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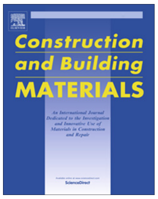

Innovative usages of stainless steel slags in developing self-compacting concrete

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HIGHLIGHTS

- Stainless steel slags (SSOS and SSRS) were employed to develop SCC.
- Effects of SSOS and SSRS flowability and viscosity of SCC were observed.
- Mechanical and durability properties of the SCC were investigated.
- Strength formula for the stainless steel slags-based SCC was successfully provided.
- Relationships between compressive strength, UPV, RN, and surface resistivity were established.

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ABSTRACT

This paper deals with development of self-compacting concrete (SCC) containing stainless steel oxidizing slag (SSOS) and stainless steel reducing slag (SSRS) – byproducts of the stainless steel makings. The oxidizing slag was employed as fine and coarse aggregates in substituting to conventional materials (sand and gravel) with various percentages (i.e. 0%, 50%, and 100%). Meanwhile, the reducing slag was used as a part of ordinary Portland cement (e.g. 0%, 10%, 20%, and 30%). As a result, a total of 12 mixtures with a fixed water–binder ratio ($w/b = 0.4$) were prepared for experiment; and its properties obtained in fresh state including density, flowability, viscosity, passing ability, and setting time and in hardened state such as compressive strength, ultrasonic pulse velocity, rebound hammer, length change, and surface resistivity were examined accordingly. The results indicate that incorporating SSOS aggregates or SSRS cement in SCC mixtures apparently reduces the workability besides effectively enhancing its viscosity. Mixture with SSOS increased shows a higher fresh density than the control, while containing high level of SSRS results in lowering that density. More interestingly, the stainless steel slags-based SCC can accelerate the hardening process, which shortening a setting time of 25% and 36%, corresponding for mixture with 50% and 100% SSOS aggregates. For hardened properties, compressive strength of SCC prepared with SSOS replacement in full exhibits slightly better or at least similar to that of the control, considerable improvement in surface resistivity, and potentially volumetric instability. Strength development models, modifying from ACI-209, have also been provided for the slags-based SCC. In addition, relationships between UPV, rebound number, and electrical resistivity versus compressive strength within 91 days have been further established.

1. Introduction

The worldwide production of stainless steel slag is rapidly increased, accounted to nearly 38.1 metric tons in 2013 [1]. During stainless steelmaking process, a vast majority of solid wastes, especially slags is generated from the plants. Approximately, each three metric tons of stainless steel products release one tone of stainless steel slag. When producing stainless steel from iron scraps, two types of slag are involved: stainless steel oxidizing slag (SSOS) and stainless steel reducing slag (SSRS). The former stainless slag with about two thirds comes from the electric-arc furnaces (EAF), called as EAF slag whereas the latter with about one thirds is discharged during the basic refining process of stainless steel manufacturing in ladle furnaces (LF) (often called as LF slag). In 2010, Taiwanese manufactures produced over 1.5 million tons of crude

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stainless steel; and consequently, about 500 thousand tons of stainless slags and other wastes were created for disposal [1]. Information, because of containing several toxic ingredients such chrome, nickel, lead, cadmium, stainless slags may be harmful materials for not only environment, but also human health. Therefore, it is necessary to treat them prior to any utilizations or landfills. Recycling the wastes would be promising line of research with regard to eco-environmental benefits. Both SSOS and SSRS mainly contain several metal oxides such as silica, alumina, lime, and magnesia. Much amount of non-ferrous metal and less iron oxide in the chemical constituents would be found for stainless steel slags. A number of previous studies believed steel/stainless steel slag powder owns the hydraulic properties due to existence of C_2S, C_3S, and C_4AF [2]. These slags can be considered as weak cement owing to much less the C_3S content than ordinary Portland cement (OPC). In addition, the basicity index, expressing the cementitious and/or pozzolanic characteristic, of SSRS is basically higher than that of SSOS and significantly lower than that of either granulated blast furnace slag (GGBFS) or OPC.

Reviews of literatures show that steelmaking slags have been essentially used in construction fields, limited in production of aggregates for concrete, road beds and cement substitution as well. Potential volumetric changes (expansion) during hydration and carbonation would be the largest obstacle for reuse of these slags, inherently remaining much free lime and magnesia [2–4]. Manso et al. [4–6] revealed EAF slag after an appropriate weathering treatment process and crushing into a suitable particle-size distribution can be a high-quality coarse aggregate in combination with natural fine aggregate for developing heavy concrete. This slag aggregate concrete exhibits better mechanical and durability properties comparing to conventional concrete, despite difficulties in mix preparations. Positive results were also obtained by Arribas et al. [7] and San-José et al. [8] when studied on concrete mixtures in which the oxidizing slag substituted for natural coarse aggregate. However, the chloride penetration on steelmaking concrete may be severe when contacts with marine environment or sea water.

