Value added utilization of by-product electric furnace ferronickel slag as construction materials: A review

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Abstract

This paper reviews the potential use of electric furnace ferronickel slag (FNS) as a fine aggregate and binder in Portland cement and geopolymer concretes. It has been reported that the use of FNS as a fine aggregate can improve the strength and durability properties of concrete. Use of some FNS aggregates containing reactive silica may potentially cause alkali-silica reaction (ASR) in Portland cement concrete. However, the inclusion of supplementary cementitious materials (SCM) such as fly ash and blast furnace slag as partial cement replacement can effectively mitigate the ASR expansion. When finely ground FNS is used with cement, it shows pozzolanic reaction, which is similar to that of other common SCMs such as fly ash. Furthermore, 20% FNS powder blended geopolymer showed greater strength and durability properties as compared to 100% fly ash based geopolymers. The utilization of raw FNS in pavement construction is reported as a useful alternative to natural aggregate. Therefore, the use of by-product FNS in construction industry will be a valuable step to help conservation of natural resources and add sustainability to infrastructures development. This paper presents a comprehensive review of the available results on the effects of FNS in concrete as aggregate and binder, and provides some recommendations for future research in this field.

Keywords: Ferronickel slag; fine aggregate; supplementary cementitious binder; concrete; geopolymers.

1. Introduction

Concrete is the second most consumed material in the world and the demand of concrete is increasing day by day. As a result, about 7.5 billion cubic meters of concrete is produced every year for construction purposes (USGS, 2016). Concrete usage has an annual growth rate of 6% (Ghods et al., 2017). Generally, a significant part of concrete's volume is occupied by fine aggregate, which plays an essential role in the properties of concrete such as workability, strength and durability. River sand has been used extensively as natural fine aggregate due to its beneficial effects and high availability in many parts of the world. However, excessive and unplanned sand dredging from rivers can cause severe disturbance to the aquatic ecosystem and potentially increase the failure risk of hydraulic structures (Preciso et al., 2012; Liu et al., 1991; Padmalal et al., 2008; Davis et al., 2000). As a result, uses of various alternatives to river sand are explored and used in many parts of the world. Some possible alternative fine aggregates are manufactured sand (M Sand), offshore sand, slag sand, bottom ash, copper slag sand and quarry dust (Masterbuilder, 2014).

Similarly, the use of various industrial by-products as a supplementary cementing material (SCM) has attracted keen interest in the construction industry. Among different SCMs, fly ash, blast furnace slag and steel slag are the most popular and have been studied extensively during the last few decades. The application of fly ash and blast furnace slag as SCM can improve the durability properties of concrete significantly by pozzolanic reaction (Achal et al., 2011; Berndt et al., 2009; Lee et al., 2006; Wang et al., 2008a; Wang et al., 2008b; Yeau et al., 2005). However, the binder occupies only a small volume fraction of concrete which is about 12-16%. Besides, grinding of these by-products is energy intensive. Therefore, researchers have been trying to use industrial by-products as aggregate as this needs little or no processing of the raw by-product. It has been reported that the utilization of coal bottom ash, coal fly ash, steel slag, blast furnace slag and plastic wastes as a partial replacement of sand in concrete exhibits satisfactory strength and durability performance. In addition, the application of high density industrial slag as an aggregate improves the strength properties of concrete (Aggarwal et al., 2007; Andrade et al., 2009; Pofale et al., 2010; Yüksel et al., 2007; Ismail et al., 2008). Higher percentages (50%) of sand replacement by steel slag also improved the strength properties of concrete (Qasrawi et al., 2009). Furthermore, production of self-healing concrete using carbonated steel slag aggregate has been reported in literature (Pang et al., 2016). Steel slag aggregate is not only applicable in concrete production but also can be utilized in road construction, wastewater or gas treatment and as a fertiliser in agriculture production (Yi et al., 2012). On the other hand, the application of bottom ash as a partial replacement of sand reduces the strength properties of concrete due to the low density of the bottom ash than sand; however, it improves the fresh properties and the durability properties including permeability, wetting-drying cycles and freezing-thawing resistance of concrete (Aggarwal et al., 2007; Andrade et al., 2009; Yüksel et al., 2007). Similarly, the inclusion of recycled plastic as fine aggregate reduces the strength of concrete (Ismail et al., 2008). However, the application of fly ash as a partial replacement of sand improves the strength properties of concrete (Pofale et al., 2010).

Recent studies show that, there is a potential to utilize electric furnace ferronickel slags (FNS) as construction materials. FNS is produced as a by-product in nickel smelters. Nickel is produced by smelting of nickel ores in different countries. The nickel ore is smelted in an electric arc furnace at temperatures of about 1500 to 1600 ^{o}C and the by-product molten slag is cooled by water or air (Choi & Choi, 2015). There are two main types of ores that are commonly used for extraction nickel, one is sulphide ore and the other is garnierite ores. The garnierite ores are mostly used for world nickel production (Dalvi et al., 2004). Garnierite ores generally contain very low percentages of Nickle such as 1% to 2%. As a result, a significant quantity of slag is generated during the production of nickel (Coey et al., 1999; Saha & Sarker 2017a; Saha & Sarker 2017b). It is estimated that approximately 12 to 14 tonnes of nickel slag is produced in the production of one tonne nickel alloy (Saha & Sarker, 2016). The physical properties of FNS are suitable to use as an alternative to sand in concrete. It has low water absorption and high density and hardness (JSCE, 2016; Sakoi et al., 2013). Due to the presence of a significant amount of amorphous silica, finely ground FNS has shown reactivity when used with Portland cement or with an alkali in geopolymers (Maragkos et al., 2009). FNS aggregate has been successfully used in various construction works where high-density concrete is the primary requirement such as wave-dissipating blocks, cable anchors, rockfill dams and gravity retaining walls (Choi & Choi, 2015). Therefore, this paper reviews the current state of using FNS as a sustainable construction material.

2. Properties of FNS

FNS can be classified into two different classes depending on the cooling method of the molten slag, known as air-cooled slag and water-cooled slag. The air-cooled slag is slowly cooled by the air in an open pit whereas water cooled slag is rapidly cooled by using water as shown in **Fig. 1** (Choi & Choi, 2015). As seen from **Fig. 1,** air-cooled nickel slag is light grey in colour and brittle in nature. As a result, it can be crushed very easily (Sato et al., 2011). On the other hand, water-cooled FNS is dark in colour, spherical in size with hollow structure and slippery in nature (JMIA, 1991).

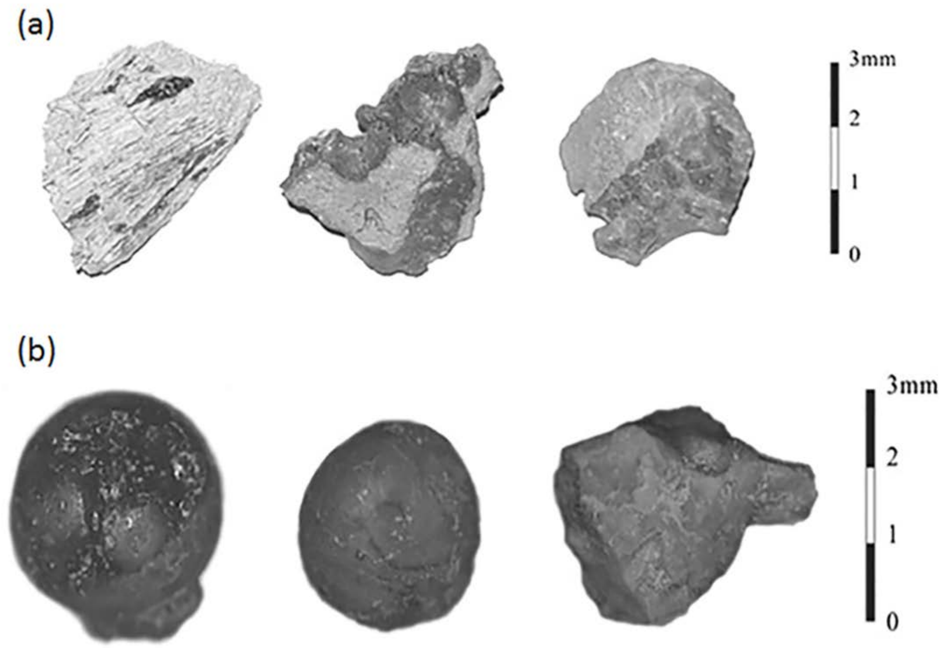

Fig. 1. FNS (a) air-cooled and (b) water-cooled [Choi & Choi, 2015].

Table 1 Chemical compositions of nickel slag (mass %).

Material	FNS-A [Sato et al., 2011]	FNS-W [Sato et al., 2011]	FNS-W [Komnitsas et al., 2007; 2009; 2013]	FNS-W [Maragkos et al., 2009]	FNS-W [Lemonis et al., 2015]	FNS-A [Choi & Choi, 2015]	FNS-W [Choi & Choi, 2015]	FNS-W [Saha & Sarker, 2016;2017a, 2017b]	FNS [Fidancevska et al., 2003]
SiO_2	55.6	52.7	32.74	40.29	41.18	62.80	58.1	53.29	19.8
Al_2O_3	-	-	8.32	10.11	5.98	1.95	2.29	2.67	12.25
Fe_2O_3	7.57	6.70	43.83	37.69	40.02	7.13	11.10	11.9	17.62
MgO	27.8	34.0	2.76	5.43	7.79	24.70	26.50	31.6	9.66
SO_3	0.06	0.04	0.18	-	0.64	0.03	0.04	-	0.87
CaO	5.18	2.30	3.73	3.65	4.12	2.07	0.29	0.42	4.48
Na_2O	-	-	-	-	0.09	0.13	0.09	0.11	0.33
K_2O	-	-	-	-	0.37	0.02	0.06	-	0.04
Cr_2O_3	-	-	3.07	2.58	2.75	-	-	1.08	2.48
NiO	-	-	0.1	0.09	0.13	-	-	0.1	0.30
Co_3O_4	-	-	0.02	-	0.02	-	-	0.01	0.14
LOI[a]	-	-	-	-	-	0.94	1.24	0.83	-
Type of ores	-	-	laterites	laterites	laterites	-	-	garnierite	
Source	Japan	Japan	LARCO, Greece	LARCO, Greece	LARCO, Greece	SNNC, South Korea	SNNC, South Korea	SLN New Caledonia	-

[a] loss of ignition; FNS-A: air-cooled FNS slag; FNS-W: water cooled FNS slag

The chemical compositions of FNS obtained from different sources are presented in **Table 1.** The chemical composition of FNS primarily consists of SiO_2, MgO, and Fe_2O_3 (Saha & Sarker, 2016). This material consists of amorphous silica as well as crystalline minerals such as enstatite, forsterite and dropsied. The chemical compositions of this slag can be different depending on its source, processing and cooling method (Lemonis et al., 2015; Maragkos et al., 2009; Komnitsas et al., 2007). Generally, nickel slag generated from laterite ore contains a high Fe_2O_3 and low MgO whereas, that from garnierite ore contains low Fe_2O_3 and high MgO. It is also noticeable that the air-cooled FNS consists of high SiO_2, low MgO and high CaO compared to the water-cooled FNS (Choi & Choi, 2015; Sato et al., 2011). The physical properties of FNS are presented in **Table 2.** It can be seen from the table that generally air-cooled FNS shows high density and high water absorption than the water-cooled FNS (Choi & Choi, 2015; Togawa et al., 1996). In contrast, Sato et al. (2011) reported higher density of air cooled FNS than water-cooled FNS. Therefore, properties of FNS from a new source have to be determined as its properties may vary depending on the source and the processing method.

