



# Use of basic oxygen furnace slag fines in the production of cementitious mortars and the effects on mortar expansion

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## HIGHLIGHTS

- Basic oxygen furnace (BOF) slag fines used as aggregates are indicative of potentially deleterious expansion.
- Replacing cement with BOF slag fines reduces the compressive strength of mortars.
- Autoclave expansion of cementitious materials is highly related to mineralogical changes.
- BOF slag fines are suitable for the production of alkali-activated slag (AAS) mortars.
- AAS mortars produced with BOF slag fines have high volume stability.

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## ABSTRACT

The purpose of this study was to examine the properties of ordinary Portland cement (OPC) and alkali-activated slag (AAS) mortars produced with basic oxygen furnace (BOF) slag fines, and to reveal the effects of BOF slag fines on the expansion of the cementitious mortars. The use of BOF slag fines in OPC mortars significantly reduced the compressive strength and slightly increased the volume expansion of the mortars. Significant changes in mineralogical composition were observed in the OPC mortars produced with BOF slag fines after autoclaving. On the other hand, the AAS mortars produced with BOF slag fines had compressive strength comparable to normal OPC mortars, and their volume expansion was much lower than the AAS-Control and all the OPC mortars. The mineralogical compositions of the AAC mortars before and after autoclaving were almost identical. The results of this study indicate that the BOF slag fines are suitable to partially replace the binder for the production of AAS mortars, and the resulting AAS mortars have high volume stability.

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## 1. Introduction

Some steel slags, such as basic oxygen furnace (BOF) slag and electric arc furnace reducing slag, have properties of volume expansion and high alkalinity which are major issues when aiming to recycle the steel slag in construction [1]. Solving the volume expansion problem of steel slags is vital for slag recycling and reuse [2–7]. In Taiwan, more than 1.5 million tons of BOF slag are produced every year. Currently, the uses in backfilling materials and controlled low strength concrete are the major routes to dispose of the BOF slag, but there are many concerns about the construction quality and related environmental issues [8,9]. The major constituents of BOF slag are normally CaO and SiO<sub>2</sub>, and the ratio of CaO to SiO<sub>2</sub> is about 2:1. The common mineral

constituents of BOF slag include calcium silicates, calcium hydroxide, silicon dioxide, iron oxides, and some aluminates and carbonates [10,11]. Although the chemical composition of BOF slag is similar to that of cement clinker, BOF slag is quite different from cement with regard to mineralogy [10]. The main kind of silicates in BOF slag is Ca<sub>2</sub>SiO<sub>4</sub> (slow hydration rate) rather than Ca<sub>3</sub>SiO<sub>5</sub> (a major compound of cement, high hydration reactivity), so the cementitious reactions of BOF slag are not obvious under normal conditions of hydration.

During steel manufacturing, excessive lime (CaO) and dolomite (CaMg(CO<sub>3</sub>)<sub>2</sub>) are usually injected into BOF to maintain the slag basicity in order to prevent the corrosion of the refractory materials [12]. Consequently, some free CaO and MgO remain in the BOF slag after refining. Xie et al. [13] indicated that the hydration rate of BOF slag was initially very slow, because some BOF slag particles had a dense surface and the slag surface was coated with a layer of barely permeable aluminosilicate. The coating layer thus

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also protected the free CaO and MgO from water. However, when the hydration process continued, some alkaline substances gradually increased and thus accelerated the hydration reactions of BOF slag. Subsequently, water went into the interior of BOF slag and reacted with free CaO and MgO, thus resulting in the delayed expansion. In addition, the varying particle sizes of BOF slag and the nonhomogeneous distribution of free CaO and MgO in BOF slag can cause uneven expansion that is difficult to predict or control. The volume expansion of BOF slag consequently limits its application in construction and building materials. Wang et al. [14] reported that the cement mortar specimens cracked and some of them broke in pieces when using BOF slag as the aggregates. Montenegro et al. [15] examined the use of a steel slag with the potential for expansion in the construction of embankments, and it was indicated that some mixtures of soil and the steel slag showed expansion behavior.

In Taiwan, BOF slag is crushed, sieved, and separated magnetically to recover the iron-rich particles before reuse in civil engineering materials. The remaining parts are then divided into several particle size ranges, most of which are reused as aggregates in asphalt concrete. However, there are more than 400,000 tons of BOF slag fines (particle size < 4.75 mm) generated annually from the slag treatment processes, and they are too small to use in asphalt concrete. We have to consider the three key characteristics to effectively recycle the BOF slag fines; i.e. volume expansion, slow hydration rate, and small particle size. Accordingly, the purpose of this study was to examine the properties of cementitious mortars produced with the BOF fines, and to reveal the effects of the BOF slag fines on the expansion of different kinds of mortars.

