Evaluation of the potential ASR of ferronickel slag aggregate and its mitigation by fly ash

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Abstract

This paper presents a study on the sustainable use of ferronickel slag (FNS) as a partial replacement of natural sand in concrete. About 12 to 14 tonnes of FNS is generated as by-product in the production of 1 tonne of ferronickel alloy. The physical properties of FNS are suitable for use as fine aggregate. However, it contains amorphous silica that may potentially cause alkali-silica reaction (ASR). Thus, the potential ASR of FNS aggregate and its mitigation by using fly ash as a partial replacement of cement was studied by using accelerated mortar bar tests (AMBT). Cement was replaced by 0%, 10%, 20% and 30% fly ash. After 21 days of AMBT, the expansions were 0.664%, 0.392%, 0.167% and 0.036% for 0%, 10%, 20% and 30% fly ash, respectively. Thus, according to the 10-day and 21-day expansion limits of AS 1141.60.1, FNS was classified as reactive for 0% and 10% fly ash, slowly reactive for 20% fly ash and non-reactive for 30% fly ash. Therefore, 20% to 30% class F fly ash was found as an adequate ASR mitigating measure for FNS fine aggregate.

***Keywords**: alkali-silica reaction; accelerated mortar bar test; ferronickel slag; fly ash*

1. INTRODUCTION

Concrete is the most highly used construction material due to its availability, ease of manufacturing, high resistance against weathering actions and flexibility of casting into different shapes. Fine aggregate is one of the key components of concrete, which acts not only as a filler but also contributes to its density, strength and durability. Natural sand is the most commonly used fine aggregate. However, excessive and uncontrolled sand mining has been observed in different parts of the world in order to meet the increasing demand of concrete. Excessive sand mining can cause damage to the ecosystem [1]. Thus, application of industrial by-products such as FNS as a replacement of sand can be a step forward to more sustainable concrete productions.

Alkali-silica reaction (ASR) is a durability concern of concrete using reactive aggregates since it may cause cracking and reduce the structural integrity. This can further accelerate the deterioration of concrete by chloride penetration and corrosion of reinforcing steel. Extensive research has been carried out in the recent years on the possible ways to mitigate the ASR expansion of various reactive aggregates. ASR may occur due to the presence of amorphous silica or defects in the crystalline structure of silica present in certain types of aggregate [2, 3]. At the initial stage of ASR, alkali ions from the pore solution attack the weekly bound silicate of aggregate and produce alkali silicate gel and silicic acid. The silicic acid may further react with alkali and produce more alkali silicate gel. This gel has an affinity to absorb moisture from the surroundings and exert swelling pressure in concrete. Concrete usually cracks when this pressure results in stresses exceeding its tensile strength [4, 5]. Despite a significant progress on the knowledge of ASR mechanism in the last few decades, recently found deleterious ASR expansion in structures such as Seabrook Power Plant has risen concerns about the evaluation of newly adopted materials in concrete structures [6]. An enormous amount of slag is generated as by-product in the production process of ferronickel alloy due to the usual low grade of Nickel ores found in the earth. FNS aggregate has high density and low water absorption properties that makes it a suitable alternative to natural sand in concrete. Our previous studies [7, 8] showed that 50% replacement of natural sand by the FNS fine aggregate improved aggregate gradation and achieved optimum strength with good workability of freshly mixed concrete. Therefore, this aggregate combination has been used in the present study to evaluate the effect of different percentages of fly ash on the ASR of FNS aggregate. Fly ash was used as partial replacement of cement by 0%, 10%, 20%, and 30%, and its effectiveness to mitigate the potential ASR has been investigated using the accelerated mortar bar test. Porosity of hardened mortar specimens by the volume of permeable voids (VPV) test was carried out in order to understand the effect of fly ash percentage on ASR.

2. MATERIALS AND METHODS

Ordinary Portland cement (OPC) and a class F fly ash were used as binders. The OPC and fly ash had a specific surface areas of 370 and 330 m^2/kg, respectively. The specific gravity of OPC and fly ash were 3.15 and 2.20, respectively. Granulated FNS aggregate was produced by water-cooling of the molten slag which is a by-product of the smelting of garnierite ore. It was sourced from the stockpile of SLN, New Caledonia. The densities of natural silica sand and FNS aggregate were 2160 kg/m^3 and 2780 kg/m^3, respectively. The physical properties of FNS and sand are given in Table 2.1. The images of their physical appearance are shown in Figure 2.1. It can be seen that FNS aggregate consists of higher density, voids ratio and fineness modulus than those of natural sand. Due to the higher angularity, the FNS particles did not flow in the sand flow cone test and resulted in a higher voids ratio of the aggregate. The coarseness of FNS aggregate is reflected in its higher fineness modulus value as compared to that of natural sand. Furthermore, Table 2.2 shows the chemical composition of FNS is primarily silica, magnesia and iron oxide, while fly ash composed of silica and alumina. Thus, this fly ash can be categorized as Class F. Though, FNS consist of high percentage of magnesia, it's not in amorphous nature. In our previous study [4, 7], we have conducted quantitative X-ray diffraction analysis (XRD) which pointed out this magnesium oxide is crystalline Forsterite Ferron. This mineral has a melting point of 1890 ºC which is highly stable and do not undergo any reaction with binders.