Table 2 Physical Properties of FNS aggregate

Physical properties	FNS-A [Choi & Choi, 2015]	FNS-W [Choi & Choi, 2015]	FNS-W [Saha & Sarker, 2017c]	FNS-A [Sato et al., 2011]	FNS-W [Sato et al., 2011]	FNS-W [Sakoi et al., 2013]	FNS-W [Shoya et al., 1999]	FNS-A [Togawa et al., 1996]	FNS-W [Togawa et al., 1996]
Specific gravity (g/cm^3)	3.11	2.81	2.85	2.93	3.08	2.84	2.97	3.02	2.84
Water absorption (%)	1.64	0.71	0.42	1.87	0.13	1.98	1.2	2.20	0.73

3. Performance of FNS as aggregate in concrete

3.1 Fresh properties

3.1.1 Workability

Workability is defined as the ease of transportation, placement, compaction and finishing of the concrete mixture. Slump test is the most recognized test to measure the workability of concrete. Workability of concrete primarily depends on water-cement ratio, binder compositions, and aggregates. For example, the concrete mixtures with a constant water-cement ratio, the slump variation depends on the aggregate properties such as gradation, particle size, particle density and angularity. A well-graded aggregate exhibits higher workability than a poorly graded aggregate. Besides, larger particles require less water to saturate the surface. Hence, the workability increases with the increase of aggregate particle size for the same water content. Moreover, workability of concrete reduces with the increment of the angularity and the interlocking friction of aggregate (Santamarina, 2008; Hu & Wang, 2005). The variation of flow value of concrete using FNS aggregate is shown in **Fig. 2**. Saha and Sarker (2017c, 2017d) determined workability of cement mortar containing FNS fine aggregate using the flow test as per AS 1012.3.1 (2014). It was found that flow of mortar gradually increased up to 50% replacement of sand by FNS; however, flow then reduced for the use of 100% FNS as fine aggregate. The authors explained that high angularity and large size of FNS aggregate caused internal friction, which reduced the flow of mortar for FNS content of more than 50%. In contrast, Shoya et al. (1999) found that the workability of concrete reduced marginally with the increase of FNS. The authors conducted both slump flow test and V-funnel flow test to determine the workability of concrete and noticed similar results. The authors described that, due to the poor gradation as well as high angularity of FNS aggregate, it showed higher internal friction between the particles. As a result, it reduced workability of concrete. Moreover, a technical report by Japan Mining Industry Association (JMIA, 1991) indicated that the slump value of FNS aggregate mixed concrete is identical when compared with the conventional aggregate concrete.

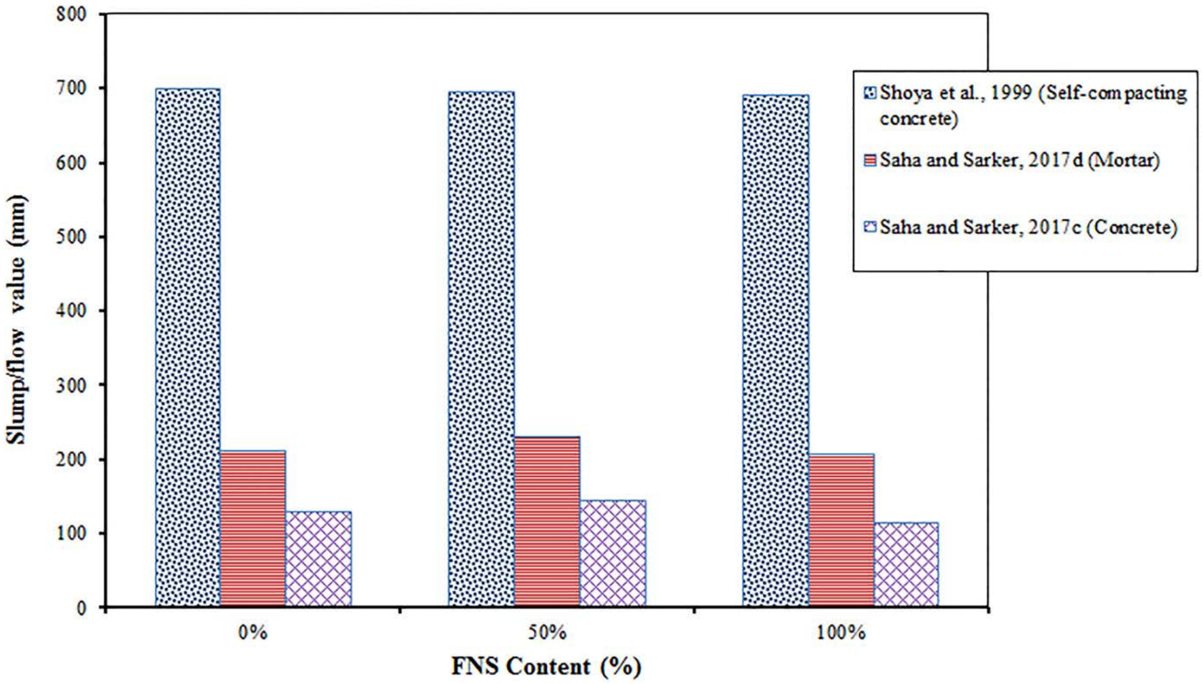

Fig. 2. Workability of FNS concrete/mortar.

3.1.2 Bleeding

The accumulation of water on the surface of concrete after compaction and finishing is known as bleeding. Segregation of aggregates is the primary reason behind bleeding of freshly mixed concrete. Usually, high density aggregates exhibit higher bleeding. On the other hand, water has the lowest density among all materials in a concrete mix. As a result, water can easily get separated from the other constituents of a concrete mixture. This phenomenon also depends on other factors such as poor mixing of concrete, excess workability and excessive vibration. FNS aggregate has a higher density than natural sand. Therefore, bleeding of concrete using FNS aggregate is of particular interest. The bleeding properties of concrete using FNS aggregate are shown in **Fig. 3**. According to the bleeding tests of Shoya et al. (1999) as per JIS A 1123 (1997), FNS aggregate concrete showed identical bleeding as compared to conventional aggregate concrete, and the magnitude of bleeding was below 0.003 (cm^3/cm^2). However, Sato et al. (2011) reported that bleeding of FNS aggregate concrete increased with the increase of FNS content in the mixture. The authors suggested that this increase of bleeding was due to the higher unit weight of FNS aggregate than sand. Thus, consolidation of aggregate particles in a freshly mixed concrete led to increased bleeding. In their study, the amount of bleeding for conventional concrete and 100% FNS concrete were 0.28 and 0.33 (cm^3/cm^2), respectively. Furthermore, Togawa et al. (1996) used furnace slag, silica fume and limestone powder as a SCM in FNS concrete to reduce bleeding.

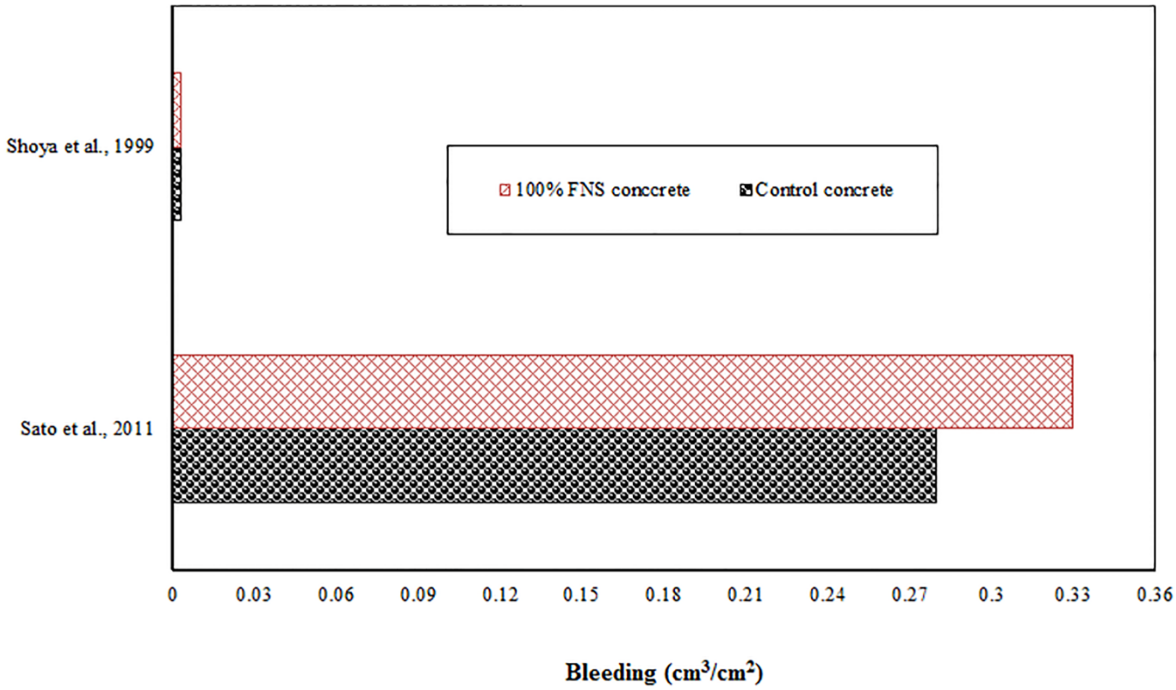

Fig. 3. Bleeding of FNS concrete.