## 2. Materials and methods

### 2.1. Materials

The BOF slag fines used in this study were sampled from a slag treatment plant in Kaohsiung, Taiwan. In this plant the original BOF slag generated by an integrated steel mill was crushed, sieved, and separated magnetically to recover the iron-rich constituents and produce aggregates for the use in asphalt concrete. However, the slag particles with a size of less than 4.75 mm are too small to be aggregates, so another recycling method should be found

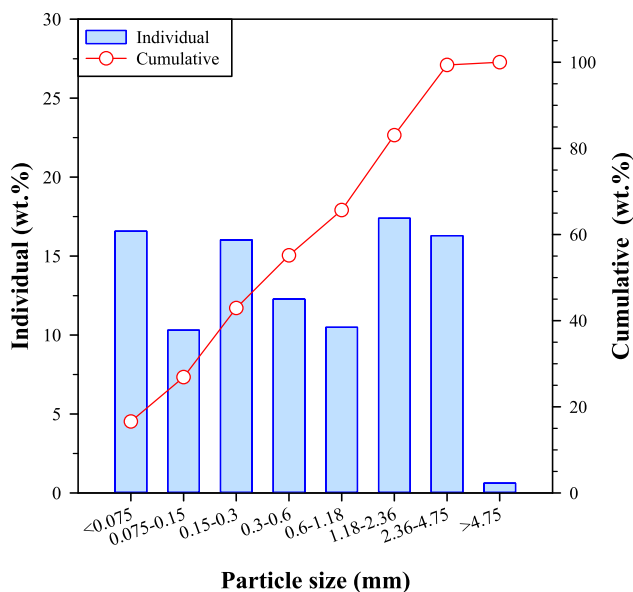


Fig. 1. Particle size distribution of the BOF slag fines.

Table 1

Chemical compositions of OPC, GGBFS, and BOF slag fines.

wt%	OPC	GGBFS	BOF slag fines
CaO	64.6	41.1	38.5
SiO <sub>2</sub>	22.1	32.7	18.1
Al <sub>2</sub> O <sub>3</sub>	5.4	14.5	2.4
Fe <sub>2</sub> O <sub>3</sub>	3.1	0.4	28.7
MgO	1.4	4.7	7.2
SO <sub>3</sub>	NA <sup>1</sup>	0.4	NA <sup>1</sup>
LOI	1.1	0.6	4.4

<sup>1</sup> NA: not available.

out. Fig. 1 shows the particle size distribution of the BOF slag fines sampled for this research. The proportions of different particle size ranges were between 10.3 and 17.4 wt%, except for the particles >4.75 mm. The particles <0.15 mm, which accounted for a total of ~27 wt% of the BOF slag fines, were used as an alternative material for cementitious mortars. On the other hand, all the BOF slag particles were ground to pass through a 0.15 mm mesh and also used to produce cementitious mortars.

Two kinds of cementitious mortars were produced in this study by using ordinary Portland cement (OPC) and ground granulated blast-furnace slag (GGBFS) as binders. The OPC and GGBFS were replaced with 20 wt% of the BOF slag fines for the mortar production. Table 1 shows the chemical compositions of the OPC, GGBFS, and BOF slag fines. CaO and SiO<sub>2</sub> were the main constituents of these three materials, but the amounts of Fe<sub>2</sub>O<sub>3</sub> and MgO were much higher in the BOF slag fines, which may affect the properties of the mortars. When using GGBFS as a binder, an aqueous solution that contains NaOH and Na<sub>2</sub>SiO<sub>3</sub> was added as an alkaline activator. The alkali equivalent (Na<sub>2</sub>O percentage by mass) was set at 4%, and the Ms. modulus (SiO<sub>2</sub>/Na<sub>2</sub>O molar ratio) was controlled at 1.00. The resulting mortars are usually called alkali-activated slag (AAS) mortars.

### 2.2. Material testing and analyses

The standard test method ASTM C1260 [16] was employed to determine the volume stability of the BOF slag fines. The mortar bars (25 × 25 × 285 mm) were prepared by mixing cement with the BOF slag fines at a weight ratio of 1:2.35 and using a water-cement ratio of 0.47 by mass. After curing in a moist cabinet for 24 h, the mortar bars were removed from the molds and then immersed in 1 N NaOH solution at 80 ± 2 °C. The percentage change in length of the mortar bars was calculated each day during the testing period. The OPC and AAS mortars were produced according the standard test method ASTM C109/C109M [17], and 50-mm cubic specimens were prepared for the compressive strength testing. Experiments were conducted following the standard test method ASTM C151/C151M [18] to determine the expansion of hardened OPC and AAS pastes exposed to the autoclave conditions. After curing in the moist closet for 24 h, the hardened paste specimens were removed from the molds and tested in an autoclave at 2 ± 0.07 MPa for 3 h, and afterwards their changes in length were recorded. The BOF slag fines and the fragments of hardened pastes were crushed and ground to a fine powder with a particle size less than 75 μm (No. 200 mesh, USA standard testing sieve) for the X-ray diffraction (XRD) analysis. The powder samples were analyzed using an XRD spectrometer (Bruker, D8 Advance) with Cu Kα radiation to acquire their mineralogical composition. The XRD step-scan mode was carried out at 0.03°2θ per step in 5–55°2θ with a data collection rate of 2 s/step. The pore size distribution of OPC and AAC mortars was examined using a mercury intrusion porosimeter (MIP, Thermo Scientific, Pascal 240).

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