A combination of 50% natural sand with 50% FNS aggregate was used in this study. The proportions of materials in the mortar mixtures are given in Table 2.3. The mixtures with 0%, 10%, 20% and 30% fly ash are designated as OPC100, FA10, FA20 and FA30, respectively.

The accelerated mortar bar test (AMBT) samples were 25 mm × 25 mm × 275 mm mortar bars. The samples were cured in a hot water bath at 80 °C for 24 hours after demoulding. After taking the initial length reading, the samples were immersed in 1M sodium hydroxide solution at 80 °C, and the changes in length were measured at the time intervals given in AS 1141.60.1 [9]. Porosity was determined by measuring the volume of permeable voids according to the ASTM C 642 test procedure [10]. After curing for 28 days, the specimens were oven dried at 110 °C for 3 days to reach the mass equilibrium and then immersed in water for 48 hours. The saturated surface dry (SSD) weight of the sample was then determined. Porosity was calculated by utilizing these mass values of the specimen.

Table 2.1: Physical properties of aggregates

Property	Sand	FNS
SSD density (kg/m^3)	2160	2780
Fineness modulus	1.95	4.07
Water absorption	0.35	0.42
Uncompacted voids ratio (%)	32.42	44.39
Average flow time (s) in sand flow cone tests	17.19	Did not flow

Figure 2.1: Photographs of fine aggregates: sand (left) and FNS (right) Table

Table 2.2: Chemical properties of fly ash and FNS

Material	CaO	SiO_2	MgO	Al_2O_3	Fe_2O_3	Na_2O	LOI
FNS	0.42	53.29	31.6	2.67	11.9	0.11	0.83
Fly ash	0.6	76.34	0.54	14.72	3.69	0.19	0.53

*LOI: Loss on Ignition

Table 2.3: Mortar mixture proportions

Mix ID	Binder (kg/m^3)		Fine aggregate (kg/m^3)		Water to binder ratio (w/b)
	OPC	Fly ash	Sand	FNS	
OPC100	602	-	678	678	0.47
FA10	542	60	678	678	
FA20	482	120	678	678	
FA30	421	181	678	678	

3. RESULTS AND DISCUSSION

3.1 Accelerated mortar bar expansions

The average 10-day and 21-day expansions of mortar bars with different proportions of fly ash are shown in Figure 3.1. It can be seen that the OPC100 specimens exceeded the 21-day expansion limit of AS 1141.60.1. After 21 days of the test, the expansion was 0.664%, which exceeds the allowable limit of 0.30%. The use of 10% fly ash as cement replacement reduced the 21-day expansion to 0.392% which was a 41% reduction as compared to that of the control samples. However, the expansion was above the allowable limit and it was in “reactive” category as classified by the Australian Standard. The use of 20% fly ash in the binder reduced the 21-day expansion by 75% as compared to the control samples. At the end of 10 and 21 days of AMBT exposure, the expansions were 0.053% and 0.167%, respectively. These value of expansions classify the mix as “slowly reactive” as per the Australian standard. Further increase of fly ash to 30% reduced the 21-day expansion by 95% as compared to the control specimens.

The expansions for using 30% fly ash after 10 and 21 days of exposure were 0.017% and 0.036%, respectively. According to AS 1141.60.1, these expansions are categorised as “non-reactive”. Photographs of the specimens at the end of 21 days of AMBT are presented in Figure 3.2. It can be seen that the specimens of mixtures OPC100 and FA10 experienced some visible cracks on the surface.

This is consistent with the 10-day and 21-day expansions that classified both the mixtures as “reactive. However, the number of cracks in the specimens of FA10 were significantly less than in those in the specimens of OPC100. The width of cracks in the specimens of FA10 were also less than those in OPC100. This shows that 10% fly ash reduced the severity of the ASR of FNS aggregate. As shown in Figure 3.2, the specimens of FA20, which were classified as “slowly reactive” by the 10-day and 21-day AMBT expansions, did not exhibit any surficial crack in visual inspections. Also, the specimens of FA30, which were classified as “non-reactive”, did not show any cracking on the surface. Therefore, the use of 30% class F fly ash as an SCM is considered adequate for mitigation of the expansion associated with 50% FNS as fine aggregate.