3.2. Hardened properties

3.2.1 Compressive strength

Compressive strength is the most commonly used hardened properties of concrete. Although aggregate has a significant role on the strength properties of concrete, it depends primarily on binder composition and water-cement ratio. The compressive strength test results of FNS aggregate concrete collected from various published works are presented in **Fig. 4**. Togawa et al. (1996) found that compressive strength is slightly increased for up to 50% replacement of sand by FNS; however, there is a reduction in compressive strength at 100% replacement level. After that, Shoya et al. (1999) showed a similar trend of strength of concrete using FNS aggregate. It can be seen that the compressive strength for control, 50% FNS, and 100% FNS concretes were 41.2, 45.7 and 41.7 MPa, respectively. The FNS aggregates used in their study had a higher unit weight, fineness modulus and hardness compared to natural sand. As a result, it improved the particle packing when used in concrete.

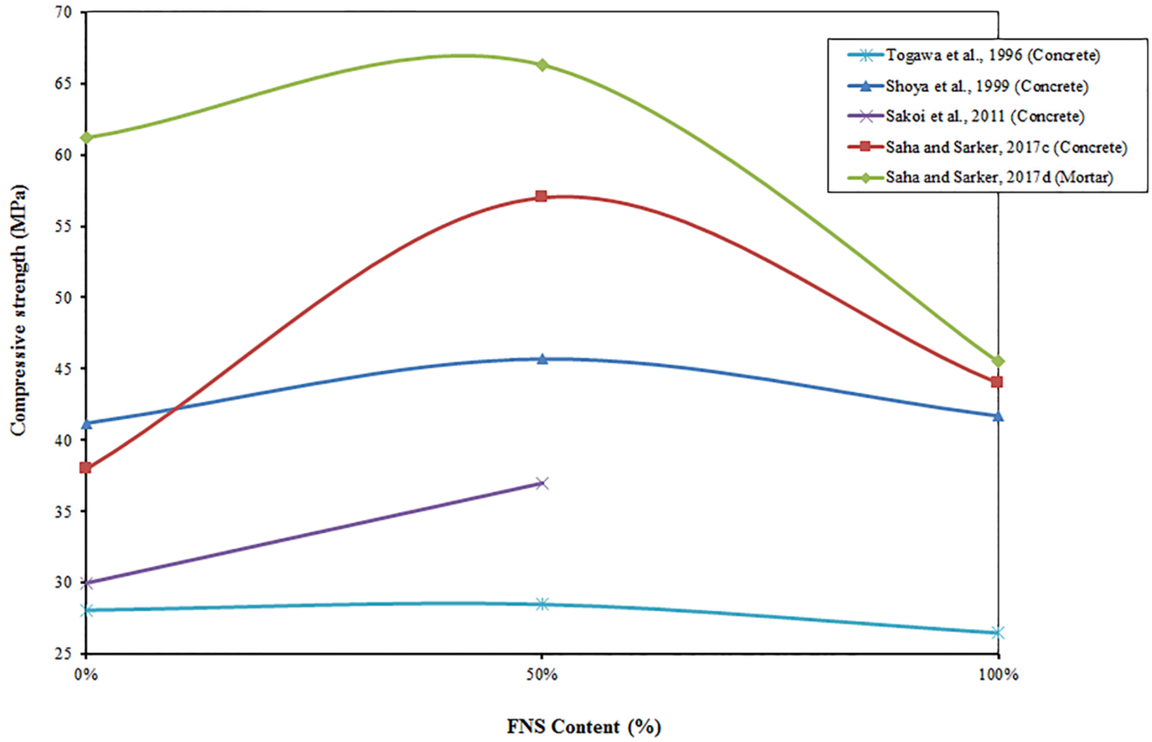

Fig. 4. Compressive strength of FNS concrete.

Therefore, 50% replacement of sand by FNS aggregates showed better strength performance in concrete, whereas 100% FNS aggregate reduced the compressive strength of concrete due to the poor gradation of slag aggregates. In addition, full replacement of sand by FNS increased the voids ratio due to high fineness modulus of the FNS aggregates. Similarly, Sakoi et al. (2013) reported that 50% FNS aggregate showed higher compressive than the normal concrete. Recently, Saha and Sarker (2017c, 2017d) tested both concrete and mortar according to AS 1012.9 (2014) and ASTM C109 (2016), and observed similar phenomena. The FNS used in these studies had higher density and larger particle size compared to sand. Therefore, the compressive strength of concrete increased as a partial replacement of sand by FNS. Higher density and better aggregate gradation of FNS aggregates lead to the increase of compressive strength. On the other hand, full replacement of sand by FNS exhibited lower compressive strength than the control concrete due to the larger size and angularity of the FNS which increased the internal voids.

3.2.2 Modulus of elasticity

The modulus of elasticity is a significant property of concrete. This value represents the stiffness and rigidity of concrete material. Modulus of elasticity of concrete is often expressed as a function of its compressive strength. However, modulus of elasticity also depends on the aggregate properties. The modulus of elasticity test results from previous research works are presented in **Fig. 5**. Sakoi et al. (2013) and Shoya et al. (1999) pointed out that modulus of elasticity of concrete increased with the increase of FNS aggregate content. It can be seen that modulus of elasticity increased from 28 to 32 GPa up to 50% replacement of sand by FNS (Sakoi et al., 2013). In a similar study, Saha and Sarker (2017c) reported that modulus of elasticity increased with the partial replacement of sand by FNS; however, it then decreased at the full replacement of sand by FNS. Therefore, the higher modulus of elasticity of concrete is mainly attributed to the presence of the high density FNS aggregates, which improves the density of concrete by increasing the stiffness and rigidity of concrete samples.

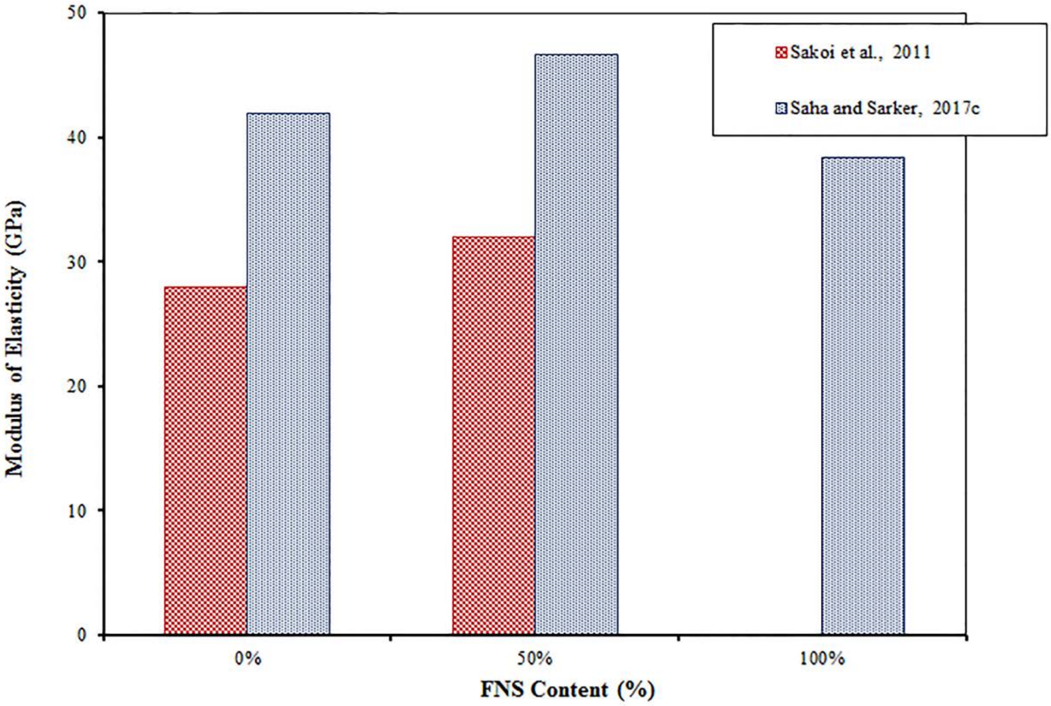

Fig. 5. Modulus of elasticity of FNS concrete.

3.2.3 Flexural and Tensile strengths

Generally, concrete is weak in tension. Therefore, the reinforcement came into practice to improve the tensile strength capacity of concrete. Usually, Steel bars in concrete structures carry the majority of the tensile stress. Furthermore, concrete sections without reinforcement can withstand a small amount of tensile stress due to lateral forces and internal stress. This property depends on the compressive strength of concrete as well as the properties of aggregates. Higher angularity and roughness characteristics of aggregate have a positive effect on tensile strength of concrete due to improved friction and interlocking between the binder matrix and aggregate surface (Molugaram et al., 2014; Wu et al., 2001). At the beginning, Shoya et al. (1999) reported that tensile strength of FNS aggregate concrete is identical to that of conventional concrete. Recent test results according to AS 1012.10 (2014) in a study by Saha and Sarker (2017c) are shown in Fig.6. It can be seen that, tensile strength of 50% FNS aggregate concrete was higher than the control concrete. However, 100% FNS aggregate concrete showed lower tensile strength than the control concrete. The splitting tensile strengths were 4.33, 4.73 and 3.94 MPa for the control, 50% FNS and 100% FNS concrete, respectively.

