Construction and Building Materials 123 (2016) 135–142

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Expansion due to alkali-silica reaction of ferronickel slag fine aggregate in OPC and blended cement mortars

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HIGHLIGHTS

- The ASR expansion of a ferronickel slag fine aggregate was studied.
- The slag was found reactive because of its amorphous silica content.
- Cement replacements by fly ash and GGBFS as ASR mitigating measures were investigated.
- Fly ash was found effective in reducing expansion below the allowable limits.

ARTICLE INFO

Article history:
Received 6 April 2016
Received in revised form 17 June 2016
Accepted 29 June 2016

Keywords:
Alkali-silica reaction
Fine aggregate
Ferronickel slag
Supplementary cementing material

ABSTRACT

About 14 tonnes of granulated ferronickel slag (FNS) is produced as a by-product in the production process of 1 tonne of ferronickel. The physical properties of FNS are suitable for its use as fine aggregates in concrete. This paper presents a study on the expansion due to alkali-silica reaction (ASR) of mortar bars containing different percentages of FNS aggregates originated from garnierite ore. Accelerated mortar bar test (AMBT) was performed to measure the expansion of the samples. FNS was found to be reactive in Portland cement mortar according to the AMBT results. Class F fly ash and ground granulated blast furnace slag (GGBFS) were used as the ASR mitigating measures of the FNS aggregate. Experimental results show that the use of GGBFS was unable to reduce expansion to the required level. However, the use of 30% class F fly ash as a supplementary cementitious material was found to be effective in reducing the 21-day ASR expansion below 0.3% required by the Australian Standard. Observations by scanning electron microscopy confirmed the effectiveness of fly ash in mitigation of the ASR products of FNS aggregates.

1. Introduction

Laterite, garnierite and pentlandite ores are the primary sources of nickel. The ore is smelted in an electric furnace or rotary kiln in order to produce ferronickel. The granular slag comes out as a by-product of the production process of ferronickel. The slag is classified into three types, depending on its cooling methods such as slow-cooling granulated, wind granulated and water granulated [1]. The ore contains low grade nickel and it undergoes through three major stages such as pre-reduction, reductive smelting and ferronickel enrichment in the process of producing ferronickel. A large quantity of slag is produced in the process of ferronickel production. Safe disposal of the slag is considered as a major issue for the ferronickel plants worldwide [2]. Almost 14 tonnes of slag is generated per tonne of ferronickel production [3]. On the other hand, in order to prevent the rapid depletion of natural fine aggregates, the use of industrial by-products and recycled aggregates in concrete has been studied extensively for the past few decades. The Japan Industrial Standard (JIS) 5011-2 [4] has produced recommendations for using FNS as aggregates in concrete. Sato et al. [5] and Sakoi et al. [6] showed that replacing natural fine aggregate with air granulated FNS produced in Japan exhibited higher compressive strength and modulus of elasticity of concrete. Shoya et al. [7] and Sugita et al. [8] reported that 50% replacement of aggregates by the FNS exhibited better durability properties as compared to the control specimens. The study evaluated the permeability, carbonation and drying shrinkage properties of concrete. Though slags produced in different smelters may appear similar physically, their chemical compositions can vary significantly depending on the source of the ore and the manufacturing process. It is also essential to investigate the potential of

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http://dx.doi.org/10.1016/j.conbuildmat.2016.06.144

alkali-silica reaction (ASR) of an aggregate. This is because certain aggregates can cause expansion due to ASR depending on their chemical compositions. Deleterious ASR may result in large expansion causing concrete structures to crack.

Stanton [9] identified that concrete structure can suffer from the deleterious expansion due to ASR. Cole et al. [10] reported surface cracking and expansion of old dams in Australia suffering from ASR. The mechanism of ASR is complicated and there are differences in opinions among the researchers. According to Lee [11], the reactive silica in aggregate is depolymerised in a highly alkaline condition. Hydrolysis of the silica takes place in the presence of sodium and potassium hydroxides and an alkali silicate gel is formed. This gel absorbs a large quantity of water from the surroundings resulting in an expansion of its volume. This expansion of the alkali-silica gel causes micro-cracking inside the aggregate as well as at the interface between aggregate and cement paste [12]. Usually, aggregates with amorphous structure, lattice defects and large surface area are more susceptible to ASR expansion [13]. The crystalline structure of silica is stable and the amorphous silica is considered to be reactive [14]. The presence of calcium is also regarded as an important factor in ASR expansion. The calcium content of the binder has a significant influence on the expansion due to ASR. The ASR expansion increases with the rise of calcium content in the binder [15]. Chatterji [16] showed that the expansion could be reduced by leaching out of the $Ca(OH)_2$ from concrete. It was also observed that the reactive silica did not cause any harmful expansion if there was no calcium available in the binder [17]. The presence of a higher percentage of calcite was also found to cause greater expansion of concrete [18]. Since ASR is a slow process, accelerated tests of mortar or concrete specimens are usually conducted to assess the alkali reactivity of an aggregate. Such accelerated tests are recommended in testing Standards and Codes. A correlation between the accelerated ASR test results and the actual ASR in concrete structures was shown by Carse and Dux [19].