In regard to cement application, there have been few studies focusing on developing a cement substitute from steelmaking/stainless slag. This is logically explained by the large variation in chemical composition of the used slags, which must be considered as a case study. More recently, a number of published research works has showed that ladle reducing slag as grinding into finely particle-sizes exhibits the potentially hydraulic attribute. A study of Kourounis et al. [9] manifested that the higher slag content in blended cements (OPC + steel slag), the lower strength was observed at all ages. Also, the setting time of the blended cements was extended with an additional slag, resulted from the crystal size structure of C_2S. Hydrated rate of steel slags was improved with appropriate treatments such as remelting and water quenching the received slags, reported by Muhmood et al. [10]. Such treating made an increase not only in the basicity index but also in the water absorption capacity which are factors for enhancing the cementitious behavior. In addition, substitution of steel slag with GGBFS could create a mortar characterized by slow hydration rate and superior in the 28-day strength in comparison with the pure ladle reducing slag mortar [11]. Similarly, almost no significant changes in compressive strength beyond 28 days were found when replacing 20% GBFS by steel slag [10]. An investigation of Sheen et al. [12] revealed that compressive strength of blended mortar made with a substitution of 30% OPC by weight with SSRS was better than that specified by ASTM C150. Moreover, their observation showed that the SSRS with fineness of 4400 cm^2/g was equivalent to the GBFS Grade 80 described in ASTM C989. Recent evidence suggests that mechanical activation via a prolonged milling in ethanol suspension could substantially accelerate the reactivity of ladle reducing stainless steel slag [13].

Self-compacting concrete (SCC) is a special concrete with emphasis on workability, strength, and durability [14,15] having widespread applications in building industry due to several advantages such as high fluidity, good segregation resistance, and excellent capability of self-passing through reinforcement gaps/corners of reinforced formworks without need of mechanical compaction. The distinguishing features of SCC mixture is to require a high cement content, low water–powder ratio, and considerably low coarse aggregate volume. The present work is to investigate innovative application of stainless steel slags in developing SCC mixtures, expected to save traditional materials for sustainable development. Particularly, weathering and crushing SSOS was employed as both recycled fine and coarse aggregates for SCC, correspondingly substituting partially and fully to natural ones. In addition, powdered SSRS was used as a part of cementitious in conjunction with OPC.

2. Laboratory experiment

2.1. Materials used

In the present study, two stainless steel slags i.e. SSOS and SSRS with an appropriate treatment supplied by Lihwa Corp. (in Taiwan) were employed for experiment (Fig. 2). First, the SSOS from the process of scrap melting and oxidizing of stainless steel manufacturing was slowly cooled in outdoor environment for more than six months before an appropriate crushing to make coarse aggregate (CA) with maximum size of 12.5 mm. Such inexpensive treatment of SSOS aiming at volumetric stabilization was similar to other slags when considered as materials for concrete production, widely proposed in several studies [5,16]. The fine fraction with a large proportion generating from primary crushing of raw stainless steel slag is used as fine aggregate (FA) after a magnetic separation of metallic elements. The SSOS aggregates using in this research work have a black color, rock-like appearance, and mainly consist of common oxides (more than 80%), such as CaO, SiO_2, and FeO or MgO. Fig. 1 shows the grading curves for SSOS fine and coarse aggregates, fully matching the ASTM C33. Secondly, the white-dusty SSRS was created by a fast cooled process at high temperature with jets of pressurized water and undergone over several weeks of weathering. After passing through the No. 200 sieve (75 μm), the disintegration reducing slag was further milled by the Los Angeles Abrasion Machine at 5000 rpm with a 1 mm zirconium ball to produce a powdery material of high fineness (5500 cm^2/g), which could be regarded as a cement substitution. The properties of stainless slag described above are presented in Table 1.

Fig. 1 plots the grading curves for natural fine and coarse aggregates, whose fineness moduli are 2.87 and 6.22, respectively. The water absorption is 2.2 and 1.3 for coarse and fine aggregates, respectively. In addition, the ordinary type I Portland cement with the fineness of 3851 cm^2/g and the specific gravity of 3.15 is used in the research work.

2.2. Mix-proportions

The densified mixture design algorithm (DMDA) [17] was used to develop the SCC mixtures for the investigation. The key idea of this method is that better performance of SCC will be achieved with mixture having higher physical density. Accordingly, to obtain the highest density, fly ash should be included in the mixture

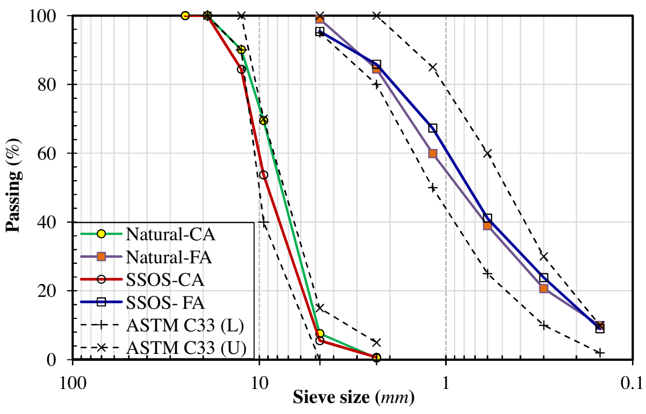

Fig. 1. Particle-size distribution of coarse and fine aggregates.