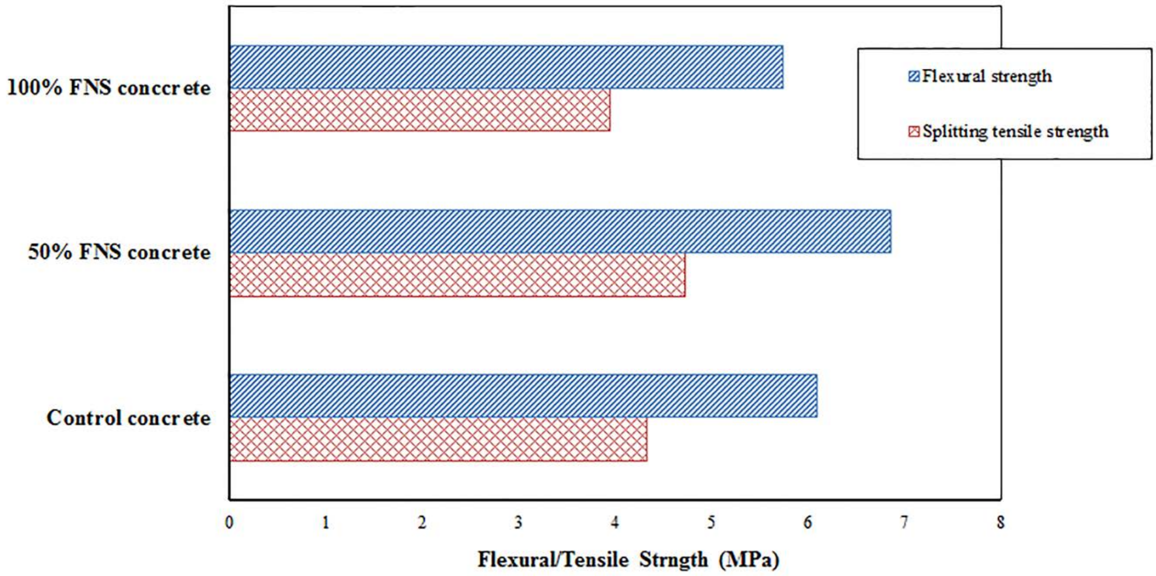

Fig. 6. Flexural and tensile strength of FNS concrete [Saha & Sarker, 2017c].

FNS concrete also showed similar flexural behaviour, as shown in **Fig. 6**. Concrete containing 50% FNS aggregate showed higher flexural strength compared to control concrete; however, strength slightly declined in the 100% FNS concrete (Saha & Sarker, 2017c). Therefore, the inclusion of 50% FNS in fine aggregate improved the tensile and flexural strengths of concrete. However, full replacement sand by FNS resulted in a poor particle size distribution and higher angularity of FNS aggregates that increased the internal voids of the mixture (Saha & Sarker, 2017c) to result in the decline of strengths.

3.3. Durability properties

3.3.1 Alkali-silica reaction

Alkali-silica reaction (ASR) is a complex phenomenon in concrete. Although it has been studied extensively during the last few decades, still there is a debate among scientists about its mechanism. Generally, ASR takes place between the reactive silica of aggregates and the alkaline solutions in micro pores of concrete. The primary sources of alkali is the binder matrix. The silica present in aggregates in the form of quartz is chemically inert. However, poorly crystalline silica has an affinity to react with alkali and generate amorphous hydrous silica (Swamy 2002; Ichikawa and Miura 2007). In addition, researchers also investigated the percentage of amorphous silica in reactive aggregates from various sources and the corresponding expansions by accelerated mortar bar test (AMBT) and concrete prism test (CPT) (Grattan-Bellew et al., 2010; Saha and Sarker 2016; Shehata and Thomas 2000; Shafaatian et al., 2013; Moser et al., 2010). The authors noticed that there is an inherent relationship between the expansion of the samples and the percentage of amorphous silica in aggregate. This relationship is that expansion increases with the increase of the percentage of amorphous silica in aggregates. However, the relationship may vary due to the variations in aggregate source, aggregate type and test type. Therefore, the percentage of amorphous silica content in aggregate acts as a governing factor in ASR mechanism and sometimes small proportion of amorphous silica in aggregate can cause expansion of concrete and mortar.

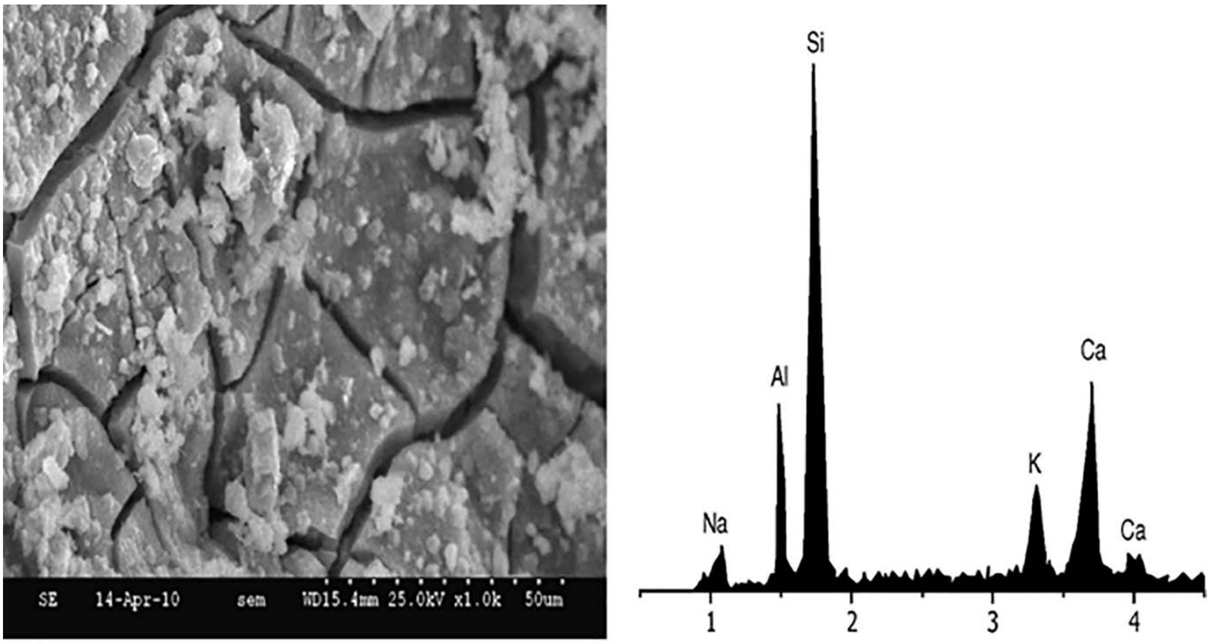

Fig. 7. Microstructure of ASR affected FNS specimen [Choi & Choi, 2015].

At first, Tomosawa et al. (1997) studied ASR of concrete using FNS aggregates. The authors concluded that the application of low alkali cement and addition of fly ash or ground granulated blast furnace slag are effective measures to suppress the reactivity of FNS aggregates. Then, Choi & Choi (2015) reported that the water-cooled FNS aggregates showed excessive ASR expansion, whereas air cooled FNS aggregates exhibited small expansion as in control specimens. According to their tests as per ASTM C1260 (2014), the ASR expansion of water-cooled FNS mortar was within a range of 0.6 to 0.8% after 28 days; however, both the reference mortar and air-cooled FNS aggregate mortar showed approximately 0.05% expansion. The authors indicated two primary reasons behind the ASR of water-cooled FNS aggregates. Firstly, the rapid cooling of FNS by water leads to formation of microcracks on the surface of FNS particles. As a result, the dissolved silica and water can be transported through the cracks. Secondly, the rapid cooling leads to poorly crystalline and non-crystalline silica in FNS aggregates. The microstructure of ASR affected specimens are given in **Figs. 7** and **8** (Choi & Choi, 2015; Saha & Sarker, 2016). It can be seen that the aggregate surface is affected by extensive cracking due to the formation of ASR gel and the chemical composition of this gel confirms the presence of high amount of silica, calcium, alumina and alkali. Recently, Saha and Sarker (2016) pointed out the formation of ettringite in the cracks of ASR affected FNS samples.

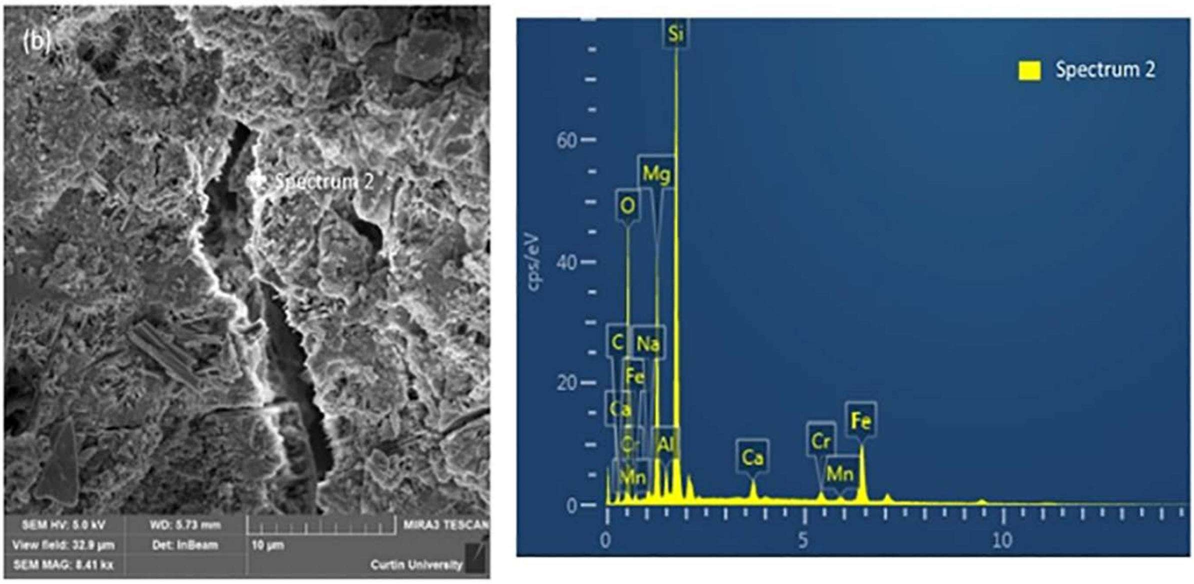

Fig. 8. Microstructure of ASR affected FNS specimen [Saha & Sarker, 2016].

