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Greener self-compacting concrete using stainless steel reducing slag

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HIGHLIGHTS

- A self-compacting concrete made with SSRS as filler and cement substitution.
- Influences of SSRS on workability of concrete were observed.
- Mechanical and durability properties of the SCC were investigated.
- Strength formula for the proposed SCC was successfully provided.
- Relationships between strength and other parameters have been well established.

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ABSTRACT

This paper presents the results of a study on self-compacting concrete (SCC) made with stainless steel reducing slag (SSRS). Two kinds of SSRS, being different in the surface area (e.g., 1766- and 7970 cm^2/g), were employed as filler and cement substitution, respectively. A series of six mixing proportions with a change of SSRS-cement ratio replacing ordinary Portland cement (OPC) from 0% to 50% (increment 10%) were developed for experimental work. The workability, observed via slump flow, slump-flow time (T_{500}), V-funnel time, and Box-filling tests, and the setting time test were involved for freshly-mixed SCC. The hardening and durability parameters such as compressive strength, ultrasonic pulse velocity (UPV), rebound hammer (RH), water absorption, electrical resistivity, and sulfate resistance were estimated, accordingly. The testing results indicate that the workability and viscosity can be satisfactory without the use of viscosity modifying agent as usual. The slump flow increased when 20% or less SSRS substituted for OPC; both the T_{500} and V-funnel flow time are prolonged for SSRS-based mixtures. Moreover, compressive strength is reduced gradually as the SSRS ratio increases; and SCC made with 30% or less SSRS achieves the required strength of Grade 30 concrete. Also, a strength predictive model, modified from the existing one has been successfully proposed (error range of ±5%). In addition, relationships between compressive strength and UPV, RH number, and electrical resistivity have been successfully established with a high degree of correlation. Finally, a replacement ratio of 10% SSRS could provide the highest sulfate resistivity, evaluating by weight-loss test.

1. Introduction

Self-compacting concrete (SCC), or self-consolidating concrete, is a special type of high performance concrete (HPC) with emphasis on improving strength and durability. SCC was first developed in Japan and has been considered as an important achievement in concrete technology for the last two decades [1]. It has widespread applications in building industry because of excellent capability of self-passing through reinforcement gaps and self-filling corners of reinforced formworks without need of mechanical compaction during placement process. High fluidity, self-compacting ability, and good segregation resistance in fresh state are remarkable characteristics of SCC [1,2]. Moreover, this concrete possesses most of benefits of a HPC: low porosity, high compressive strength as well as good durability [1].

Unlike conventional concrete, mixture proportion of SCC usually requires a high cement content, low water–cement (w/c) ratio, and considerably low coarse aggregate volume. In addition, powder component (referring to materials of particle-size smaller than 0.125 mm, including aggregate fraction, additions and cement) is basically higher than that in conventional concrete to provide a homogeneous and cohesiveness for mixture [3]. The low w/c is achieved by the use of a small quantity of water-reducing agent

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in SCC mix, like normal vibrated concrete. Besides, a viscosity-modifying agent (VMA) is often added to SCC mixtures to enhance rheological requirement and segregation resistance [4]. The VMA can be partially or fully replaced by a high content of fine fillers (active or inert) [1]. Previous studies have exhibited that Class F fly ash [5], blast furnace slag [2], limestone powder [3], glass filler, silica fume, recycled aggregate powder [1], or metakaolin [4] were effective additives to maintain the workability and deformability of SCC mixtures.

