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An assessment on volume stabilization of mortar with stainless steel slag sand

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HIGHLIGHTS

- A mixture mortar was developed using pre-treated stainless steel oxidizing slag as aggregate.
- Free lime content existing on treated slag was determined for each month.
- Expansion of the mortar were measured using autoclave and heating catalysis methods.
- Effects of replacing level and pre-treatment periods of slag on mortar were investigated.
- Relationships between compressive strength and UPV on the specimens were established.

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ABSTRACT

This study aims at employing stainless steel oxidizing slag (SSOS) as fine aggregate, replacing river sand in mortar mixtures with various ratios (e.g. 0%, 25%, 50%, 75%, and 100%). The received slag was left outdoor from 1- to 8 months as a treatment before be used as aggregate. The content of slag expansion source (free lime) was first determined after the end each month of stabilization. The X-ray diffraction (XRD) technique was offered to identify the mineralogical of the treated slag. Next, fresh and hardened properties of the stabilized-slag mortar including flow table, expansion, compressive strength, ultrasonic pulse velocity were examined in laboratory, accordingly. The expansion in term of length change of the slag mortar bars (25 × 25 × 285 mm) was investigated after the autoclave and heating catalytic (100 °C) curing conditions. The results indicated that free lime content is gradually decreased over times when SSOS exposed to air environment and effectively restricted the expansion capacity of the slag mortar. In addition, a higher SSOS replacement ratio a larger expansion is measured on the mortar bars. Meanwhile, a lesser period of slag treatment could make the specimens fracture at a lower level of slag substitution. The expansion of mortar bar under the autoclave is similar to that of about 72–96 h heating catalysis. Moreover, compressive strength of mortar is improved when containing as much as slag in mixtures, although this induces less workability of fresh mortar.

1. Introduction

Stainless steel production have been rapidly increased for last decades, globally amounted to 41.5 million tons in 2015 [1]. As a result, a great amount of slag has been discharged in manufacturing stainless steel, causing many concerns regarded environmental impacts. Approximately, each three tons of stainless steel products provides one ton of stainless steel slag, in which two kinds of slag are involved when producing stainless steel from iron scraps: stainless steel oxidizing slag (SSOS) with about two thirds and stainless steel reducing slag (SSRS) with about one-third [2]. The former slag was generated from an electric arc furnace (also known as EAF slag), the latter was discharged from a converter (Argon Oxygen Decarburization – called as AOD slag). Chemically, similar to other steel slags, stainless steel slag contains several metal oxides such as silica, alumina, lime, and magnesia. High amount of non-ferrous metal and much less iron oxide than that of ordinary steel slag in the chemical constituents would be characterized for stainless steel slags [2]. Moreover, SSOS is known as a crystalline rock, which is stable in morphology.

Unlike carbon steel slag, which was popularly studied with an in-depth understanding, stainless steel slag has only attracted to

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scholars recently [3]. Very few applications on stainless steel slag are found in literature due to containing several toxic in mineral compositions (e.g. chrome, nickel, lead, cadmium...). These ingredients are harmful to human health and environment as well. Therefore, leachable chromium of these slags is mandatory before landfills or reuse, especially in construction [4]. To date, review of literature shows that stainless steelmaking slag can be used in civil works. But very few reports conducted on the use of in concrete production as aggregate, roadbed, asphalt or cementitious material [5–8]. Sheen et al. [9–11] have conducted a series of researches on utilization of stainless steel slag as aggregate or binding material in concrete production and positive results were reported. Adegoloye et al. [3,12] conducted an experiment on concrete with aggregate from stainless steel slags (EAF slag and stabilized AOD slag). These studies exhibit that stainless steel slag aggregate concrete performs slight improvement in mechanical properties and noticeably decrease in durability. And, increase in linear expansion in comparing to conventional concrete was another consideration. Volume instability (expansion) and carbonation due to in presence of free (un-hydrated) lime (f-CaO) and periclase (f-MgO) in combination with a disintegration of the slag pieces would be a major contribution to durability reduction and strength loss as times goes by [11,12]. When contact with water from any resources, free lime and periclase transform into portlandite ($Ca(OH)_2$) and brucite ($Mg(OH)_2$), respectively under room temperature, resulted with volume increase significantly [12]. The hydrated process of free lime happens slowly to compare with burnt lime, taken within 30 min because the structure of free lime is believed denser, and sometimes may be locked up within the slag particles and decrease ability of the moisture absorption. On the other hand, the hydrated process of periclase is much slower than free lime, even at favorable condition, as its nature. As a result, concrete or pavement made with such steel slag aggregate is progressively deteriorated for a long time.

In volume instability viewpoint, applicable steel slag must have the free lime content lower than 2–3% or even up to 4% in asphaltic layer. Otherwise, slag must be further treated before use as construction materials [13]. To limit effect of volume instability, the steel slag must be stabilized, controlled or treated with appropriate methods. Leaving of steel slag in outdoor environment for several months as a treatment (depending on particle size) is beneficial to apply but need more land for disposal [14]. In addition, temperature catalytic, hot-water (40–70 °C) or steam aging, Sumitomo Kawasaki aging, autoclave techniques also sufficiently enhance the stabilized process which could shorten the treatment time [15–17]. Besides, it is not always easy to accurately estimate the volumetric expansion of a specific kind of slag due to its diversity in chemical reaction between oxides existing in slags and environmental conditions. Recently, Wang et al. [18] has provided a theoretical equation in prediction of volume expansion based on free lime content of steel slag, inducing by chemical and physical factors.

