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Alkali–silica reactivity of cementitious materials using ferro-nickel slag fine aggregates produced in different cooling conditions

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HIGHLIGHTS

- The ASR of cementitious materials using FNS fine aggregates was experimentally evaluated.
- The ASR of FNS fine aggregated is strongly affected by the cooling speed and particle size of FNS.
- The FNS-W exhibited higher alkali–silica reactivity than FNS-A.

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ABSTRACT

In this study, the alkali–silica reactivity of cementitious materials using ferro-nickel slag (FNS) fine aggregates was experimentally evaluated for potential use in concrete. The results revealed that the reactivity of cement mortars using the aggregates varied with the cooling speed and particle size of the FNS. For example, the rapidly (i.e., water-) cooled FNS exhibited higher alkali–silica reactivity than its gradually (air-) cooled counterpart. The particle size of the water-cooled FNS also affected the reactivity of the specimens. Furthermore, the partial replacement of FNS with sea sand, and of cements with fly ash or ground granulated blast furnace slag was effective in reducing the alkali–silica reactivity of cementitious materials containing FNS as fine aggregates.

1. Introduction

Owing to the dwindling availability of natural aggregates for concrete in the construction market and the predicted depletion of natural aggregates, the use of recycled aggregates is expected to increase gradually [1]. However, recycled aggregates may be detrimental to the environment and lead to additional processing costs; quality control of these aggregates is also difficult [2–3]. Securing various sustainable sources of aggregates that can replace natural aggregates and maintain the quality of concrete is therefore essential.

Ferro-nickel slag (FNS) is a byproduct of the ferro-nickel from the nickel ore refinement process. Following the preliminary reduction process at temperatures ranging from 700 to 800 °C, FNS is produced when the nickel ores are melted at temperatures between 1500 and 1600 °C in an electric furnace and the byproducts are cooled in water or air. Owing to its excellent properties such as low absorption rate (0.6–1.6%), dense structure, and high hardness, FNS has significant potential for use as a fine aggregate for concrete [4,5]. In particular, the absolute dry specific gravity of FNS fine aggregates is 10–25% larger than that of regular aggregates; FNS could therefore be effectively used for structures such as wave-dissipating blocks, cable anchors, rockfill dams, and gravity retaining walls that require heavy weights [6]. It was reported that the slump and setting times of fresh mortar containing FNS fine aggregates are generally similar to those of mortar containing normal aggregates [6], although the air contents of the former are 1% larger than those of the latter [6].

FNS consists mainly of SiO_2, MgO, and FeO, and is composed of non-crystalline minerals as well as a mixture of crystalline minerals such as enstatite, forsterite, and diopside [6,7]. The chemical composition and characteristics of these crystalline and non-crystalline minerals vary with the cooling condition used in the production process [7,8].

Two types of FNS are produced, depending on the cooling speed. The air-cooled FNS (FNS-A) appears gray (visually), is lumpy after cooling, and hence crushing is required to render it useful as a fine aggregate [6]. The crushed FNS-A contains many fine particles, and can therefore be used as a modifier for subgrade material in

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concrete pavement, even more so than as a fine aggregate of concrete [9]. In contrast, the water-cooled FNS (FNS-W) is dark green and has a sphere-like shape after cooling [6]. FNS-W has a significant potential to be used as a fine aggregate for concrete owing to its low absorption rate and its similar particle size to that of fine aggregates typically used in concrete [4]. However, the rapid (water) cooling employed during production, results in large amounts (80–90%) of non-crystalline minerals and a bluish green acicular structure of the FNS-W, which leads possibly to a high amorphous-silica content [10–13]. Therefore, concrete with FNS-W as a fine aggregate undergoes an alkali–silica reaction (ASR) [14]. The ASR leads to a reduction in the durability of cementitious materials; in order to serve as an effective fine aggregate of concrete, the expansion stemming from the ASR of the FNS must be lower than the limit set by, for example, the ASTM C 1260 standard [5].

Similar to the ASR of regular reactive aggregates, the ASR of FNS fine aggregates results from the reaction of alkali ions (Na^+ and K^+) in the cement with reactive silica; this silica resides on the surface and in the bulk of the aggregates; the alkalis are present in the pore solution of the hardened concrete solution, i.e., in a high-pH environment [6,12,15,16]. Therefore, the potential for alkali–silica reactivity of cementitious materials using FNS as a fine aggregate is influenced mainly by the amorphous silica of the FNS. The non-crystalline-mineral content and the concentration of the constituent amorphous silica, vary with the cooling speed. In fact, high concentrations of silica in the FNS during melting, is conducive for the deposition of forsterite; the ASR potential of the FNS depends on the amount of forsterite deposited [6,7,17,18].