Use of supplementary cementitious materials (SCM) such as fly ash, blast-furnace slag and silica fume is usually considered as a mitigating measure against the ASR expansion of concrete. However, the effectiveness of an SCM in reducing the ASR depends on the type and dosage of the SCM, and the type of the reactive aggregate. The effectiveness of an SCM depends on its alkali content, with higher alkali content exhibiting higher expansion [20]. Shehata and Thomas [21], and Shafaatian et al. [22] showed that expansion of mortar specimens containing reactive aggregates was reduced by the use of fly ash as a partial replacement of cement. Fly ash can significantly reduce the alkalinity of pore solution resulting in a reduction of the ASR [23]. The addition of reactive aggregates in powder form with the binder can also reduce the ASR as the powder acts as a pozzolana and reduces the alkalinity of the pore solution [24]. Although ASR is being studied for the past few decades, the exact chemical reactions that cause the expansion and cracking of concrete remains in shadow.

The ASR expansion of FNS fine aggregate produced in the smelters of New Caledonia has been investigated in this study. This particular FNS is extracted by pyro-metallurgy from garnierite ore and cooled down by sea water. It has different chemical compositions than the FNS aggregates used in the studies available in the literature. Our other study [25] investigates the utilisation of the ground FNS as a partial replacement of cement. Petrographic analysis of the FNS showed the existence of glass containing amorphous and cryptocrystalline silica that might cause ASR when used as aggregates in concrete. Therefore, a study on the potential ASR expansion of the aggregate is essential for its development as an alternative fine aggregate for concrete. Accelerated ASR tests were conducted on mortar specimens containing different percentages of FNS as a replacement of natural sand. Fly ash and GGBFS were used as partial replacements of cement and their effectiveness on the ASR expansion were studied. Microstructural analysis using scanning electron micrographs (SEM) and energy-dispersive X-ray spectroscopy (EDS) was performed to obtain an insight into the ASR products and the resulting expansions observed for the mortar mixtures containing different percentages of the FNS and SCMs.

2. Experimental work

2.1. Materials

The materials used in this study were ordinary Portland cement (OPC), FNS, class F fly ash and GGBFS. The chemical compositions of these materials are given in Table 1. It can be seen that the main components of the FNS were SiO_2, MgO and Fe_2O_3. The CaO content of the fly ash was very low (0.6%) as compared to that of GGBFS (41.2%). The SiO_2 content of the fly ash (76.4%) was much higher than that of GGBFS (32.5%). Furthermore, Na_2O content was less in fly ash (0.19%) than in OPC (0.29%) and GGBFS (0.27%). Fig. 1 shows a comparison between the physical appearances of the FNS and natural sand. It can be seen that FNS aggregates comprised of angular particles of varying sizes, whereas, natural sand is spherical and of much more uniform size. Physical properties of the fine aggregates are given in Table 2. The fineness modulus of the FNS was higher than that of the natural sand.

The grain size distributions of the natural sand, FNS and their combinations are shown in Fig. 2. The upper and lower limits of the grading requirements recommended by the Australian Standard AS 2758.1 [26] are also plotted in this figure. It can be seen that the particle size distributions for all the combinations are within the recommended limits of the AS 2758.1, except for 100% FNS, for which the distribution is slightly beyond the lower limit between 300 μm and 1.8 mm sizes. It is also evidenced that the grading curve becomes more smooth and continuous when the FNS and natural sand are mixed together. The most well-graded particle size distribution was obtained for the combination of 50% FNS with 50% natural sand.

2.2. Specimens and test methods

Petrography and expansion tests are two most common tests used for identification of the alkali reactivity of aggregates. However, petrography test has the limitation of its efficiency in identifying the fine-grained reactive silica [27]. Accelerated mortar bar test (AMBT) was performed in this study, as it has been well accepted as a quick and efficient test to determine the alkali reactivity of fine aggregates. Since the aggregates slow reactivity might not come into reaction within a short period of 21 days, the test can be continued for a longer period of time [28]. Therefore, the test was extended up to 64 days in this study. The tests were conducted in accordance with the AS 1141.60.1 Standard [29]. The mortar bars were cast from mixtures with a water to binder ratio of 0.47 and binder to the fine aggregate ratio of 1:2.25, as recommended in the Standard. The test specimens were made from mortar mixtures with FNS replacing natural sand by 25%, 50%, 75% and 100%. Fly ash and GGBFS were used as replacements of cement by 30% in order to study their effectiveness on mitigation of the ASR of FNS. A 30% cement replacement was selected as this percentage is considered to give a substantial reduction in the CO_2 emission with a reasonable reduction in the strength of concrete [30]. The mixture proportions of the mortars are given in Table 3. The binder of the mixtures of Series A was 100% OPC and those of Series B and C had 30% fly ash and 30% GGBFS respectively.

Table 1
Chemical compositions and loss on ignition (LOI) of OPC, FNS, fly ash and GGBFS (mass %).

Material	OPC	FNS	Fly ash	GGBFS
SiO_2	20.29	52.52	76.34	32.45
Al_2O_3	5.48	2.33	14.72	13.56
Fe_2O_3	2.85	10.80	3.69	0.82
MgO	1.24	33.16	0.54	5.10
SO_3	2.49	0.06	0.11	3.20
CaO	63.11	0.27	0.60	41.22
Na_2O	0.29	0.12	0.19	0.27
K_2O	0.45	0.04	0.96	0.35
Cr_2O_3	0.02	–	–	–
P_2O_5	0.17	0.01	0.10	0.03
SrO	0.05	–	–	–
TiO_2	0.27	0.04	0.61	0.49
Mn_2O_3	0.08	0.49	0.07	0.25
ZnO	0.04	–	–	–
LOI[a]	3.39	0.01	0.53	1.11

[a] Loss of ignition.