study the fracture behavior of lime-cement masonry mortars prepared with various proportions of lime and cement. Different amounts of Electric Arc Furnace – EAF-(black) slag and Ladle Furnace –LF-(white) slag were used in substitution of conventional aggregate. By varying the Water/Binder ratio the characteristics of the mortars in the fresh and the hardened state have been studied, it is about the density, occluded air, water absorption and compressive strength at 28 days. The fracture properties were examined by Response Surface Methodology (RSM). The effects of slag content, binder content and age on fracture energy were analyzed using Central Composite Design and compared with experimental data from a three-point bending test. The results of the model closely coincide with the test results in their analysis and prediction of the mechanical strength of the mortars. In these results, it was noticed that the EAF (black) slags had an unfavorable effect on the lime-cement mortars with high cement contents, unlike those dosed with LF (white) slag and different compositions of lime and cement that significantly improved their fracture behavior in comparison with the other lime-cement mortars under study.

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1. Introduction

The results of the model closely coincide with the test results in their analysis and prediction of the mechanical strength of the mortars. In these results, it is worth noting that the EAF (black) slags had an unfavorable effect on the lime-cement mortars with high cement contents, unlike those dosed with LF (white) slag and different compositions of lime and cement that significantly improved their fracture behavior in comparison with the other lime-cement mortars under study [1]. Fractures and cracks in renderings assist the action of aggressive external agents on the materials, such as rainwater, low temperatures and the occurrence of humidity and dryness, which can inflict significant structural damage on facings and on their thermal and acoustic properties [2]. Fracture energy, a fundamental fracture parameter, refers to fracture resistance and the notch fracture toughness of a concrete. It is generally determined as a material property in concrete fracture mechanics and fracture analysis [3].

The first studies on structural cracks of concretes considered the cement paste and the aggregate as elastic and brittle lineal elements, while the microcracks were the consequence of their non-lineal stress-deformation behavior, when subjected to compressive strain [4,5]. Subsequently, Sponer [6] determined that the non-linear behavior of mortars and concretes under compressive stress/strain was likewise related to the non-lineal weakening of the cemented bond, so it would not depend so much on cracks due to loss of surface adherence produced by the deformation process.

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Mortar and concrete have for many years been considered brittle materials when subjected to traction stress. There have been many attempts to use the principles of Fracture Mechanics to advance models of study that could determine the fracture of the material with macroscopic cracks and its behavior. As a consequence of the heterogeneity of mortar and concrete composition, the application of Linear Elastic Fracture Models is not habitual in laboratory specimens. Nevertheless, over recent years, important advances have taken place in the study of the fracture behavior of quasi- brittle materials and the mechanisms of their operation, especially with reference to the fracture in Mode I (traction) of concrete, mortar, rocks and bricks. However, there is still a long road ahead in the study of fracture processes under combined load-bearing conditions of traction and shear stress (Mixed Mode I/II). The most advanced works have occupied themselves with the study of fiber-reinforced concrete [7]. Mortar fracture properties have been investigated in both experimental studies, e.g., fracture properties of mortar [8], crack propagation in cementitious mortar [9], microcracking in cement mortar [10] and crack deflection [11].

Among the most novel references are the modifications introduced in the recommendations contained in RILEM TC-187-SOC [12]. Likewise, the most recent investigations and publications in Spain by the Spanish Fracture Group are worth highlighting, which cover among others the analysis of concrete in Mixed Mode [13], and research on fly-ash [14] that studied mechanical behavior, in terms of temperature, between a commercial Portland cement and two new cementitious materials. In addition, in 2011, a study [15] investigated the relation between crack propagation and the type of failure in concrete beams reinforced without stirrups. Enfedaque [16] conducted a study of fracture energy in reinforced mortars with glass fibers, observing that this type of material has a fracture energy that is four times higher than conventional values.

Experiments with these mathematical tools may be done that place the material against the action of external quantitative and qualitative external factors, with the aim of understanding their response capability in different situations, similar to those that can occur in reality [17].

Efforts to recycle by-products generated in the steelmaking industry have opened the door to innovative research on useful construction materials, as substitutes for and with equivalent performances to those manufactured with conventional raw materials [18].

