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Lime-cement mortars designed with steelmaking slags as aggregates and validation study of their properties using mathematical models

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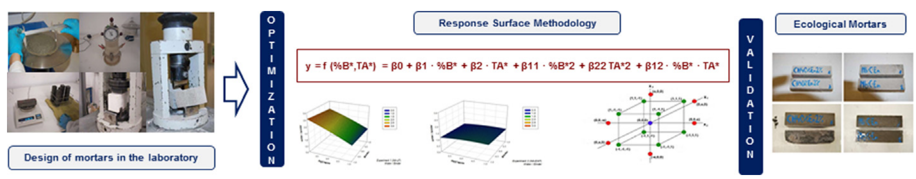
HIGHLIGHTS

- The lime/cement ecological mortars dosed with EAFS and NA showed similar porosity levels.
- Recycled materials with 100% EAFS have higher densities and a better mechanical behaviour.
- Entrained air increased with higher quantities of cement while bigger amount of lime produce compact mortars.
- Response Surface Methodology (RSM) is an acceptable method to predicting the properties of these lime ecological mortars.

GRAPHICAL ABSTRACT



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ABSTRACT

In this paper, ecological masonry mortars as a new building material are design, using a mix of calcium lime and Portland cement as binder, together with steelmaking waste aggregate (Electric Arc Furnace Slag and Ladle Furnace Slag), in substitution of natural aggregate and, subsequently a comparative study was made using mathematical models. To do so, different reference mortar types were prepared with various proportions of calcium lime CL-90-S and Portland Cement CEM I 42.5 R as binder, together with a natural siliceous aggregate. Subsequently, and separately, the natural siliceous aggregate (NA) was progressively substituted by LF and EAF slags. The mixtures designed were analyzed in the laboratory through characterization tests (European Standard), and a comparative study was made with the reference mortars. Surface Response Methodology (RSM) was applied to test whether the mathematical model could acceptably predict the behaviours of these types of mortars, analytical process that allow predicting the behaviour of a material without having to complete the entire series of necessary laboratory tests. Comparing the results obtained in the laboratory and those estimated through mathematical models RSM of each of the properties, it can be affirmed that the methods of mathematical prediction were useful for the study of these ecological mortars for use in construction.

1. Introduction

The construction sector is not oblivious to scientific progress, incorporating innovative technologies and new materials in its productive systems. The option of using materials from a circular economy, more environmentally friendly, represents a move towards the future integration of industrial processes, converting the waste generated in one industrial activity into a potential raw material for other production processes contributing to consolidate the concept to "*ecological construction*" or "*Green Building*" [1,2], such as steelmaking slag, polyurethane foam from the

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refrigeration and automotive coolant industries [3,4] and Construction and Demolition Waste [5–7]. By doing so, respect for the environment, by designing and producing new ecological materials, will constitute a social value which has to be considered by industrial firms committed to quality of life and its promotion in our society.

The use of steelmaking slags as aggregates in the manufacture of construction materials contributes to sustainable industrial development, avoiding their deposit in landfills without a defined use and the resulting environmental fall with the contamination of soils by filtration of leachates or by the impact on the landscape [8]. The design of ecological mortars manufactured with industrial waste avoids the overexploitation of natural stone resources, contributing to the sustainable development and to restoration of degraded natural spaces [9,10].

The use of steelmaking aggregates has been studied in earlier research in the design of asphaltic mixtures [11], gypsum mortars [12], cement mortars [13,14] and concretes [15,16]. The results obtained have been positive, because their properties are equivalent to the properties of materials manufactured with natural aggregates, with good mechanical performance and durability [17–19].

The EAFS have a good hydraulic behaviour, as they can develop mechanical resistance when reacting with the mixing water. Also pozzolanic behaviour, as they are able to combine with limestone compounds of cement in the presence of water, giving rise to new hydraulic compounds [20].

Research with mixtures of cement, aggregate and LFS also show an increase in long-term mechanical strength. Due to their composition, they have elements that, combined with each other, can develop hydraulic behaviours [21].

In this paper, the use of waste generated in the steelmaking industry, Electric Arc Furnace Slag (EAFS) and Ladle Furnace Slag (LFS) were studied as raw materials for the manufacture of ecological masonry mortars, using a mix of cement and calcium lime as binder.