The main aim of this work is assessed to investigate effects of stabilization periods of stainless steel slag on engineering properties of slag-based mortar. Received stainless steel oxidizing slag (SSOS) was left outdoor environment as a treatment for different durations, from 1- to 8 months before used as a part of fine material for developing a SSOS-based mortar. Firstly, free lime content of the studied slag was estimated after each month using a combination of ethylene glycol method and gravimetric analysis. X-ray diffraction technique was offered to identify transformation in elemental components of the weathering slag. Secondly, fresh and hardened properties of the stainless steel slag mortar (e.g. flow, compressive strength, ultrasonic pulse velocity, and expansion) were examined. Thereby, influences treatment time of the slag and its content on proposed mortar behavior were discussed. The expansion of the slag-based mortar bars was investigated under autoclave and temperature catalytic curing.

2. Experimental program

2.1. Materials used

Type I Ordinary Portland cement (OPC) with the grade of 42.5, stainless steel slag, and natural sand were used in the experiment. The cement fully complies with ASTM C150 [19]. The stainless steel oxidizing slag (SSOS) used in this work is carried out in an electric arc furnace (EAF), collected from the China Lihua stainless steel plant (Taiwan) following the technique of sampling for aggregate (ASTM D72). It has apparent specific gravity of 2.88 and water absorption of 1.21%. The received slag was exposed to outdoor for periods, varying from 1- to 8 months (from January to August 2016) for stabilization. After above-mentioned durations of weathering, the slag was dried in an oven for 24 h before crushing in a jaw crusher and magnetically screened thereafter. Only particles passed the No. 4 (4.75 mm) sieve and matched the required size-grading for fine aggregate concrete as per ASTM C33 [20] (see Fig. 1) were collected for the experiment. The chemical compositions of slag were examined by X-ray fluorescence (XRF), and shown in Table 1. It is revealed that SiO_2 and CaO are main components (72.2%) and low ferric oxide (0.81%); and the basicity index (CaO/SiO_2) of 1.23. The free lime content was repeatedly tested after each month of weathering, varied from 0.61 to 1.2% (Section 3.1). Moreover, natural sand used in mixture conforms to ASTM C33. It has the specific gravity of 2.6 and the water absorption of 1.25% (Table 2).

2.2. Mix proportions

In the present work, weathering SSOS was used to replace natural fine aggregate (e.g., 0%, 25%, 50%, 75%, and 100%) in developing mix proportion of slag-based mortar. According to ASTM C109 [21], the cement, sand and water ratio is 1:2.75:0.485, proportioned by mass. However, testing results showed that the slag mortar mixtures with this water-cement ratio perform a low flowability, being less than 100 ± 5 with 25 drops of the flow table test, as per ASTM C1437 [22]. Consequently, too much porosity on the specimen's surface was observed (see Fig. 2(a)). When immersing in various aging methods, these specimens exhibit a potential for fracture. So, it is necessary to adjust the water-cement ratio for slag-based mixtures, in order to make testing results do not affect by other variables. After several trial mixes, to reach a flow of 110 ± 5 of the standard mix, the water-cement ratio is fixed at 0.5. As shown in Fig. 2(b), there is almost no porosity on the surface ($w/c = 0.5$). Eight types of stabilized stainless slag (corresponding to exposed time from 01 to 08 months) replaced natural sand with five levels (0%, 25%, 50%, 75%, and 100%) as reported on Table 3. Consequently, 40 mixtures were provided for the work.

2.3. Sample preparation and testing procedures

2.3.1. f-CaO testing and XRD analysis on weathering slag

The stabilized slag at different periods in outdoor environment was first ground fine enough completely passed the 0.075 mm –sieve (No. 200) before determining the f-CaO content. Two samples of each treated slag were prepared for this test and the average values were reported. A combination of the *hot ethylene glycol method* and *thermal gravity metric analysis* was adopted to determine the free CaO. The former extracted the CaO and $Ca(OH)_2$ simultaneously generated by CaO reacting with H_2O at the same time; and the latter was employed to determine separately the $Ca(OH)_2$ content. These approaches in determination of free lime show its advantage of simplicity and rapidity as well as enough accuracy [17,23].

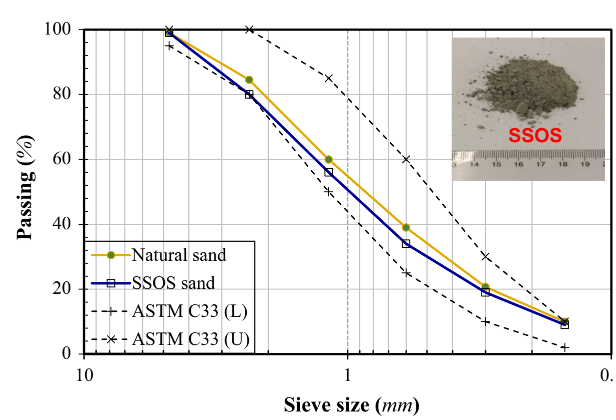

Fig. 1. Grading curves for natural and SSOS sands used in this work.