Initially, the amorphous silica present in the FNS reacts with the alkali, calcium and alumina and generates secondary ettringite, which absorbs moisture. Then, it expands with time and causes significant cracking of the samples (Saha & Sarker, 2016). It is noticeable that the FNS mortar bars with no fly ash showed expansion of approximately 0.8%; however, with the addition of 5, 10, 20, and 30% fly ash as SCM, the expansions were 0.70, 0.50, 0.15 and 0.05%, respectively, as shown in **Fig. 9** (Choi & Choi, 2015). Furthermore, 30% replacement of cement by fly ash resulted an identical expansion to the reference mortar bar. Besides, ground granulated blast furnace slag also can reduce the expansion due to ASR, but a large volume of replacement is required. It has been reported that 60% replacement of cement by blast furnace slag kept the expansion below the acceptable limit. The expansions of mortar bars for using 15, 30, 45 and 60% ground granulated blast furnace slag as a SCM were 0.70, 0.55, 0.40 and 0.10%, respectively (Choi & Choi, 2015).

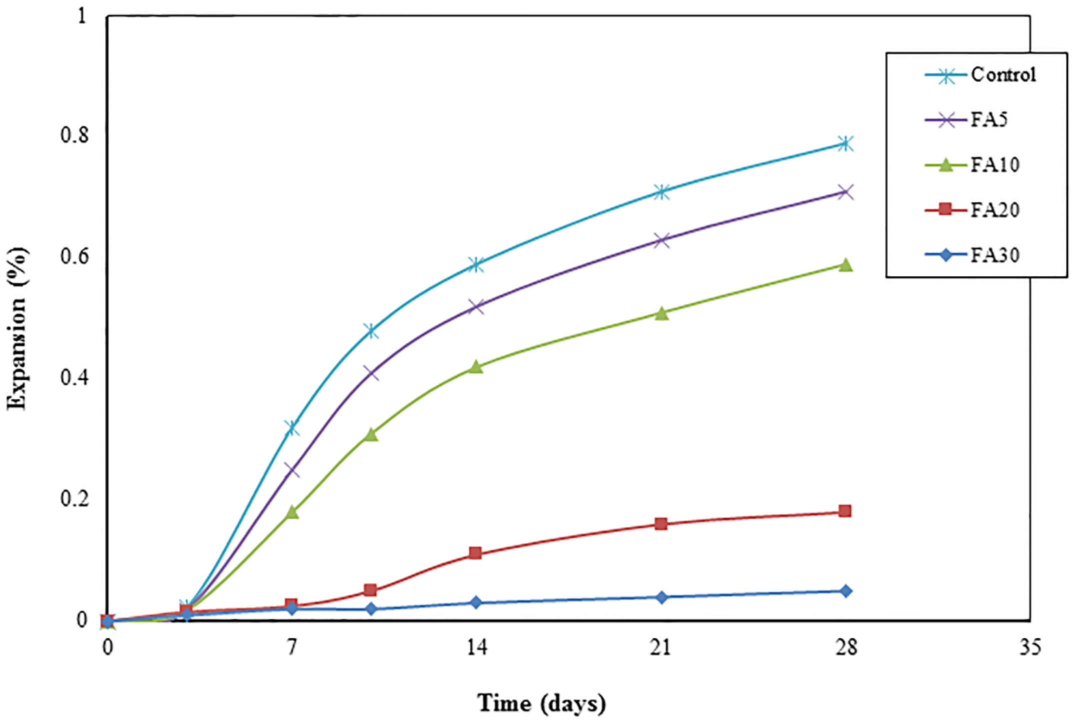

Fig. 9. Influence of class F fly ash in FNS samples as an ASR mitigation technique [Choi & Choi, 2015].

The mechanism of fly ash to reduce the ASR is mainly dependent on four factors. Firstly, the inclusion of fly ash can reduce the hydroxyl ion in pore solution (Shehata et al., 1999; Shi, 2004). Secondly, it can minimize the pore size and the thickness of the transition zone between cement paste and aggregates (Kuroda et al., 2000; Mehata & Monteiro, 2006). Thirdly, it can reduce the aggregate dissolution rate (Shafaatian et al., 2013). Lastly, fly ash can reduce the percentage of portlandite from the binder, which acts as a buffer to maintain the pH of pore solution (Hou et al., 2004). **Fig. 10**. Shows the microstructure of a mortar specimen containing FNS aggregate and fly ash as an SCM after the accelerated mortar bar test (AMBT) (Saha & Sarker, 2016). It confirms the formation of primary ettringite with a high calcium to silica ratio (Ca/Si) due to the hydration of cement and the pozzolanic reaction of fly ash that has the properties of low viscosity and swelling pressure (Vayghan et al., 2016). Therefore, the use of fly ash as an SCM is considered an adequate measure to mitigate the potential ASR of FNS fine aggregate.

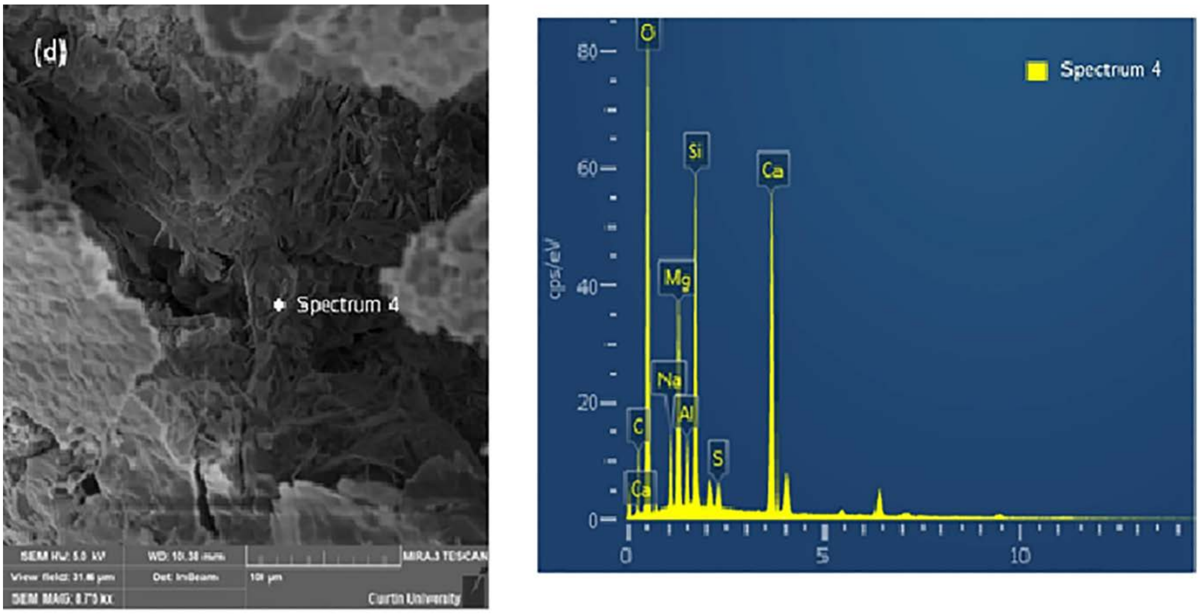

Fig. 10. Microstructure of FNS Samples with 30% fly ash under AMBT [Saha & Sarker, 2016].

3.3.2 Freezing and thawing resistance

Resistance to freezing and thawing cycles evaluates the soundness of concrete in exposures to adverse weather conditions. Concrete samples are exposed to the repeated cycles of freezing and thawing in this test. Usually, the samples are exposed to -18 ^{o}C for freezing and 4 ^{o}C for thawing in a cyclic order within 2 to 5 hours. The freezing and thawing resistance test results are found in various published are presented in **Table 3**.

Table 3 Freeze and thaw resistance of FNS concrete.

FNS (%)	[1]RDME (%) 300 Cycles [Sakoi et al., 2013]	RDME (%) 300 Cycles [Sato et al., 2011]	[2]DF (%) 300 Cycles [Shoya et al., 1999]
0	85	85	71.6
25	-	82	-
50	82	-	84.7
100	-	80	86.4

[1] Relative Dynamic Modulus of Elasticity; [2] Durability Factor

It can be seen that two different kinds of assessments are adopted in determination of the resistance against freeze-thaw exposures, namely dynamic modulus of elasticity and durability factor. In tests according to JIS A 1148 (2010), Sakoi et al. (2013) found that FNS samples showed almost similar relative dynamic modulus of elasticity after freeze and thaw cycles when compared to the control specimens. On the other hand, Sato et al. (2011) reported a decreasing trend of relative dynamic modulus of elasticity for FNS samples. Besides, Togawa et al. (1996) suggested that the use of limestone powder can improve the durability characteristics of FNS concrete. Shoya et al. (1999) reported that durability factor of FNS concrete increased as compared to control concrete after the freeze and thaw cycles tested as per ASTM C 666 (1992). From **Table 3,** it can be seen that the durability factor was slightly over 70% for the control specimens, whereas the durability factors of specimens containing 50% and 100% FNS were 85% and 87%, respectively. This increase of durability factor was attributed to the higher density and lower fineness modulus of FNS aggregates than natural sand.

3.3.3 Drying shrinkage

The loss of capillary water from the hardened concrete mix leads to contraction of concrete which is known as drying shrinkage. High drying shrinkage can cause internal cracks and warping as well as external deflection in concrete. Generally, drying shrinkage of concrete depends on cement paste volume, water-cement ratio and water absorption of aggregates. The drying shrinkage test results of FNS aggregate concrete are presented in **Table 4**.

Table 4. Drying shrinkage of FNS concrete.

FNS (%)	Drying shrinkage ($\times 10^{-5}$ strain)	
	[Sakoi et al., 2013]	[Shoya et al., 1999]
0	35	51
50	40	45
100	-	42

Shoya et al. (1999) showed that the use of FNS as aggregate in concrete reduced drying shrinkage slightly as compared to the control concrete. In their tests the drying shrinkage for control, 50% FNS and 100% FNS concrete were 510, 450 and 420 micro strains, respectively. The water content of these specimens were 165, 160 and 155 kg/m^3, respectively. Therefore, FNS aggregate concrete specimens with the lower water-cement ratio resulted in lower drying shrinkage, as expected. However, Sakoi et al. (2013) found that drying shrinkage of FNS concrete was slightly higher than control specimens. High water absorption of FNS aggregates resulted in greater drying shrinkage of these samples since the water cement ratio was kept constant for all the mixes. The drying shrinkage ranged between 350 and 400 micro strains in their study under. Nevertheless, drying shrinkage of the specimens containing FNS aggregate was within the range of values usually observed in concrete using natural sand as fine aggregate.