There are various references on the use of steelmaking slags for the manufacture of mortars and concretes [19]. EAF (black) slags and LF (white) slags, because of their properties, have been used as aggregate in substitution of lime and siliceous sands with good results. Likewise, EAF (black) slags have been used in partial substitution of cement dosages in masonry mortars [20–23]. Performance, in both cases, was equivalent to those of a conventional building mortar, with good facing adherence and durability against aggressive external agents [24]. The higher strength of mortars manufactured with cement and the nature of slags, which produce more rigid and less workable mortars, points to the possibility of using lime for distension, which produces more flexible mortars that react with greater ease to the differential stresses and strains of traction and compression [25] with a good durability [26].

In view of the above, the main objective of this paper is to study the way in which either partial or total substitution of cement aggregate by both EAF (black) slags and LF (white) slags in lime-cement mortars, fabricated with cement and lime, affect the linear properties of these mortars in construction. To do so, Response Surface Methodology (RSM) and Central Composite Design (CCD) software were used, with fracture energy output variables taken from three-point bending tests [27] (Mode I).

2. Experimental program

2.1. Raw materials

A Portland cement with a density of 3150 kg/m^3 and with a (Blaine) specific surface area of 3500 cm^2/g. Type CEM I 42.5 R was used, as per standard EN 197-1 [28]. Most of its particles (>85%) are below 90 μ. Its specifications are detailed in Table 1.

The lime employed in the mortars is an air calcic lime CL-90-S, in the form of Calcium Hydroxide, specified in standard EN 459-1 [29]. Its chemical composition with a real density of 2190 kg/m^3 and its (Blaine) specific surface area was between 8000 and 10,000 cm^2/g. With regard to fineness, most of its particles (>85%) were below 90 μ. Siliceous sand from a sedimentary bed referred to as "Rounded siliceous sand 0/2 mm" with a real density of 2600 kg/m^3.

EAF (black) slag and LF (white) slag totally stabilized and weathered in a supervised land dump was used as a substitute for siliceous sand. Their metallic particles removed with an electromagnetic separator. The following types of slag were used:

– Electric-arc furnace oxidizing (black) slag (EAF) taken from an electric-arc furnace. These slags form in the primary phase of steel production. The slag was classified by size, using only fragments smaller than 4 mm. The real density of the particles was 3645 kg/m^3. After washing, the chemical composition of black EAF was determined, as shown in Table 1, and was mainly found to contain iron, calcium, silica and aluminum oxides, and other minority components such as MgO and MnO.
– Ladle-furnace slag (LF) obtained from the steel-refining process in the EAF. White ladle furnace slag was also used, from the so-called "Secondary metallurgy" process, refining the molten steel obtained in the preliminary phase of steel production. Before their use, these slags were exposed to weathering, through periodic wetting and drying, for the purposes of stabilization. The real density of the white slag was 2860 kg/m^3 and its specific surface area (Blaine) was 3096 cm^2/g. Its chemical composition is shown in Table 1.

As may be seen in the SEM image of the Scanning Electron Microscopy image (Fig. 1), the black slag is formed of small fragments with multiple angular edges (Fig. 1a). When tangential forces are applied to the material, the particles are added and work between each other through multiple contact points between each one. On the contrary, the particles of white slag are very fine and have rounded forms, with less stable bonds than the black slags (Fig. 1b).

Fig. 2 shows the granulometric curve of design for all compositions. The aggregate formed of siliceous sand, white slag, black slag and mixtures of sand (50%)/white slag (50%) and sand (50%)/black slag (50%), were adjusted to the designed line.

The criterion followed for the design of the granulometric curve was as follows: a curve with grain sizes of different sieve sizes, seeking to achieve as compact an arid as possible, with the lowest volume of internal spaces to favor the strength of the mortars. In this way, the same Fineness Module was used for all of the aggregate (sand and slags) in use.

The justification for this working methodology is that the demand for water, a parameter that is conditioned by the grain size (Fineness Module), is equivalent in all of the mortars. Nevertheless, the behavior of the mixtures with white slag is very irregular, as the presence of lime in its ingredients means a high demand for water. In spite of this drawback, the same dosing criterion has been maintained (to achieve a plastic consistency) for all the mortars that have been designed.

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