Mixes were designed with different proportions of lime/cement (75%L/25%C, 50%L/50%C and 25%L/75%C). At the same time, the Natural Aggregates (NA) were progressively substituted by LFS and EAFS in other mixes. The mortars designed in that way were characterized in the laboratory, both in the fresh and in the hardened state, following the instructions in current standards.

Considering the quantitative character of the results obtained and the correlation between the properties of the different ecological mortars designed, a set of mathematical models were analysed to test whether their predictions can be applied in this investigation. In this way, the results obtained in the first phase of the laboratory study may be compared with the results of the statistical model.

There are various investigations in engineering that have successfully used mathematical methods based both on *Response Surface Methodology* (RSM) and on *Central Composite Design* (CCD), as these models allow the number of experiments to be reduced and, likewise, predict the possible non-linear effect of the relevant parameters and the interactions that take place between them [22–26].

In the construction sector, building engineers have applied these models to study the behaviour of welded metallic structures [27,28], the optimization of concrete dosages [29–31], the study of masonry mortars [32,33], additives for concrete [34], cement paste mix design [35], and the ageing processes of asphaltic pavements [36].

Having completed the corresponding laboratory tests and characterized the lime-cement mortars, a CCD prediction model was applied, to obtain the response surfaces for the study of each property under analysis.

Comparing the test results from laboratory tests and from RSM, it may be confirmed that the results are equivalent and that the mathematical model of analysis was acceptable for the prediction of the behaviour of these ecological mortar types. Thus, it is possible to reduce the number of tests and to economize on time and material resources in the design of ecological lime-cement mortars manufactured with steelmaking slags wastes.

2. Laboratory tests

2.1. Raw materials

The following materials were used for the preparation of the ecological lime-cement mortars. Their chemical compositions were shown in Table 1:

- Portland Cement CEM I 42,5 R, with a density of 3150 kg/m^3 and a Blaine Specific Surface Area of 3500 cm^2/g, as per the specifications of standard EN 197-1 [37]. The majority of its particles (>85%) were less than 90 μ in size.
- Calcium lime CL-90-S, in the form of calcium hydroxide, as per the specifications of standard EN 459-1 [38]. Its real density was 2190 kg/m^3, presenting a Blaine specific surface Area of between 8000 and 10,000 cm^2/g. As regards fineness, most of its particles (>85%) were less than 90 μ in size.
- Natural Aggregates (NA): Washed silica sand, 0/2 mm, with a real density of 2600 kg/m^3, presenting a SiO_2 content >97%. It originated from natural fluvial deposits mined in an open air quarry located at Montorio (Burgos).
- Electric Arc Furnace slag (EAFS), previously washed and screened by sizes, from which fragments smaller than 4 mm in size were used. The real density of the particles was 3645 kg/m^3.
- Ladle Furnace slag (LFS), exposed to weathering to facilitate its stabilization through the hydration of CaO and MgO. Its granulometry was very fine, with a powdery appearance and a whitish colour, with a real density of 2860 kg/m^3 and a Blaine specific surface Area of 3091 cm^2/g.

The aggregates used in mortars (Fig. 1) were NA, substituted by different percentages of LFS (Experiment 1) and EAFS (Experiment 2). All of the mortars in the tests had the same granulometry design (Table 2), with the objective of achieving as compact a curve as possible, with the lowest volume of cavities, to favour the compactness of the mortars and to increase their mechanical strength. All of their granulometric lines presented the same Fineness Modulus.

Table 1
Chemical composition of raw materials (%).

	Fe_2O_3	SiO_2	CaO	MgO	Al_2O_3	TiO_2	Na_2O	K_2O	MnO	P_2O_5	CO_2	Others
CEM I 42.5 R	4.0	21.3	60.4	1.5	6.1	–	0.4	1.3	–	–	–	3.0
CL-90-S	0.2	–	91.5		0.6	–	–	–	–	–	1.4	2.0
NA	0.06	98.4	0.03	–	0.87	0.02	–	0.57	0.02	–	–	–
EAFS	24.5	20.9	26.7	3.2	12.1	0.68	–	0.01	4.6	0.46	–	–
LFS	2.21	17.72	56.75	9.56	6.75	0.34	0.07	0.02	0.29	0.04	–	–