3.3.4 Air permeability and carbonation

The air permeability test evaluates the pores in concrete and it gives an indication of the ease of transportation of fluids into concrete. Besides, carbonation is the reaction between CO_2 from the surroundings and $Ca(OH)_2$ of binder matrix that forms $CaCO_3$. Since the carbonation process uses $Ca(OH)_2$, it reduces the pH of concrete which may increase the risk of reinforcement corrosion. Shoya et al. (1999) determined air permeability and carbonation of FNS aggregate concrete samples using the method proposed by Nagataki and Ujike (1988). The authors used 490 kPa load-bearing pressure and the water replacement method to determine the amount of air penetrated through the concrete. The authors reported that the air permeability of FNS concrete samples were similar to the control concrete. The coefficient of air permeability ranged between 2.51 $\times 10^{-5}$ and 2.44 $\times 10^{-5}$ m/sec. Furthermore, the carbonation test of FNS concrete gave identical result to that of the control specimen. The neutralised depth of the concrete samples remained between 6.97 and 5.72 mm after 91 days (Shoya et al., 1999).

3.4. Applications in pavement constructions

Different types of industrial slag have been utilised in pavement construction as base and sub-base aggregates or as a cementitious material in recent decades. Significant research work has been carried out on the use of electric arc furnace slag (EAF) both as coarse aggregate and fine aggregate in pavement constructions (ASA, 2002; Behnood & Ameri, 2012; Wu et al., 2007; Ziari et al., 2015; Oluwasola et al., 2015; Oluwasola et al., 2015). As a coarse aggregate, this slag exhibits high skid resistance due to high angularity in surface dressing (Pasetto & Baldo 2006). In addition, the application of EAF as a coarse aggregate provides satisfactory results in asphalt in terms of strength, water sensitivity, stability and deformation (Ameri & Behnood, 2012). Furthermore, Marshall Stability and flow are significantly higher in asphalt using EAF coarse aggregate (Ahmedzade & Sengoz, 2009). Besides, the combination of EAF as a coarse aggregate with limestone as a filler provides satisfactory results. Ziari et al. (2015) reported that replacement of fine aggregate by 50% EAF aggregate in hot mix asphalt showed satisfactory performance by the reduction of air voids and improvement of stiffness. The use of this slag as a fine aggregate improves the mechanical properties such as tensile strength and stability of asphalt (Ameri et al., 2013; Behnood & Ameri, 2012). Moreover, resilient modulus of asphalt improved significantly by the use of slag aggregate which is almost twice as compared to traditional asphalt (Hainin et al., 2012; Hainin et al., 2013; Hainin et al., 2014). However, asphalt with EAF as a fine aggregate shows poor performance in water submergence test (Bagampadde et al., 1999). This is may be due to the presence of significant amount of impurities in industrial slag. Therefore, Emery (1984) suggested to remove the impurities such as lime, refectory and wood from industrial slags before its use in asphalt mixtures as aggregate. The physical properties of EAF and FNS aggregates are relatively similar as both type of aggregate possess high density, low water absorption and angular shaped particles (Saha & Sarker, 2017c; Bagampadde et al., 1999; Ziari et al., 2015). Some researchers investigated the suitability of the FNS aggregates as a fine aggregate in hot mix asphalt (HMA) (Emery et al., 1984; Wang et al., 2011; Wang & Thompson, 2011; Krayushkina et al., 2012).

Emery (1984) initially adopted nickel slag aggregate as a base material in mining road and found that nickel slag exhibited satisfactory performance in adverse traffic operating conditions. Wang et al. (2011) conducted accelerated laboratory testing by asphalt pavement analyser in order to evaluate the durability of asphalt using slag aggregate. Furthermore, the authors carried out petrographic examination to identify reactive silica and autoclave testing for evaluation of free lime and free magnesia of the FNS aggregates. According to the test results, the authors concluded that nickel slag is mineralogically, physically and environmentally stable and can be adopted as coarse aggregate and fine aggregate in HMA. Similarly, Wang and Thompson (2011) suggested that air cooled FNS can be used as a suitable alternative to traditional aggregates in the base course and HMA. In addition, Krayushkina et al. (2012) showed that FNS is a suitable alternative for HMA and can be used as a base course in a highway construction. However, research works carried out with FNS aggregate in pavement construction is very limited. Therefore, more research is necessary to carry out in the area of pavement constructions.

4. Performance of ground FNS as binder in concrete

It is well known that production of cement emits a significant amount of CO_2 to the atmosphere. Therefore, researchers have been working since the past few decades on various industrial by-products such as blast furnace slag, fly ash, steel slag, copper slag, sugarcane bagasse ash, ladle furnace slag and basic oxygen furnace slag as SCM during (Das et al., 2007; Shi & Qian, 2000; Loh et al., 2013; Shi et al., 2008; Rodriguez et al., 2009; Carvalho et al., 2017). The utilization of blast furnace slag as a SCM in concrete reduces the heat of hydration and improves the long-term strength and durability properties (Das et al., 2007). Similarly, fly ash blended concrete exhibits high durability properties including resistance to alkali silica reaction; sulphate and acid attacks (Saha & Sarker, 2016; Saha & Sarker 2017c; Shi & Qian, 2000). Besides, copper slag, sugarcane bagasse ash, ladle furnace slag, basic oxygen furnace slag can improve the strength and durability of concrete due to the presence of high amorphous silica and low free lime or magnesia (Loh et al., 2013; Shi et al., 2008; Rodriguez et al., 2009; Carvalho et al., 2017). On the other hand, steel slag consists of excessive free lime, which can cause deleterious volume expansion (Shi & Qian, 2000). Thus, industrial waste containing high amorphous silica and low free CaO or MgO can be used as SCM. The chemical properties of FNS, as presented in Table 1, shows that it usually contains high silica. However, FNS from some sources have very high amount of MgO, which is over 20%. Excessive amount of free magnesia can cause volumetric instability of concrete.

Mo et al. (2005) pointed out that the presence of high MgO in binder reduces shrinkage-cracking in concrete. This MgO leads to an autogenous expansion in later curing ages, as a result, it can compensate the concrete's contraction due to cold weather and shrinkage (Mo et al., 2005). However, the maximum allowable limit of MgO in a SCM is 15% as per AS 3582.2 (2016). It generates Bruucite ($Mg(OH)_2$) by the hydration of MgO, which is expansive in nature. As a result, it can increase the concrete volume by up to 17% and also lead to loss of strength. Rahman et al. (2017) studied the soundness and the strength properties of FNS blended concrete. The authors found that the strength properties were slightly lower due to reduction of lime content. On the other hand, the soundness test results including Le-Chatelier, autoclave and extended heat curing were within the allowable limit in FNS samples. In addition, X-ray diffraction (XRD) analysis traced the presence of MgO in the form of forsterite as presented in **Fig. 11**. The crystalline structure of forsterite is orthorhombic, which is chemically inert and stable (Klein et al., 1998). Therefore, the MgO present in the form of forsterite does not participate in hydration reaction to produce expansive $Mg(OH)_2$ (Maghsoudlou et al., 2016; Kosanović et al., 2005). Therefore, FNS samples did not show any significant expansion in soundness tests (Rahman et al., 2017).

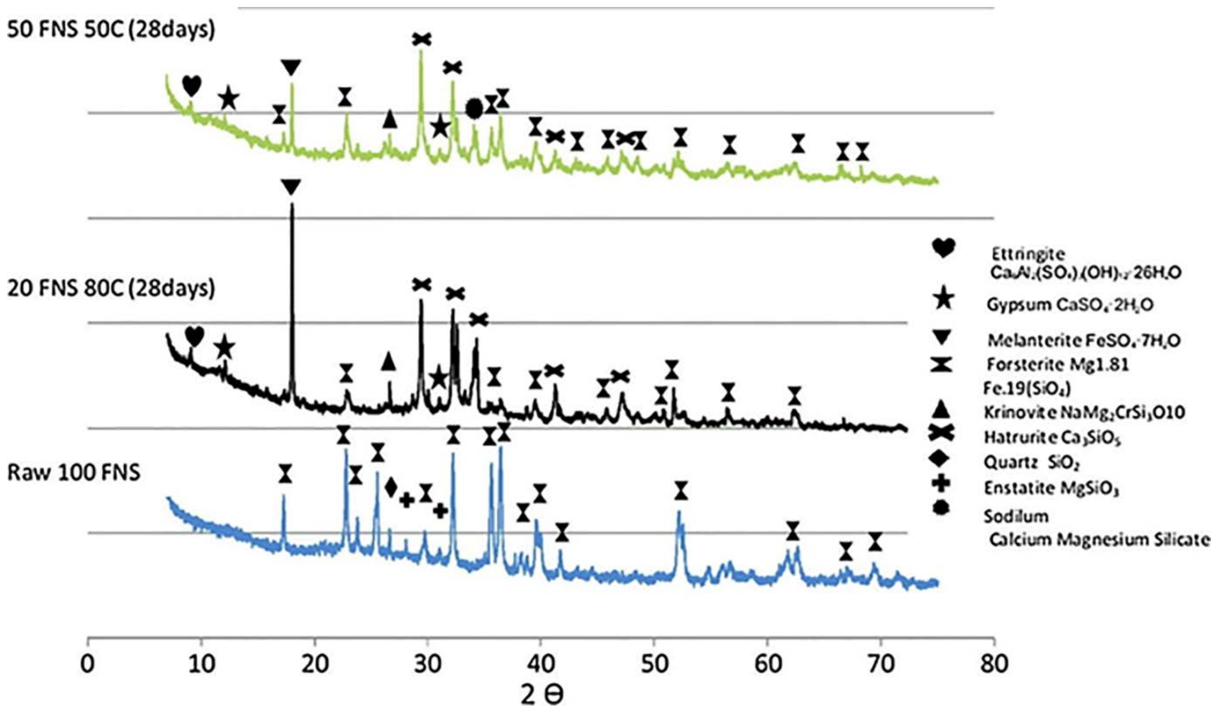

Fig. 11. Phase analysis of raw FNS and FNS blended cement pastes [Rahman et al., 2017].