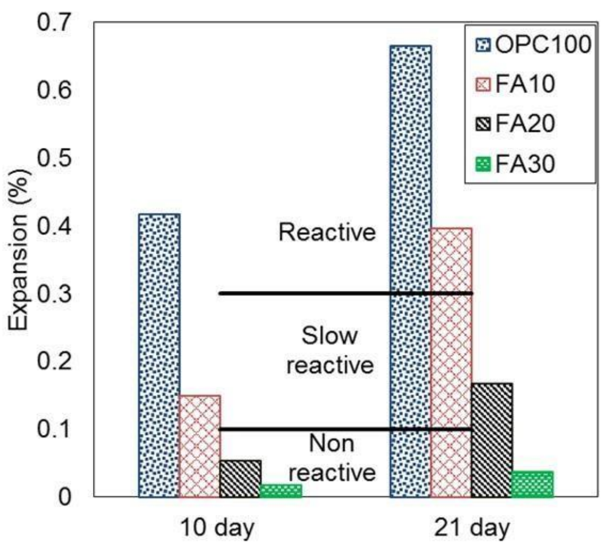

Figure 3.1: ASR expansion of mortar bars.

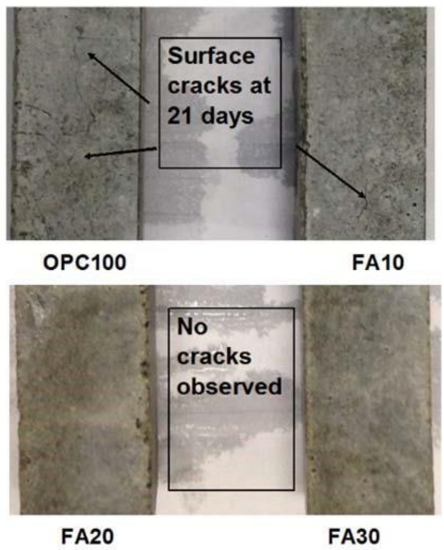

Figure 3.2: Comparison of samples after AMBT.

3.2 Porosity

The changes in volume of permeable voids of mortar specimens with the increase of fly ash are presented in Figure 3.3. It is noticeable that porosity gradually decreased with the increase of fly ash. The average VPV of the control samples was 17.97% that decreased to 17.50%, 15.24% and 14.40% with the inclusion of 10%, 20% and 30% fly ash, respectively. Therefore, porosity reduced by 3%, 16% and 20% with the use of 10%, 20% and 30% fly ash, respectively. This phenomenon is attributed to the densification of microstructure by pozzolanic reaction and filling effect of the unreacted fly ash particles. Thus, fly ash reduced the internal voids which helped reduce the accumulation of pore solution and reduce ASR gel formation.

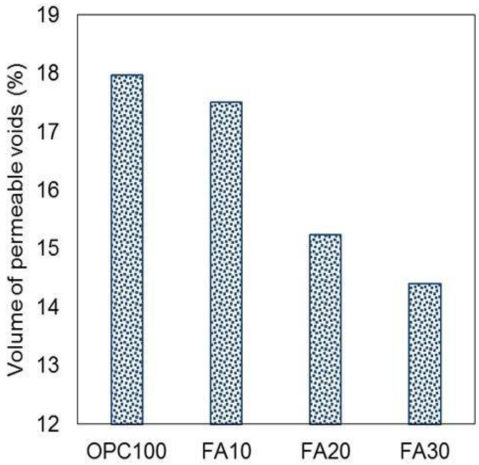

Figure 3.3: Volume of permeable voids mortars.

4. CONCLUSION

The ASR of 50% FNS fine aggregate with natural sand was investigated by using the accelerated mortar bar test (AMBT). The effect of using fly ash as cement replacement by up to 30% was studied as mitigation of potential ASR expansion of FNS aggregate. The AMBT expansion of mortar bar specimens was found to decrease with the increase of fly ash content. According to the 10-day and 20-day expansion limits of the Australian Standard, the mortar bar specimens were classified as reactive, slowly reactive and non-reactive for the fly ash contents of 10%, 20% and 30%, respectively. Some cracks were observed after 21 days of the test in the specimens using no fly ash or 10% fly ash. No surface crack was seen in the specimens using 20% and 30% fly ash. The volume of permeable voids decreased from 18% to 14% by the use of 30% fly ash which shows densification of the binder matrix by pozzolanic reaction of fly ash. This reduced the alkalinity of pore solution that reduced the ASR of FNS aggregate. Therefore, the use of FNS aggregate and fly ash can be considered as a feasible option for production of technically sound and environmentally friendly concrete.

5. ACKNOWLEDGEMENT

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