International Symposium

HANOI GEOENGINEERING 2022

Innovative Geosciences, Circular Economy and Sustainability

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INNOVATIVE GEOSCIENCES,
CIRCULAR ECONOMY AND SUSTAINABILITY

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USING STEEL SLAG AGGREGATES: A GREEN MATERIAL AS FUNCTIONAL FILLERS IN SMART ULTRA-HIGH PERFORMANCE CONCRETE WITH SELF-SENSING ABILITY

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Abstract: Steel slags are the waste products of steel manufacturing. The steel slag can be used as a mineral admixture in concrete or an aggregate in concrete. In this study, fine steel slag aggregates (manufacturing by using Slag Atomizing Technology) which contain almost no free CaO and MgO were used as a fine aggregate in ultra-high performance concrete (UHPC). In addition, the fine steel slag aggregates with high electrical conductivity was potential electrically conductive functional fillers in smart concrete with self-sensing ability. The self-sensing ability of smart UHPC containing steel slag aggregates was investigated. The UHPCs containing SSAs produced high workability (250 mm in diameter) and compressive strength (185 MPa). The addition of steel slag aggregates enhanced conductive network of functional fillers in the smart UHPCs, thus improved self-sensing ability of smart UHPCs under compressive loading. As the compressive stress increased, the electrical resistivity of smart UHPC clearly decreased. Based on change in electrical resistivity of smart UHPC, the change in compressive stress of specimens was observed and vice versa. Hence, steel slag aggregate, a green material, was potential fine aggregate for concrete as well as functional filler for enhancing self-sensing ability of smart concretes.

Keywords: Steel slag aggregate; Ultra high performance concrete; Self-sensing; Green materials.

1. INTRODUCTION

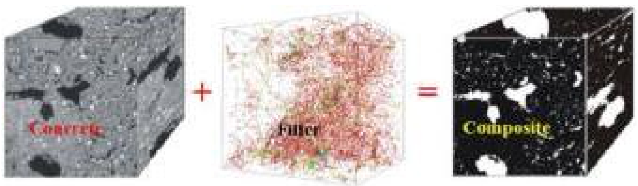
Steel slag aggregate is a waste product of steel manufacturing, which should be considered as a green resource (Jiang et al., 2018). Steel slag can be classified into basic oxygen furnace (BOF) slag or an electric arc furnace (EAF) slag based on steel manufacturing technology. During the manufacturing of carbon and stainless steels, a significant amount of by-product steel-slag is produced, accounting for about 15-20 wt.% of the total steel output (Das et al., 2007). The chemical compounds in steel slag generally include SiO_2, CaO, Fe_2O_3, Al_2O_3, and MnO (Jiang et al., 2018).

In Vietnam in 2020, (Huyen Trang and Quyen, 2020) reported that the annual production of steel is about 20 million tons while that of steel slag is about 2,2 million tons (11-12% steel production (Hien, 2016)).

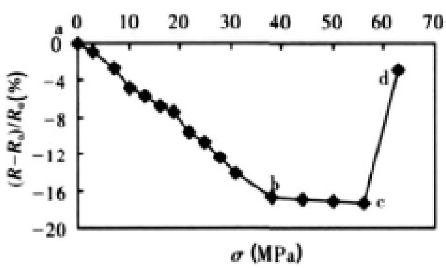
Huge amount of steel slag leads to occupation of lands and potential pollution of water and soil owing to the alkaline leachates from steel slags. Thus, utilization of steel slags as a recycled material for concrete is an interested topic for environmental protection.

Researches have recently shown that steel slag would be used as a coarse or fine aggregate for concrete (Rondi et al., 2016; Saxena and Tembhurkar, 2018). Moreover, concrete containing steel slag aggregate displays satisfactory compressive strengths and flexural strengths (Rondi et al., 2016; Saxena and Tembhurkar, 2018). However, it should be noted that free CaO and MgO in steel slag aggregates can generate increasing the volume of concrete at long term condition (Jiang et al., 2018).