Furthermore, Lemonis et al. (2015) conducted a hydration study on the FNS blended samples and found that the FNS blended samples exhibited a slower rate of hydration than the control samples. Thus, the compressive strength development was slower in FNS mixed concrete than in the conventional cement concrete. However, the amorphous silica present in FNS reacted at the later ages and formed secondary calcium silicate hydrate (C-S-H) gel and improved the density of microstructure. The study also showed that the use of ground FNS as part of the binder similar water demand as for the control mix. Similarly, Katsiotis et al. (2015) concluded that the presence of FNS slowed down the hydration process and the strength development in FNS blended concrete. In addition, the authors reported an increase of compressive strength at later stages of curing due to the effect pozzolanic reaction of FNS. FNS has not been studied extensively by the scientific community unlike fly ash or blast furnace slag. Therefore, further research is recommended in this area.

5. Performance of FNS in geopolymer

Geopolymer is an emerging alternative binder to Portland cement. Significant amount of research has been carried out on the development of geopolymer concrete during the recent time (Hardjito et al., 2005; Hardjito et al., 2004; Geopolymer Institute, 2017; Yang et al., 2014; Zheng et al., 2010; Zhang et al., 2017). Geopolymer is considered as a binder of low carbon footprint since Portland cement is replaced by industrial by-products such as fly ash, metakaolin or slag. In geopolymerisation, an aluminosilicate material such as fly ash, GGBFS or metakaolin is activated by an alkaline solution to generate three-dimensional polymeric chains (Hardjito et al., 2005). It was shown in past works that strength and durability of geopolymer concrete are comparable to those of Portland cement concrete (Hardjito et al., 2004). As a result, geopolymer concrete has been recently used in some industrial applications. One example is the Brisbane West Wellcamp Airport (BWWA) in Australia constructed in 2014 (Geopolymer Institute, 2017).

It is noticeable from the chemical compositions of FNS that it contains substantial amounts of SiO_2 and Al_2O_3. Thus, it has the potential to replace fly ash partially or entirely in fly ash based geopolymer concrete. Yang et al. (2014) showed that 20% FNS was found to be an optimum quantity as a binder in geopolymer concrete that exhibited the highest strength and lowest shrinkage properties. The authors explained that the FNS contained high SiO_2 and MgO with relatively low Al_2O_3 as compared to fly ash. Consequently, it increased the Si/Al ratio of the geopolymer ingredients and improved compressive strength. The microstructural images of 0% and 20% FNS geopolymer concrete are presented in **Fig. 12**, it can be seen that microstructure of 20% FNS geopolymer specimens were denser as compared to the specimens without FNS. However, a higher dosage of FNS (40% and 60%) led to the reduction of strength due to lower Si/Al ratio (<2) and presence of large pores. In addition, Zheng et al. (2010) suggested an intermediate Si/Al ratio for the optimum results. In another study by Yang et al. (2014) pointed out that, MgO present in the FNS experienced an elevated temperature extractive metallurgy, thus became inert. As a result, the issue regarding the volume stability in fly ash in geopolymer concrete was not noticeable due to the addition of FNS as a binder.

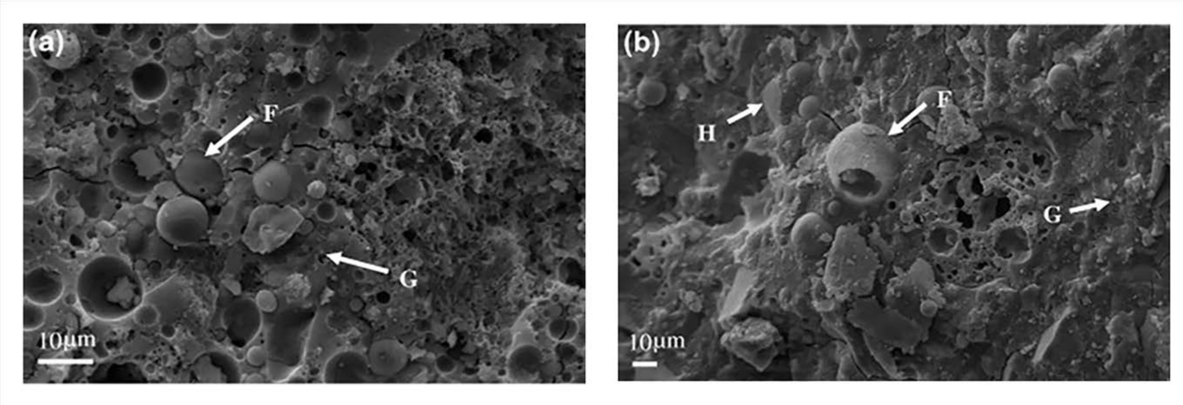

Fig. 12. Microstructure of fly ash geopolymer with (a) 0% FNS and (b) 20% FNS. (F-fly ash particles, H-HMNS particles, G-gel phase formed.) [Yang et al., 2014].

In another study, Zhang et al. (2017) reported that the use of 20% and 40% FNS in geopolymer improved compressive strength as compared to fly ash based geopolymer. The authors also pointed out that FNS geopolymer has an emission of 0.19-0.23 tonnes of CO_2 per tonne of concrete, which is significantly less than the traditional cement concrete. Furthermore, microstructure analysis revealed formation of Na-Al(Mg)-Si-O-H gel in the FNS based geopolymers. Therefore, the authors concluded that the MgO present in the FNS was not chemically inert since it took part in the geopolymerisation process. Furthermore, according to Maragkos et al. (2009), the characteristics of FNS geopolymer depends on the solid to liquid ratio (S/L). The optimum quantity of S/L and NaOH concentration were 5.6 g/mL and 7M, respectively in their study. This optimum conditions exhibited a significantly high compressive strength of 118 MPa and very low water absorption of about 0.8%. In addition, Komnitsas et al. (2007) investigated the properties of kaolinite based geopolymer with ground FNS blends. The authors found that heating time and the temperature had a negligible effect on the compressive strength, whereas curing period had a prominent effect on strength development. The reaction phases of geopolymer binders were identified by XRD, the results are shown in **Fig. 13** (2007). The presence of various minerals such as trona, sodalite, thermonatrite and maghemite can be seen in the geopolymer binders. These minerals are primarily composed of Na, Si, Al and O. It is noticeable that there was no sign of MgO in the chemical analysis. Thus MgO present in FNS acted as inert in the chemical reactions. It can be noted that the geopolymer samples showed excellent resistance to freeze-thaw cycles. However, it displayed strength loss in the acidic environment due to the formation of aragonite, akermanite, halite, magnesium calcite and calcite minerals on the surface of the samples. These minerals are formed due to carbonation under acidic environment. Komnitsas et al. (2009) pointed out that the presence of alkali in FNS accelerated the hydration process. The authors confirmed that only Si, Al and O participated in hydration reaction by using Fourier Transform Infrared Spectroscopy (FTIR) analysis. Finally, Komnitsas et al. (2013) also evaluated the effect of NO_3^- or SO_4^{-2} in the geopolymer mixture. According to the experimental results, the presence of these ions reduced strength development due to the consumption of alkali, thus minimized the formation of a gel. Besides, Sakkas et al. (2014) evaluated the effect of fire exposure on the FNS based geopolymer. The authors found that these geopolymers had a low thermal conductivity and high fire resistance like commercial fire resisting materials. The authors also reported 120 MPa compressive strength, which is in the ultra-high strength concrete category.

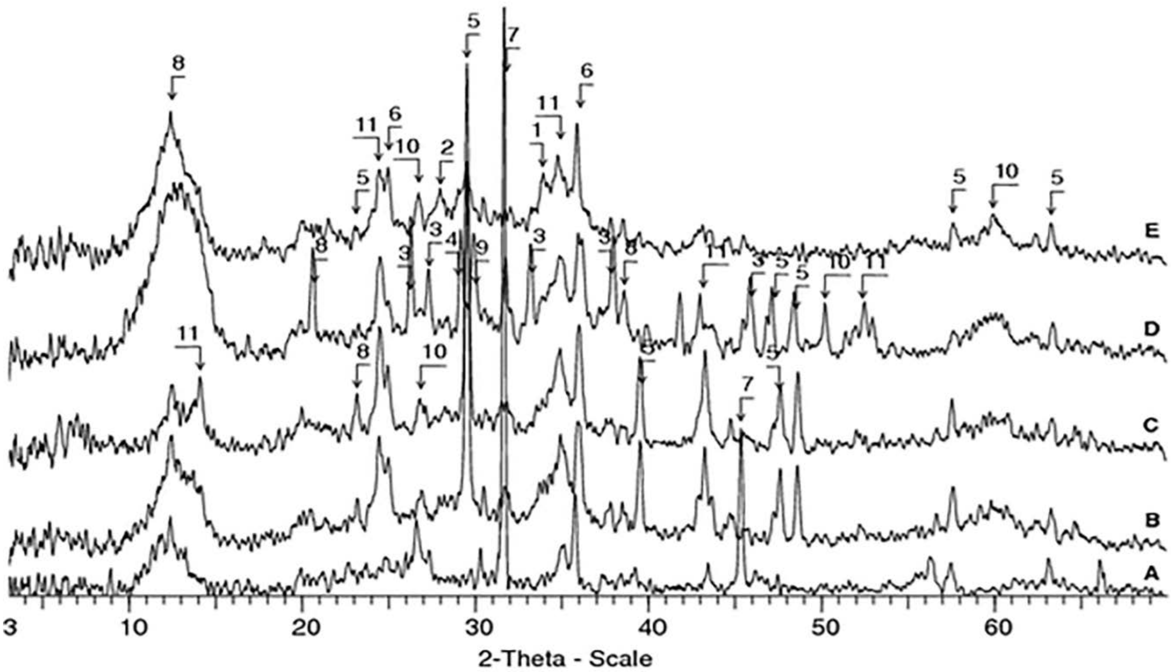

Fig. 13. XRD analysis of geopolymers with FNS under various conditions (A: 60 °C–24 h–7 d; B: 60 °C–24 h–28 d; C: 60 °C–48 h–28 d; D: 80 °C–48 h–28 d; 1: Kaolinite, 2: Maghemite, 3: Magnetite, 4: Quartz, 5: Sodalite) [Komnitsas et al., 2007].