Stainless steel reducing slag (SSRS), a byproduct of steel making, is discharged from the reducing condition of basic refining process (secondary steel making operation). It includes AOD (Argon Oxygen Decarburization) and LM (Ladle Metallurgy) slag. The dicalcium silicate (γ-C_2S), merwinite ($Ca_3Mg(SiO_4)_2$), bredigite ($Ca_7Mg(SiO_4)_4$) and periclase (MgO) are observed to be major minerals in these slags [6]. Stainless steel slag is a glassy granular material, mainly compounded of several metal oxides (e.g., CaO, SiO_2, and Al_2O_3), similar to ground granulated blast furnace slag (GGBFS). However, it is highly variable in chemical composition, reported from previous researches [7,8]. Generally, the CaO and Al_2O_3 contents are found to be higher than those of other slags, whereas the FeO or Fe_2O_3 constituent is observed to be much less [8]. High free lime (CaO) and magnesia (MgO) would result in volumetric changes (expansion) during hydration and carbonation process of steel making slag [6,9]. Information, alloy steel slag contains several toxic ingredients such as chromium, lead, nickel, cadmium, which would be harmful for not only environment, but also human health [7,8]. Therefore, it is necessary to treat them prior to their applications or landfills. In practice, in comparison with blast furnace slag, the application scope of steel making slag is essentially limited in production of aggregates for road pavement or concrete [6,10,11]. Shi [12] revealed that ladle slag fines passing through the +100 mesh do not show any cementitious property in water owing to containing a majority of γ-C_2S. However, more recently, a number of investigations have showed that fine-particles (less than 45 μm) steelmaking slag is potentially hydraulic as the presence of alkali activator [12], or, blast furnace slag, or OPC. Adolfsson et al. [13] manifested that blending ladle slag with GGBFS would create a mortar with a slow hydration rate and superior in the 28-day strength in comparing with usage of ladle slag only. The LM slag was also employed as a part of sand and cement in mortar manufacturing for construction industry, published by Rodriguez et al. [14]. Mechanical activation via prolonged milling has been suggested to be a reasonable way to enhance the reactivity of various minerals including stainless steel slag when mixed with water [6,12,15]. Sheen et al. [16] believed that substituting SSRS with fineness of 4400 cm^2/g for 30% Portland cement by weight could provide a mortar whose compressive strength is higher than the ASTM C150. Moreover, their result showed at this fineness, the SSRS would be equivalent to the ASTM C989 Grade 80 of blast furnace slag.

Substituting OPC by mineral admixtures is generally accompanied with compressive strength reduction comparing to the control, especially at early ages. It was found that there has been a decrease in compressive strength with an increase in replacing ratio slag or Class F fly ash [2,17]. From their results, the strength reduction became less significant after 56-, or 91 days. Similarly, Uysal and Yilmaz [3], who investigated on SCC incorporating with powders of limestone, basalt, marble, have reported a consistent result. However, Madandoust and Mousavi [4] studied the strength development of SCC and explored there is a pronounced improvement of strength (up to 27%), when metakaolin (MK) is employed. Ultra-fine particles of MK would be responsible for the mentioned distinction.

Indeed, high cement content and the use of chemical admixtures in mixture might increase the cost of SCC. Therefore, replacing them by industrial byproducts would be a promising feasibility in construction industries, addressing toward reusing waste resources instead of natural materials, reducing environment pollution, as well as enhancing economical profits. This paper deals with investigating fresh and hardening properties of SCC with SSRS as a filler and cement substitution.

2. Laboratory studies

2.1. Materials used and mixture proportions

In this study, materials used to prepare a self-compacting concrete include Type I ordinary Portland cement (OPC), natural fine and coarse aggregates, stainless steel reducing slag, and water-reducing admixture. Two kinds of water-quenched SSRS with Blaine fineness of 1766 cm^2/g and 7970 cm^2/g providing by China Corp. in Taiwan (namely as SSRS1766 and SSRS7970), were used in the SCC mixture as filler and cement substitution, respectively (see Fig. 1). The first slag passing through the #75 μm sieve has the relative specific gravity of 2.85 and the second one passing through the #25 μm has this value of 2.83. These slags were first tested and fully met the environmental acceptance via the toxicity characteristic leaching procedure (TCLP) [18], as reported in Table 1. Chemical composition and physical properties of OPC and SSRS are presented in Table 2. The coarse and fine aggregates are crushed limestone and river sand conforming to ASTM C33 [19]

Table 1
TCLP of stainless steel reducing slag (SSRS) used in this study.

Items	TCLP* (mg/L)						
	Cr	Cu	Cd	Pb	As	Hg	Cr^{+6}
SSRS	0.18	<0.05	<0.01	0.31	0.0012	<0.0005	<0.5
Standard	5.0	–	1.0	5.0	5	0.2	2.5

[*] TCLP: toxicity characteristic leaching procedure [18].

Fig. 1. The SSRS7970 (left) and SSRS1766 (right) used in this study.