The sudden catastrophic of civil structure without warning such as Nanfang'ao bridge collapse (Taiwan, 2019), Ponte Morandi motorway bridge collapse (Italy, 2018) caused human deaths and property damage. Structural health monitoring (SHM) system for predicting and preventing the sudden failure of structures is concerned more and more. Currently, in field of SHM, smart concretes with self-stress sensing ability have been being studied to overcome the drawbacks of current attached or embedded sensors including low durability, high cost, and detecting localized damage. The self-stress sensing ability of the smart concrete is based on the piezoelectric response of concretes, i.e., the fractional change in electrical resistance (FCR), under external loads. The conductive functional fillers such as carbon black, carbon fibers, multiwall carbon nanotube were generally added to enhance the conductive network within the composites and leads to improve FCR of concrete under load and consequently enhance the self-sensing capacity (Han et al., 2014). Figure 1 shows the structure of smart concrete (Figure 1a) and a typical self-stress sensing response of smart concrete (Figure 1b). As can be seen in Figure 1b, in the first stage, as the compressive stress increased the fractional change in resistance increased (minus value means that the electrical resistance decreased with increasing compressive stress) owing to decreasing the distance between functional fillers. In second stage, as conductive network of functional fillers was stable, the FCR little changed even the compressive stress continuously increasing. In third stage, as concrete sample generated major cracks, the electrical resistance of sample increased.



a) smart concrete with functional fillers



b) Self-stress sensing ability of smart concrete

Figure 1. Typical self-stress sensing of smart concrete with functional fillers (Han et al., 2014).

However, the dispersion of conductive functional fillers in ultra-high performance concretes (UHPCs) was difficult owing to low water per cement ratio and high density of UHPC matrix.

In this study, the steel slag aggregate (SSA) which has high electrical conductivity was used as an aggregate as well as functional fillers in the smart concrete based UHPC matrix. Fresh and hardened properties and self-sensing characteristics of smart UHPCs were investigated and discussed.

2. EXPERIMENT

2.1. Materials and specimen preparation

Table 1 shows the matrix components of smart concretes. Cement (Type I), silica fume from Elkem company, silica powder with maximum size of 0.1 mm, and superplasticizer (SP) based polycarboxylate containing 30% solid were used. 1.5 vol.% short smooth steel fibers (0.2 mm in diameter and 6 mm in length) was added to the matrix for improving crack resistance and conductive network of functional fillers as well. Steel slag aggregates, PS ball type, manufactured from Ecomaister co.ltd., were used as fine aggregates in the matrix of the UHPC. PS Ball stands for Precious Slag Ball, which is an innovative material that can be produced by the rapid cooling of slag which generated from steel making process by Slag Atomizing Technology (SAT). Fast heat exchange of the falling down liquid steel to a high speed airflow convert liquid steel slag stream into spherical slag balls at various sizes. Thus, PS Ball provides a perfect atomizing of materials size, hardness, density, and durability as well as non-toxic environment. PS balls contain almost no free CaO and MgO (free CaO content is below 0.15%), which help to avoid volume instability of concrete at long term condition (www.ecomaister.com).

Table 1. Matrix composition

Cement	Silica fume	Silica powder	SSA	Water	SP	fiber (vol. %)
1.0	0.15	0.25	1.0	0.2	0.042	1.5

Figure 2 shows images of SSAs with ball shape and 0.39 mm in maximum particle diameter were used. Table 2 summarizes the components of SSAs. The heavy metal elution from PS ball including Pb, Cu, As, Hg, Cd, Cr6+, and CN were not detected (www.ecomaister.com).

Figure 2. Image of steel slag aggregates.

Figure 3. Image of smart UHPC specimens.