From the above discussion, it can be seen that FNS can be a viable supplementary material in fly ash or metakaolin based geopolymer mixtures. However, there is a debate among the researchers about the role of MgO in geopolymerisation. Yang et al. (2014) and Zhang et al. (2017) reported that MgO participated in hydration reaction, whereas Komnitsas et al. (2007, 2009, 2013) argued that magnesium acted as chemically inert in FNS based mixtures. It also depends on the source of the FNS. Therefore, FNS from a new source has to be thoroughly investigated before its application as a geopolymer precursor.

6. Environmental effects

Though the utilization of industrial by-products as binder or aggregate in concrete brings several advantages, their effects on the surrounding environment due to possible leaching of heavy metals into the groundwater or soil needs to be investigated (Hillier et al., 1999; Marion et al., 2005; Srivastava et al., 2008). Marion et al. (2005) conducted a comparative study in order to identify the leaching of heavy metal from concrete containing blast furnace slag as SCM and porphyry as manufactured aggregate. The authors found that heavy metals released were negligible and well below the regularity limits as per United States Environmental Protection Agency (USEPA, 2009). Similarly, Li et al. (2012) found that leaching of toxic metals from concrete mixed with municipal solid waste incineration bottom ash were below the recommended limits. Manso et al. (2006) conducted a study on EAF slag where, it was used as both binder as well as aggregate in concrete. The authors observed that the leaching of toxic metals were well below the regularity limits in both cases. However, the leaching of heavy metals from the concrete containing EAF slag as a binder were higher as compared to concrete with EAF slag aggregates due to higher cloistering effect. Furthermore, Motz and Geiseler (2001) concluded that the leaching of heavy metals from concrete with steel slag aggregate was negligible and environmentally safe for commercial applications. Besides, the application of pozzolanic materials such as fly ash and silica fume can play a vital role to reduce the leaching of manufactured aggregate by stabilizing the toxic chemicals in pore solution (Yousuf et al., 1995).

It can be seen from **Table 1** that FNS contains some heavy metals such as Cr, Ni and Co. Therefore, it is necessary to assess the leaching properties of FNS as an aggregate or binder. FNS has been used in landfill applications in Korea. Kang et al. (2014) examined the soil from different locations where FNS was used as a landfill material. The authors conducted an investigation to determine the number of heavy metals which can be possibly leached out from FNS. This experimental study revealed that though the pH of the soil was higher than silt, leaching of heavy metals were well below the allowable limits recommended by the United States Environmental Protection Agency (USEPA, 2009). In addition, Saha and Sarker (2017c) conducted a tank leaching study on the concrete samples with full and partial replacement of sand by FNS fine aggregate. The authors collected the leachate after 64 days immersion of the specimens and carried out the chemical analysis to determine the heavy metals in the leachate. The water volume was five times of the concrete volume in their study. The results showed that leaching of heavy metals increased with the increase of FNS content; however, the amount did not exceed the regulatory limits according to the standards (USEPA, 2009). Katsiotis et al. (2015) evaluated the leaching phenomena by tank diffusion in FNS blended concrete according to NEN 7375 (2004). The authors reported that the leaching of heavy metals were within the toxicity limits. On the other hand, geopolymer samples were reported as less susceptible to leaching of heavy metals in the surrounding environment due to low porosity. According to Komnitsas et al. (2013), FNS geopolymers encapsulated the heavy metals such as Pb, Cu, Cr and Ni. Therefore, heavy metals could not leach out from the concrete and maintained the structural integrity. In addition, Fidancevska et al. (2007) pointed out that heavy metals in FNS aggregate are chemically inert. Similarly, Demotica et al., 2012 concluded that toxicity of FNS was less than the maximum allowable concentrations by the standard (USEPA, 2009) and FNS is classified as a non-hazardous material. Recently, Huang et al. 2017 stated that leaching toxicity of Cr in the case of the mortar containing 30% FNS powder is rather low (<0.2 mg/L), which meets the standard GB 30760 (2014). However, Tangahu et al. (2015) found that the concentration of Cr in FNS from reclamation area exceeded the quality standard in toxicity characteristic leaching procedure (TCLP) based on Indonesia's government regulation.

From the above discussion, FNS was generally shown to be an environmentally friendly construction material. Its application as a binder or aggregate in concrete and geopolymer exhibited very low leaching of heavy metal. Therefore, this slag can be used in construction practice without any harmful impact on the environment.

7. Limitations and further research

From the above discussion, it is apparent that FNS is an environmentally friendly construction material and its use will reduce the waste management cost of the nickel industries. However, the use of FNS so far has been very limited and is mainly remained in land filling with some use in concrete productions (2017c). There is some notable research work carried out using this material as an aggregate in concrete around 1990 and eventually, this material has been added to the Japanese Industrial Standards (JIS) in 1994 (JSCE, 1994). However, Tomosawa et al. (1997) noticed that this slag is alkali-silica reactive and suggested that the use of low alkali cement or blast furnace slag or fly ash as a supplementary binder to prevent the resulting expansion. Consequently, alkali-silica reactivity is a hindrance to the use wide application of FNS as fine agregate in concrete. The concrete manufacturers are reluctant to use an alkali-silica reactive aggregate. On the other hand, the application fly ash is a well-established ASR mitigation technique. It is also noted that published research related to ASR of FNS are insufficient. Choi and Choi (2015) and Saha and Sarker (2016) used accelerated mortar bar test to assess the reactivity of this aggregate under aggressive environment. Therefore, there is a scope to evaluate the long-term ASR performance of FNS aggregates in concrete. Shehata and Thomas (2000) used 18 different types of fly ash with reactive siliceous limestone (Spratt) to evaluate the ASR for two years. In their study, class F fly ash was was found to be more effective to mitigate the ASR as compared to class C fly ash. The continuation of their study indicated that 25% or 40% cement replacement by Class F fly ash was effective to mitigate the deleterious ASR expansion after 18 years of field exposure; however, control concrete with reactive aggregate suffered from excessive expansion and cracking (Thomas et al., 2011). The reactivity of different aggregates can be different, which mainly depends on its mineral composition. Therefore, an experimental study to evaluate ASR of concrete containing FNS aggregate with various proportions of class F fly ash needs to be conducted. Such test results will concrete manufacturers with detailed knowledge on the mitigation of potential ASR of FNS aggregates in concrete. Although ASTM C1293 (2015) suggests conducting the ASR experiment for a duration of two years, a longer testing period of 5 to 10 years will be highly efficient to identify any slow reactivity phenomena of FNS aggregate combined with fly ash. Besides, an experimental study can be conducted using ground FNS (after grinding as cement substitution) as ASR mitigation technique in FNS aggregate concrete or mortar.

The presence of high percentage of magnesium in FNS is hindering its application as a SCM. The chemical analysis of FNS indicates the presence MgO it is about 30% (Table 1). It has been well established that, presence of excessive MgO can lead to deleterious expansion after 2-5 years of curing due to the hydration reaction of MgO (Du, 2005). The maximum allowable limit of MgO is 15% in a binder according to AS 3582.2 standard (2016). However, Rahman et al. (2017) reported that the MgO present in FNS aggregate is in a crystal form known as forsterite, which is does not take part in reactions in Portland cement systems. Komnitsas et al. (2007, 2009, 2013) also reported the similar statement for FNS based geopolymers. However, Yang et al. (2014) and Zhang et al. (2017) stated that the MgO present in FNS is not chemically inert based on hydration reaction product in geopolymer concrete. Moreover, it can be concluded that the variation in experimental results between the researchers is due to the different sources and manufacturing process of FNS and the differences in use. Therefore, a detailed investigation is needed in order to understand FNS as a binder from any particular source in order to evaluate the crystal structure of magnesia and its effect on the durability properties of FNS concrete. Besides, 20% replacement of binder by FNS in control concrete or fly ash/metakaolin based geopolymer concrete will keep the MgO content below 10%, which is acceptable as per AS 3582.2 standard (2016). The FNS slag has not been adopted widely due to the lack of extensive research on the durability properties of FNS blended concrete.

Recently, the application of FNS has been studied extensively in geopolymers. However, hydration reactions associated with geopolymer are yet to be completely understood, as it has issues regarding volume stability (Zuhua et al., 2009; Chanh et al., 2008; Zhang et al., 2009). Moreover, further research is needed to identify the fresh and durability properties of FNS blended cement concrete as well as geopolymer concrete.

8. Conclusions

The following conclusions can be drawn based on the conducted review study:

- The use of FNS reduces the workability of the concrete. Furthermore, the bleeding increases slightly in presence of high-density FNS aggregate.
- The utilization of FNS up to 50 % replacement of natural sand improves the mechanical properties such as compressive strength, modulus of elasticity, tensile strength and flexural strength.
- The durability properties of FNS concrete such as air permeability and carbonation similar to those of conventional concrete. However, there is a dispute among the researchers about the freeze and thaw resistance of FNS due to the difference in the FNS properties. Moreover, drying shrinkage is higher in FNS concrete.
- The potential ASR expansion of FNS aggregate is an important aspect that needs to be considered in mix designs. The presence of amorphous silica in water-cooled FNS aggregate may cause ASR expansion. Use of SCMs such as fly ash and blast furnace slag as partial cement replacement is an effective way to mitigate the potential ASR expansion of FNS fine aggregate.
- FNS is a suitable alternative to natural aggregates for pavement construction.
- The MgO present in FNS is in a crystalline structure known as forsterite, which is highly stable in hydration reactions both in OPC concrete and geopolymer concrete.
- FNS shows satisfactory performance as a binder in both OPC concrete and geopolymer. In fly ash based geopolymer, the use of 20% FNS exhibits higher compressive strength than the reference concrete.
- There is no negative impact on the environment due to the utilization of FNS in the concrete industry.
- Finally, the utilization of FNS as aggregate or supplementary binder will be a good step towards sustainable infrastructure development.

Acknowledgements

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