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Enhancing flowability and sustainability of ultra high performance concrete incorporating high replacement levels of industrial slags

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HIGHLIGHTS

- Rapid-cooling EAF oxidizing slag was applied in UHPC to substitute fine aggregates.
- Ecological benefits achieved by using less energy intensive constituents in UHPC.
- Two types of industrial slags were successfully adopted in UHPC.
- V-funnel apparatus was newly designed to evaluate filling capability of UHPC.

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ABSTRACT

Ultra high performance concrete (UHPC) is an emerging construction material with its superior mechanical properties. However, UHPC requires high amount of energy intensive materials including cement, which could cause unfavorable environmental impact compared to normal concrete. Various eco-friendly UHPC mix designs are proposed by incorporating industrial slags and limestone powder in order to decrease environmental overload and enhance flowability concurrently. Particle packing analysis is carried out for mixture proportioning of the UHPC mixes using different solid constituents. Two types of industrial slags, ground granulated blast-furnace slag and rapid-cooling EAF oxidizing slag are effectively substituted cement and natural fine aggregates in UHPC, respectively. Flowability of UHPC is quantified using flow test and two V-funnel apparatus with different size. Sustainability potential of the suggested UHPC mixtures adopting various low energy intensive materials is characterized by comparing crucial environmental impact categories. Synergistic effects in flowability and ecological aspects can be achieved when two forms of industrial slags used together.

1. Introduction

Ultra high performance concrete (UHPC) is one of the most advanced cement-based materials having superior mechanical properties, e.g. compressive strength [1], ductility [2], impact resistance [3,4] and durability [5]. To achieve high compressive strength, UHPC mixtures are typically designed to have not only a very low water to cement ratio but highly densified microstructures. UHPC generally have high flowable characteristics even with their low water to cement ratio, by using high amount of special superplasticizers. It is desirable to use small amount of superplasticizers in UHPC for practical reasons including lowering material cost while maintaining their other mechanical properties.

Various attempts have been made to enhance flowability of concrete by adding supplementary chemical components or partially substituting constituents of concrete in order to lower inter-particle friction. Khayat [6] reviewed different types of viscosity-enhancing admixtures to produce high flowable, yet cohesive cement-based materials. Furthermore, limestone powder (LP) can adequately improve fresh properties of cement based composites with its physical and chemical effects. Yahia et al. [7] found a substantial increase of the viscosity of mortar and adequate rheological properties by applying a suitable dosage of limestone filler in self-consolidating concrete (SCC). In addition, Shi et al. [8] revealed that proper use of silica fume and slag as a binder in UHPC could lead to positive synergistic effects on the flowability, but negative effects on long term compressive strength and total heat of hydration.

Flowability of concrete can be characterized by different testing method. Slump and slump flow are the most common and practical methods to evaluate consistency of concrete. The flow test using the flow table apparatus [9] is also a practical method to investigate consistency of mortars in a lab scale. Since flowability is the

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most important factor in SCC, various practical test methods have been developed to evaluate fresh properties of SCC. For example, filling ability can be assessed using slump-flow, V-funnel and Orimet, and passing ability can be assessed using L-box, U-box and Fill-box [10]. Among these test methods, V-funnel is a popular test method to estimate deformability of concrete through restricted area without blockage or segregation. Van Tuan et al. [11] and Dils et al. [12] used mini V-funnel test to evaluate filling ability of UHPC without any fibers. However, very limited research carried out to evaluate V-funnel time of UHPC containing steel fibers.

In addition, there are continuous concerns on carbon dioxide emissions of cement and concrete industries especially after the Kyoto Protocol and the Paris Agreement. Since the cement production process emits about 1.6 billion tons of carbon dioxide yearly in the globe [13], numerous endeavor have been carried out to develop eco-friendly construction materials by substituting different components of concrete [14–20] and UHPC [8,11]. However, to the best of authors' knowledge, no attempt has previously been made to develop eco-friendly UHPC with industrial slags by replacing cement and natural aggregates concurrently.

This research developed eco-friendly UHPC by adopting industrial slags and LP to achieve high flowability and minimize strength loss. Particle packing analysis was carried out first to effectively substitute cement and natural aggregates in UHPC. To investigate the effects of industrial slags and LP in UHPC, flowability and compressive strength at various ages were investigated. In addition, sustainability of the developed eco-friendly UHPC was quantified.

2. Materials and mix design

2.1. Materials

The experimental program was designed to develop UHPCs having compressive strength higher than 150 MPa and high flowability by adopting industrial slags and LP. The materials used in this study were undensified silica fume containing about 95% of SiO_2, ordinary Portland cement, two types of LP with different particle sizes, ground granulated blast-furnace slag (GGBFS), silica powder with median diameter of 3.15 μm, and polycarboxylate-based superplasticizer with 25% solid content by weight. Table 1 shows oxide compositions of cement, silica fume, silica powder and GGBFS.