In this study, the potential of FNS as a fine aggregate for concrete was evaluated by determining the alkali–silica reactivity of cement mortar specimens that use FNS as an aggregate. The mineral compositions of the FNS-A and FNS-W were determined via X-ray diffraction (XRD). An electron probe micro-analyzer (EPMA) was used to analyze the distribution of Si and Mg, in the FNS-W, which was expected to have a high ASR potential owing to the high content of non-crystalline minerals; the microstructures of the inner and outer regions of the FNS-W produced at different cooling speeds were also examined via EPMA. To evaluate the ASR of concrete containing FNS-W, a series of mortar bars were fabricated and the expansion ratios resulting from the ASR were measured in accordance with ASTM C 1260. Furthermore, the chemical composition and the dissolved-silica content associated with each particle size of the FNS-W were analyzed. ASR mitigation methods of cementitious materials with FNS as the fine aggregate were also identified; this was achieved by comparing the effects on the ASR, of replacing the FNS with sea sand, and cement with fly ash and ground granulated blast furnace slag (GGBFS).

2. Experiment

2.1. Materials

The FNS used in this study was obtained from SNNC Co. Ltd., a ferro-nickel manufacturer located in Gwangyang, Jeollanamdo, South Korea. Fig. 1 shows the particle size distribution of the FNS-A and FNS-W as well as the standard grade that satisfies ASTM C 33. The FNS-A, which was crushed after being cooled in air, contained relatively coarser particles than the standard grade. In contrast, the FNS-W that was water-cooled without crushing consisted of coarse particles whose sizes exceeded the limit specified by the ASTM C 33 standard. The FNS-W consisted predominantly of 0.6–5-mm-sized particles, and had a lower fraction of 0.15–0.6-mm-diameter particles compared to the standard grade. Therefore, to facilitate their use as fine aggregates in concrete, the FNS-W must be sieved and crushed, respectively, in order to obtain 0.15–0.6-mm-diameter particles.

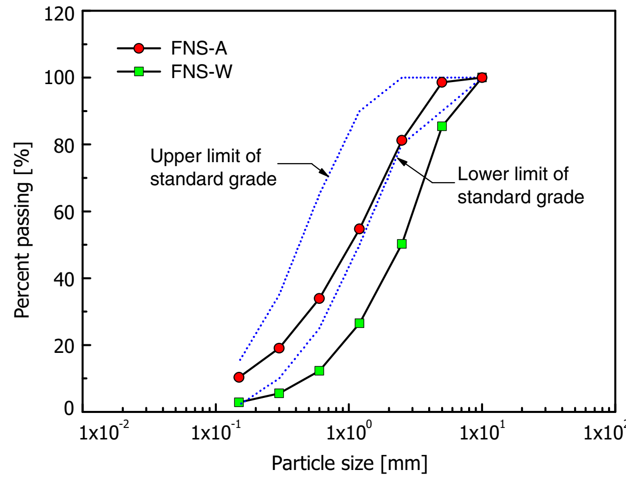

Fig. 1. Particle size distributions of the FNS-A and FNS-W.

Fig. 2 shows the particle size distribution of the type 1 Portland cement, GGBFS, and fly ash used in the experiment. These materials had average particle sizes of 13.61, 9.02, and 16.60 μm, Blaine fineness values of 3250, 4330, and 3900 cm^2/g, and dry densities of 3.14, 2.89, and 2.25 g/cm^3, respectively. The cement used satisfies the ASTM Type I standard, and has an equivalent Na_2O of 0.9%. Moreover, the GGBFS and Class F fly ash were obtained from POSCO (Gwangyang, South Korea) and the Samcheonpo Thermal Power Plant (South Korea), respectively.

Table 1 shows the chemical compositions of the materials used in the experiment. FNS consists mainly of silica, magnesium and iron oxides as well as aluminum and calcium oxides. Table 2 lists the basic physical properties of the FNS. The FNS-A and FNS-W have differing specific gravities, and their absolute dry specific gravity was 5–18% larger than those (2.5–2.8 g/cm^3) of the typical fine aggregates. Furthermore, with values of 1.87 and 1.67 kg/L, respectively, the unit volumes of FNS-A and FNS-W are both higher than those (1.52–1.63 kg/L) of the conventional fine aggregates. The overall gradation of FNS-A was finer, and hence its average fineness modulus was smaller (by 26%), than that of the FNS-W.

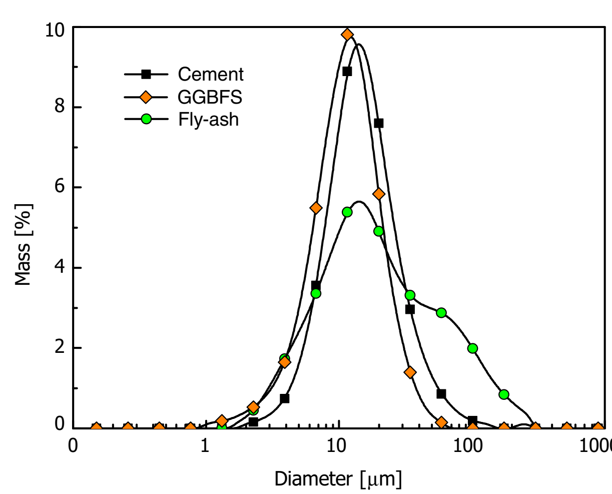

Fig. 2. Particle size distributions of cement, GGBFS, and fly ash.