A 15-L Hobart-type laboratory mixer was used to prepare specimens. The slump flow (flow table test using mini flow cone) of fresh mixtures was tested to control the workability of mixtures. Cubic compressive specimens with dimension of 50×50×50 mm^3 were prepared to investigate the hardened properties and self-sensing characteristics of smart UHPCs. Two copper wire meshes (45 mm wide and 70 mm high) were embedded 20 mm apart in each cube to become as electrodes for measuring the electrical resistivity of the smart UHPC specimens.

All specimens were covered by plastic sheet and stored in the laboratory condition for 2 days prior to demolding. After demolding, specimens were cured in hot water tank (90 ºC) for 3 days and then kept in the laboratory for 1 day prior to testing. Figure 3 illustrates images of specimens for evaluating self-sensing ability of smart UHPCs.

Table 2. Chemical component of steel slag aggregates (PS ball)

SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	Others	Note
15.5	7.9	27.6	6.0	29.2	13.7	EAF Slag

2.2. Test setup

Figure 4 shows the specimens and test set-up for measuring the electrical resistivity response of the smart UHPCs during compressive loading. An alternative current (AC) measurement (a SI 1260 impedance/gain-phase analyzer machine) with two probes was used to measure the electrical resistivity. The universal testing machine (UTM) with 300 *tonf* capacity was used to apply compressive load. The electrical resistivity (ρ) is calculated based on the measured electrical resistance (R) from alternative current (AC) measurement by using Equation 1.

$$\rho = R\frac{A}{L} \quad (1)$$

here, *A* is the cross-sectional area, and *L* is the gauge length between the two electrodes.

The fractional change in the electrical resistance (FCR) of the composite was calculated at peak stress by using Equation 2.

$$FCR = \frac{\Delta\rho}{\rho_o} = \frac{\rho_p - \rho_o}{\rho_o} \quad (2)$$

Here, ρ_o and ρ_p are the initial electrical resistivity and the electrical resistivity at point with peak compressive stress (σ_p), respectively. The FCR value is negative because the electrical resistivity decreased under compression. Thus, in this study, -1 was multiplied for the measured FCR of smart UHPCs.

Figure 4. Test setup for measuring electrical resistance of specimens during compressive loading.

3. RESULTS AND DISCUSSIONS

3.1. Fresh and hardened properties of smart UHPCs containing SSAs

Figure 5 shows the flow of smart UHPC matrix. The flow value (diameter) was 250 mm. In general, the use SSA as the aggregate produced well workability of smart UHPCs. Small diameter (maximum diameter of SSA was 0.39 mm) and spherical shape of SSAs reduced the friction between aggregates and consequently generated well flow of smart UHPCs.

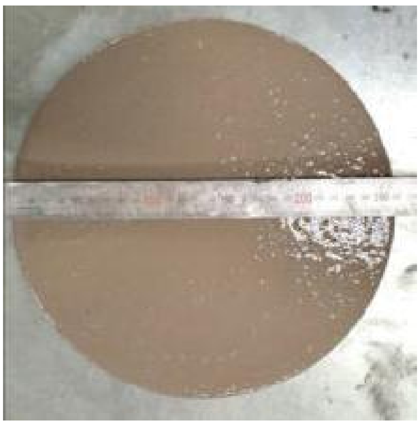


Figure 5. Flow of smart UHPC matrix.

Figure 6. The failure of smart UHPC specimen under compression.

Figure 6 shows the failure of specimen without embedded copper meshes under compression. The average compressive strength of smart UHPCs observed from three specimens was 185 MPa and standard deviation was 5 MPa. Thus, the SSAs with spherical shape and high hardness (7.5 of Mohs hardness and 43 of Rockwell Hardness while those of silica were 5.5 and 30, respectively (www.ecomaister.com)) can be used as a fine aggregate for concrete with ultra-high compressive strength (higher than 150 MPa in compressive strength).

3.2. Self-stress sensing characteristics of smart UHPCs

The self-stress sensing characteristics of smart UHPCs can be evaluated through the electrical conductivity (or the initial electrical resistivity, ρ_o) and FCR of smart UHPCs which were determined according to Equation 1 and Equation 2.