For fine aggregates, silica sands and rapid-cooling electric arc furnace (EAF) oxidizing slag with specific gravity of 3.40 were used in this study. EAF oxidizing slag is a form of by-products of steel manufacturing plant and has been used in paving road mixes and concrete [15]. However, EAF oxidizing slag has difficulties in guaranteeing the dimensional stability and chemical stability [15]. The difficulties of EAF oxidizing slag could be resolved in a way of rapid cooling of the molten slag [20]. It was also revealed that workability of concrete could be enhanced by using rapid-cooling EAF oxidizing slag (called after REOS) as fine aggregates with ball bearing effect due to its round surface [20,21]. Fig. 1 shows REOS for fine aggregates and the detail information of the REOS as aggregates in concrete can be found in Koh and Hwang [20]. The particle size distribution of solid materials used in this study is shown in Fig. 2. In addition, brass coated smooth steel fibers were used in the mixes. Each fiber is 19.5 mm long with a diameter of 0.2 mm and has a minimum tensile strength of 2450 MPa.

2.2. Packing theory and mix design of UHPC

Packing theory is an essential methodology to develop densified concrete using different sized particles. It could be possible to control fresh and hardened

Table 1
Chemical compositions of cement, silica fume, silica powder and GGBFS.

		Cement	Silica fume	Silica powder	GGBFS
Chemical composition (%)	CaO	60.6	0.27	0.20	41.9
	SiO_2	23.0	95.03	97.2	34.1
	Al_2O_3	3.41	0.0	0.0	14.8
	Fe_2O_3	3.13	0.31	0.23	0.98
	MgO	3.68	0.64	0.31	6.61
	TiO_2	0.0	0.67	0.77	1.00
	MnO	0.08	0.15	0.13	0.30
	L.O.I.	2.24	2.19	0.91	1.32

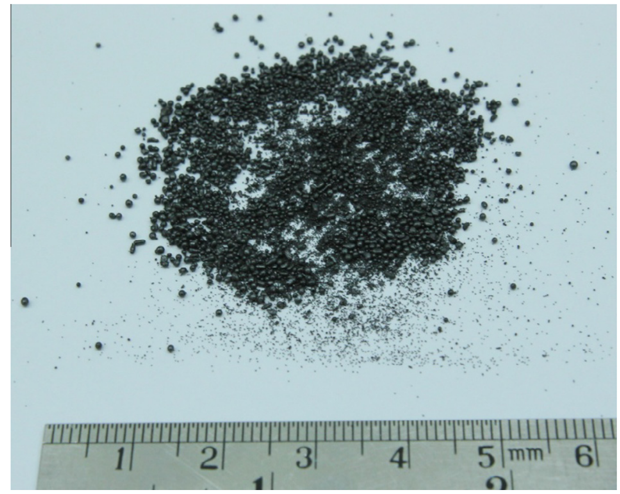

Fig. 1. Rapid-cooling EAF oxidizing slag (REOS) for fine aggregates.

properties of concrete with the proper application of packing theory since the improved particle packing results in more available water to be acting as a lubricant. To design UHPC with various solid constituents and higher flowability, Andreasen and Andersen models were used. Andreasen and Andersen [22] originally suggested cumulative distribution function for packing of a continuous particle-size distribution as follows:

$$P(D) = \left(\frac{D}{D_{\max}}\right)^q \quad (1)$$

where, D is the particle size and $P(D)$ is the cumulative percent finer than size D by volume. $D_{\max}$ and q are the maximum particle size in the mix and the distribution modulus, respectively.

Since the A&A model doesn't include the minimum size of particle size and there will be a minimum diameter in reality, the modified version of A&A model was suggested by Funk and Dinger [23] to take into account the minimum diameter of particles as follows:

$$P(D) = \frac{D^q - D_{\min}^q}{D_{max}^q - D_{min}^q} \quad (2)$$

where, $D_{\min}$ is accounting for the minimum particle size (μm) in the mix. Hunger [17] suggested q values in the range of 0.22∼0.25 for SCC. It is recommended to use smaller q for the mix with high amount of powders (<250 μm) (Brouwers and Radix [24]). In this study, q is used as 0.22. Fig. 3 shows particle size distributions of the mixtures used in this research with the original A&A and the modified A&A models, and Table 2 describes the details of the mix proportions. It should be noted from Fig. 3 that most mixtures reasonably fall within the original A&A model and the modified A&A model.

3. Experimental methodology

3.1. Mixing procedure and preparation of specimens

Each of the 18 mixtures in Table 2 was prepared using the same process described in the following. A planetary mixer was used to prepare the UHPC mixtures. First, silica fume was mixed with all fine aggregates for approximately 5 min. Then, silica powder, cement and cement supplements (if any) were added and mixed together for at least another 5 min. Water and superplasticizer were then gradually added into the dry mixture while the mixer was spinning. After adding water and superplasticizer, the mixture became fluid usually within 3 min. Once the mixture started to show adequate consistency, high strength steel fibers were added by hands into the mixer and allowed to mixture with uniformly distributed fibers. Flowability of each mixture were measured as described in the following section. After the flow measurement, the mixture was poured into 50 mm cubic molds for compression test without any vibration. The casted specimens were covered with plastic sheets and stored at room temperature for 24 h prior to demolding. The specimens were then cured in a water tank at