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Experimental study and strength formulation of soil-based controlled low-strength material containing stainless steel reducing slag

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HIGHLIGHTS

- Twelve mixes were made with different SSRS substitution levels and *w*/*b* ratios.
- SSRS can substitute for OPC up to 30% in production of soil-based CLSM.
- An increase in SSRS ratio resulted in workability improvement, and strength reduction.
- An analytical model for predicting the strength has been successfully proposed.
- Compressive strength of the CLSM can be evaluated via UPV test with high reliability.

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ABSTRACT

Using stainless steel reducing slag (SSRS), a byproduct generated from stainless steel making process, as a cement substitute in production of soil-based controlled low-strength material (CLSM) is a major aim of this study. In the present work, surplus soil and concrete sand were blended well together with a sand–soil proportion of 6:4 by volume in order to produce fine aggregate. Totally, twelve mixtures were prepared for experiment when we changed in turn percentages of Portland cement replacement with SSRS of 0%, 10%, 20%, and 30% by weight and the water-to-binder ratio of 3.4, 3.6, and 3.8. Meanwhile, the binder content in each mixture was fixed at 100 kg/m^3. Fresh and hardening properties of the CLSM were experimentally investigated via flowability, hardening time, ball drop, compressive strength, and pulse velocity test. Testing results indicate that SSRS with the specific surface area of 4551 cm^2/g can substitute for Portland cement up to 30% in production of excavatable CLSM, commonly classified by the 28-day compressive strength of 1.034 MPa or less. In addition, increasing SSRS substitution level would result in effectively improving workability, extending setting time, decreasing pulse velocity, as well as reducing gradually compressive strength, being necessary to control the excavatability of CLSM. Moreover, based on the testing data, an analytical model for predicting compressive strength of the CLSM from one to 56 days has been developed with high reliability.

1. Introduction

Nowadays, controlled low-strength material (CLSM) is popularly used in many countries due to its acknowledged benefits and widespread applications. Self-compacting, self-leveling, low strength, and almost no measured settlement after hardening are widely agreed to be remarkable features of CLSM, and thus it is commonly used as granulated compacting soil or trench fill [1]. CLSM is a kind of cementitious material and known as other names, viz., flowable fill, plastic soil–cement or slurry material, typically comprised of a small minority of Portland cement, a large amount of fine aggregate and tap water. In addition, by definition, CLSM has a compressive strength of 8.3 MPa or less. In fact, with the maximum strength of approximately up to 1.034 MPa, it has been reported to conform well most of backfilled applications because of being easy to re-excavate with hand tools [2,3].

Utilization of waste materials in lieu of conventional ones has provided a key solution to overcome the shortage of natural resources, and this idea is a vital orientation of sustainable development. The ACI 229R [1] also recommends that depending upon availability and project requirements, any recycled materials would be acceptable to make CLSM with prior test its feasibility before uses. Historical review shows that a great number of industrial or construction wastes substituting partially or wholly for conventional materials in production of CLSM have been studied and published over the past few decades. For instance, Achtemichuk et al. [4] employed recycled concrete aggregate to produce a flowable fill without using Portland cement. Sheen et al. [5] used oxidizing slag and reducing slag generated from stainless steel

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making in replacing fine constituent and cement, respectively in development of CLSM. In addition, according to Wu [6] and Finney et al. [2], surplus clay or native soil after pipeline excavation could be reused to create CLSM for trench backfilling, and this use help to effectively consume on-site residual soil instead of removal. Vipulanandan et al. have investigated the combined use of foundry sand and clay soil in making soil–cement slurry [7]. Their results showed that addition of superplasticizer to the foundry sand–clay mixtures would result in reducing water demand and noticeably increasing compressive strength. Recently, Chen and Chang [8] have studied on production and behavior of ready-mixed soil material preparing with a combined binder (60% Portland cement and 40% blast furnace slag). Their findings exhibited a possibility of combining the benefits of CLSM and soil cement material. Moreover, Wu and Lee, [9] employed a soft excavated surplus clay (liquid limit and plastic index of 35 and 34, respectively) to produce a clay-based CLSM. Their study recommended that a mixture with cement-to-water and water-to-solid ratios of 0.5–0.7 and 0.7, respectively could be used as subgrade material for a pedestrian plaza. Additionally, Wang et al. [10] used tire rubber waste as aggregate in making lightweight CLSM. Finally, it should be noted that constituent materials and their contents may have considerable effect on the mixing water requirement and, in turn, cause a major variation in compressive strength of CLSM [11].

On the other hand, the process of stainless steel production generates a large quantity of waste from melting scraps in plants. Approximately, producing each three tons of stainless steel will create one tone of waste [12]. Stainless steel reducing slag (SSRS) discharges from reducing condition of basic refining process, called as secondary steel making operation. It includes AOD (Argon Oxygen Decarburization) and LM (Ladle Metallurgy) slag. In comparison with ground granulated blast furnace slag (GGBFS), generated from iron making, 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 [13,14]. Therefore, it is necessary to treat them prior to their applications or removal.

