Mechanical properties of alkali activated ground SiMn slag mortars with different types of aggregates

R. Navarro [a], E.G. Alcocel [b], I. Sánchez [a], P. Garcés [a], E. Zornoza [a,*]

[a] Dept. of Civil Engineering, University of Alicante, Spain
[b] Dept. of Architectonic Constructions, University of Alicante, Spain

HIGHLIGHTS

- SiMn slag has been implemented as substrate for alkali activated mortars.
- Two types of alkali activators have been used: waterglass and sodium hydroxide.
- Silica sand, limestone and recycled concrete finer fraction have been used as sand.
- Mortars prepared with silica sand offered the best performance in mechanical tests.
- Recycled sand offered poor strength, due to the absorption of activating solution.

ARTICLE INFO

ABSTRACT

This research investigates the mechanical performance and dimensional stability of mortars whose binder is prepared by alkali activation of ground granulated SiMn slag. Two types of activators have been used: NaOH and waterglass solutions. Three different types of aggregates have been tested: silica sand, limestone sand, and recycled sand obtained from recycled concrete. Three activator concentrations have been adopted in the binder design: 3.0, 3.5 and 4.0% Na_2O for NaOH solution; and 4.0, 4.5 and 5.0% Na_2O for waterglass solutions with a constant SiO_2/Na_2O of 1.0. The best mechanical performance was obtained for an aggregate/slag ratio of 2/1 when silica sand was used as aggregate: 68 MPa were obtained when waterglass was used as activator, and %Na_2O of 4.5–5.0% at 90 days; 54 MPa were obtained for NaOH as activator and 4.0% Na_2O at 90 days. Limestone sand also offered a good mechanical performance although the maximum compressive strength achieved was about 25% lower than values obtained with silica sand, but recycled concrete aggregate mortars exhibited poor results, probably due to the high absorption of recycled aggregates. The higher shrinkage was registered in mortars activated with waterglass, although autogenous shrinkage was low for all types of activators and aggregates, except for recycled concrete aggregate.

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1. Introduction

One of the most challenging concerns of our society lays on the environmental problems derived from the actual human activities, specifically those ones associated to our industrial production. In this sense, cement industry has a significant impact in the carbon dioxide emissions which is the main gas responsible of the greenhouse effect and global warming. It is estimated that cement fabrication produces a 6–7% of total carbon dioxide emissions to the atmosphere [1]. Besides, although this industry efficiency is high, it is also responsible of 2–3% of the primary energy consumption in the world [2]. To reduce these levels, the development of new binders with lower environmental hue has gained the attention of many research groups. Additionally the reuse of wastes is a traditional strategy that has been adopted in the last decades and also pursuits the same goal: to obtain construction and building materials that exhibit good performance and durability but spending lower quantities of natural resources [2–4].

In present research, this strategy has been implemented by using an alkali activated binder instead of Portland cement, a waste material as substrate for the preparation of the binder, and also including finer fraction of recycled aggregate as sand in the fabrication of mortars. The waste material whose valorisation is proposed as raw material to design the alkali activated binder is a SiMn slag generated in the production of silico-manganese iron

alloys. The global production of silico-manganese alloy in year 2016 was 12.5 million tons [5]. Typically the slag generation is about 1.2–1.4 tons for every ton of SiMn alloy produced [6]. Therefore, the slag generated is in the tune of 15.0–17.5 million tons per year, so the amount is high enough to propose its reuse and valorisation. This SiMn slag presents a silico-calcic nature similar to blast furnace slag, but with a different chemical composition: lower content of CaO and a significantly high proportion of MnO.

Chemical, mineralogical and pozzolanic characteristics presented by the SiMn slag enable its use for obtaining alkali activated materials. Kumar et al. [6] studied the effect of the mechanical activation of the slag in the activation process, and it was evidenced the potential of the SiMn slag to be activated with a sodium hydroxide. Previously to the chemical process, the SiMn slag was treated mechanically by different procedures (ball milling, attrition milling and eccentric vibratory milling). As a result, different particle size distributions and different reactivity due to physicochemical changes in the mass and the surface of the particles were obtained. Their results offered the following performance in the terms of compressive strength of pastes after 28 days of curing time: 24 MPa for ball milling samples, 66 MPa for attrition milling specimens and 101 MPa for vibration milling conditions. Other authors [7] pointed out that the high-energy milling was responsible for achieving this performance and therefore, the environmental benefits were reduced. In another study, air-cooled SiMn slag in combination with fly ash has been used to develop an alkali activated binder, able to react at room temperature with NaOH as reactant of the alkaline solution [8]. It was concluded that the addition of SiMn slag increased the system reactivity due to the additional contribution to the CaO content of the mix, so mechanical properties were improved and lower porosity was obtained. However, once again, the main inconvenient was the long milling treatment of the SiMn slag which reduced the environmental benefits of the SiMn slag reuse. Navarro et al. [9] optimized the alkali activation process of the SiMn slag using a solution of waterglass (WG) and the system was evaluated in terms of the mechanical performance, the fluidity and the shrinkage behaviour of pastes. It was concluded that a high enough compressive strength was obtained (over 45 MPa), but the initial setting time was also very variable (between 38 and 263 min) and very high total shrinkage in a 50% relative humidity (RH) ambient was additionally registered (1.5–3.0%).