Figure 7 shows the electrical resistivity and compressive stress response versus times during increasing compressive loads. ρ_o and FCR values were determined and summarized in Table 3.

Table 3. Self-stress sensing characteristic test results

Sample	ρ_o (kΩ-cm)	FCR (%)	$\Delta\rho$ (kΩ-cm)	σ_{p}, (MPa)
SP1	326.2	20.4	66.4	150.2
SP2	494.5	19.6	97.0	155.0
SP3	260.4	17.0	44.3	172.3
Average	360.4	19.0	68.5	159.2

The initial electrical resistivity of smart UHPCs was quite low (360.4 kΩ-cm), i.e., its electrical conductivity was quite high in comparison with conventional concrete owing to addition of highly electrical conductivity SSAs and steel fibers.

The electrical resistivity response of smart UHPCs under compression produced a clear trend with increasing compressive stress. As the compressive stress increased from 0 to peak stress, the electrical resistivity of smart UHPC significantly decreased.

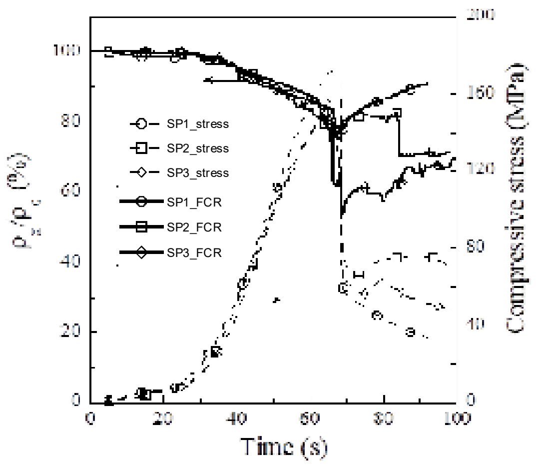


Figure 7. The electrical resistivity response of smart UHPCs under compressive load.

The smart UHPC produced a high value of FCR (19% at peak stress) under compression. Based on the change in the FCR of smart UHPCs under loading, its change in compressive stress would be obtained and vice versa. It should be noted that the compressive stress of specimens containing copper wire meshes as electrode was lower in comparison with that without copper wire meshes.

Figure 8 demonstrates the conductive network response of functional fillers in smart UHPCs under compression. As the compressive stress or strain increased, the distance between functional fillers (SSAs and steel fibers) decreased, the contacting conduction and tunneling conduction between functional fillers increased and consequently the electrical resistivity of composite decreased (i.e., the electrical conductivity increased).

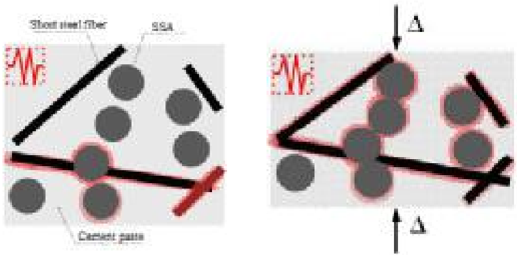


Figure 8. Conductive network of UHPC matrix with steel fiber and SSAs.

Hence, the addition of SSAs clearly improved the electrical conductivity of composite as well as FCR of composite under compression.

4. CONCLUSIONS

This study investigated the fresh, hardened properties and self-sensing characteristics of smart UHPCs containing SSAs, waste materials. The test resulted indicated that the SSA can be used as a fine aggregate in UHPC matrix as well as conductive functional fillers in smart UHPCs. The UHPC matrix containing SSAs produced a high workability (flow of 250 mm) and compressive strength (185 MPa). The addition of SSAs clearly generated high conductive network of functional fillers in smart UHPCs. Thus, the electrical conductivity of smart UHPCs with SSAs as well as the fractional change in electrical resistivity of smart UHPCs under compression was clearly enhanced. The change in stress of smart UHPCs would be observed by determining the change in electrical resistivity and vice versa.

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