Chemical analysis reveals that stainless steel slag is mainly a compound of several metal oxides (e.g., CaO, SiO_2, and Al_2O_3), which is similar to GGBFS. In addition, literature observation showed that stainless steel reducing slag is highly variable in chemical composition [14]. Generally, the CaO and Al_2O_3 contents are found to be higher than those of other slag, whereas the FeO or Fe_2O_3 is observed to be much less [12]. Fig. 1 shows the CaO–SiO_2–Al_2O_3 diagram, schematically illustrating chemical composition of cement and other mineral admixtures. In practice, a large quantity of steel making slag has been usually employed in production of aggregates for road pavement or concrete purposes, and in fertilizer production [15,16]. Lately, however, there has been a potential application of these wastes as a hydraulic supplementary after relevant treatments [13,15,17]. Several scholars have experimentally proved that steelmaking slag generally could possess both cementitious and pozzolanic characteristics when it was ground into very fine particles. For example, Adolfsson et al. [17] manifested that blending ladle slag (generated from further refining molten steel) with GGBFS would create a mortar with a slow hydration rate and superior in the 28-day strength in comparison with usage of ladle slag only. And Kourounis et al. [18] claimed that incorporation of 15% and 30% steel making slag with Portland cement could meet the requirements of strength class 42.5 and 32.5 of EN 197-1 [19], respectively. Also, mechanical activation has been suggested to be a reasonable way to enhance the reactivity of stainless steel slag. Sheen et al. [13] indicated 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 [20]. Moreover, their result showed that at this fineness, the SSRS would be equivalent to the Grade 80 of blast furnace slag in ASTM C989 [21]. Furthermore, Kriskova et al. [15] studied on the hydraulic properties of two stainless steel slag, viz. LM and AOD slag. Their findings also revealed that secondary slag might be considered as a cementitious material being similar to GGBFS because the 90-day compressive strength of LM and AOD slag could achieve 20% and 10% mortar strength of Portland cement, respectively, and these values were directly related on the water-to-binder ratio.

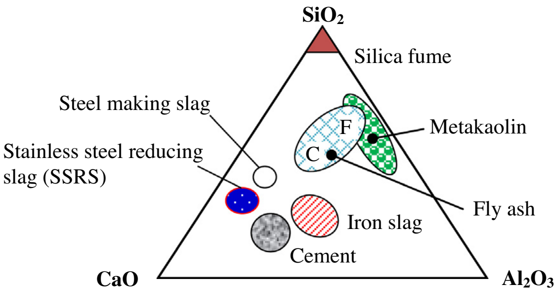

Fig. 1. A CaO–SiO_2–Al_2O_3 diagram of cement and mineral admixtures.

2. Research significance

In practice, a huge quantity of residual soil generated from either pipe trench or deep excavation projects needs to be removed. The soil-delivery work may cause a negative effect on environment and an undesirable raise of project cost due to long distance of transportation and creation of new landfills. Moreover, using SSRS, a byproduct from the stage of refined stainless steel, as cement replacement can result in enhancing both economical and environmental benefits due to reducing the use of clinker and CO_2 emissions as well [15]. The present study is addressed toward using both SSRS and Portland cement as combined binder for producing an environment-friendly and low-cost CLSM containing surplus soil as fine constituent. In a earlier research, Sheen et el. [22] have focused on the effects of fine constituent in mixture, and this paper aims to consider the influences of water content on engineering properties of the soil-based CLSM, which are investigated through an experimental program. The findings derived from the research are expected to contribute a deep understanding and corrected usage of hazardous and excavating wastes as recycled sources that is a beneficial solution in making green building materials.

3. Experimental program

3.1. Materials used

3.1.1. Stainless steel reducing slag and Portland cement

The SSRS used in this study was obtained from a local plant in Taiwan. After passing through the No. 200 sieve (75 μm), it was milled by Los Angeles Abrasion Machine at 5000 rpm with 1 mm zirconium ball to produce a cementitious material. The specific gravity is 2.84 and the specific surface area is 4515 cm^2/g, Blaine. Moreover, ordinary Type I Portland cement (OPC) conformed to ASTM C150 [20] with the specific gravity of 3.15 and specific surface area of 3851 cm^2/g was used in mixtures. The chemical and physical properties of the SSRS and OPC were shown in Table 1.

3.1.2. Fine aggregate

Fine aggregate is typically a major component of CLSM mixtures, often up to 80–85% by weight. In the present work, it was formed by well mixing concrete sand and surplus soil together in order to desirably improve the distribution of particles. The particle size of sand taken from Laonung River (located in the South of Taiwan) ranges from 0.075 to 4.45 mm, matched the ASTM C33 [23] requirements for fine aggregate in making concrete. Meanwhile, the soil was obtained from a construction site (after eliminating almost organic substances) where the proposed CLSM