As it has been previously indicated, one of the most explored strategies to reduce the environmental impact of construction and building materials is to reuse industrial by-products. Additionally, the recycling of a wide variety of residues has also been successfully implemented. Previous researches have used the alkali activated systems with different types of recycled aggregates such as waste polyethylene terephthalate (PET) granules [10], cupper slags [11], bottom ash [12], construction and demolition residues [13–15], expanded glass residue [16], crumb rubber from wasted tyres [17], ceramic wastes [18], and some authors have specifically demonstrated a good performance of fine recycled concrete aggregate [19]. The combination of binders made with industrial wastes together with recycled aggregates may produce materials with adequate performance and low demand of natural resources [18,20].

The aim of this research is to evaluate the mechanical performance and dimensional stability of mortars whose binder is prepared by alkali activation of ground granulated SiMn slag using as activator sodium hydroxide and waterglass solutions, and incorporating different types of aggregates: silica sand, limestone sand, and recycled sand obtained from recycled concrete. This study have reported the behaviour of SiMn slag to be used in a wide variety of construction and building materials.

2. Experimental

2.1. Materials

The substrate for the binder preparation was a ground granulated SiMn slag from the Ferroatlántica plant sited at Boo-de-Guarnizo (Cantabria, Spain). Table 1 shows the results of the chemical analysis obtained by X-ray fluorescence in a Philips Magic Pro spectrometer, model PW2400, which is equipped with rhodium tube and beryllium window. The determination was made using a pill sample under vacuum conditions. According to previous works [9] the slag basicity index is 0.73 and hydraulicity index is 0.85, so this residue can be classified as an acid slag with moderate hydraulicity [21–23].

The determination of the vitreous phase content by X-ray diffraction has been performed in a PANalytical diffractometer, model EMPYREAN. The complete identification and quantification have been determined by Rietveld method [24] using quartz as standard sample, $MoK_{\alpha 1}$ radiation, a scan from 3 to 35 degrees (2θ), for 5 h in 0.0113 degrees steps, at 50 kV and 50 mA. The resulting vitreous content of the slag was 96.0 ± 1.5%.

The determination of reactive silica and insoluble residue of the SiMn slag was made according to standards UNE 80225-2012 and UNE 196-2-2014 [25,26]. The results provided a 3.35% of insoluble residue and a 33.80% of reactive silica.

According to the slag chemical composition, its reactive silica content and its vitreous phase proportion, the alkali activation procedure should be successfully implemented on this materials, which is also in accordance with previous studies [9,22,27].

The granulated SiMn slag was ground in dry conditions using a laboratory ball mill Nanneti model SPEEDY 1 for 25 min. The fineness of the resulting ground slag was determined by the Blaine's air permeability method [28], a value of 5512 cm^2/g was obtained, which lays in the optimal range established by previous authors who concluded that the optimal fineness for acid slags similar to the one investigated in present research is in the range of 4500–6000 cm^2/g [23]. Additionally, the particle size distribution of the slag has been measured by a laser diffraction equipment, using a Malvern Instruments, model Mastersizer 2000. The characteristic parameters resulting from this analysis were a $D_{V,50}$ = 9.2 μm and $D_{4,3}$ = 15.2 μm. The $D_{V,50}$ is the size in microns that splits the volume distribution with half above and half below this diameter. The $D_{4,3}$ is the volume mean diameter.

Alkaline solutions used to activate the SiMn slag were prepared with a commercial sodium silicate (Na_2SiO_3 (neutral solution QP, Panreac): SiO_2/Na_2O molar ratio = 3.28) and sodium hydroxide (technical grade, Panreac). Two different types of activators and three different activator concentrations have been tested in the

Table 1
Composition of the SiMn slag determined by X-ray fluorescence analysis.

Component	SiO_2	CaO	MnO	Al_2O_3	MgO	Fe_2O_3	K_2O	Na_2O	SO_3	N.D[*]	L.O.I[**]
Mass % as oxide	36.53	29.10	12.23	9.86	4.69	0.92	1.08	0.34	2.77	2.48	−1.25

[*] N.D.: Not determined.
[**] L.O.I.: Loss on ignition at 950 °C for 1 h.