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Durability characteristics of concrete using ferronickel slag fine aggregate and fly ash

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The production process of ferronickel generates an enormous amount of slag (FNS) as a by-product, which has potential for use as a fine aggregate in concrete. However, information regarding the durability of FNS aggregate concrete is very limited in the literature. This study evaluates the durability characteristics of concrete using FNS as up to 100% replacement of natural sand and fly ash as 30% replacement of cement. The volume of permeable voids (VPV) of concrete was found to increase with the increase of FNS aggregate. As a result, sorptivity and chloride permeability showed increasing trends with the increase of FNS aggregate. However, the pozzolanic reaction of fly ash reduced the porosity of the concrete, as evidenced by scanning electron microscopy and energy-dispersive X-ray spectroscopy. The specimens with FNS aggregate and fly ash were classified as 'excellent' in terms of VPV, 'low' in terms of chloride permeability and 'good' in terms of sorptivity. The use of fly ash also reduced the strength losses of FNS aggregate concrete subjected to alternate wet–dry cycles. Overall, a durability equivalent to that of conventional concrete could be achieved when FNS was used as a partial replacement of sand together with fly ash as a partial replacement of cement.

Introduction

Use of industrial by-products as supplementary cementitious material or aggregate can improve the sustainability of concrete production by conservation of natural resources and reduction of carbon dioxide (CO_2) emission. For this reason, the use of various by-products in concrete has been subject to increasing interest in recent times. Recycled concrete aggregate, steel slag, blast-furnace slag (BFS), coal bottom ash (CBA) and foundry slag are some common by-products used as replacement for natural aggregates. It is important to understand the effect of a by-product material on the durability of concrete in order to use it in the construction of structures. This paper presents a study on the durability-related properties of concrete using ferronickel slag (FNS) in place of natural sand and fly ash as a partial replacement for cement.

Nickel smelters generate a substantial amount of molten slag as a by-product because the usual ores contain very low-grade nickel. About 12–14 t of FNS is produced as a by-product in the manufacturing process of 1 t of ferronickel (Saha and Sarker, 2017a). The molten FNS can be either solidified by air at a slow rate of cooling or granulated by water at a rapid rate of cooling. The physical properties of granulated FNS make it a potential candidate for use as a fine aggregate in concrete (Katsiotis *et al*., 2015; Saha and Sarker, 2017b). The use of FNS is considered to be safe because the quantities of heavy metals in leachates are much lower than the allowable limits. Concrete using FNS as a partial replacement for sand has exhibited improved mechanical properties, such as compressive strength, tensile strength and modulus of elasticity, as compared to those of the control specimens (Sakoi *et al*., 2013). However, full replacement of sand by FNS has reduced strength due to poor gradation of the aggregate (Shoya *et al*., 1999).

Few studies are available in the literature on drying shrinkage, freeze–thaw resistance, carbonation, permeability and the alkali–silica reaction (ASR) of FNS aggregate concrete. Sato *et al*. (2011) reported reduced freeze–thaw resistance of concrete due to bleeding caused by FNS aggregates. Similarly, Togawa *et al*. (1996) reported a reduced durability factor in freezing and thawing cycles with the use of air- or water-cooled FNS aggregates. The authors suggested that the use of supplementary cementing materials such as BFS, silica fume and limestone powder could improve the freeze–thaw resistance of concrete. Sakoi *et al*. (2013) reported that the freeze–thaw resistance of FNS aggregate concrete was identical to that of natural aggregate concrete. Tomosawa *et al*. (1997) pointed out the potential ASR expansion of FNS aggregate. However, they demonstrated that the use of low-alkali cement and supplementary cementing material such as fly ash and BFS could reduce the ASR expansion. Apparently, not every type of FNS aggregate is alkali–silica reactive. Rapidly cooled slag may contain amorphous silica that could cause ASR expansion. However, slowly cooled FNS contains crystalline silica, which is more stable and does not exhibit expansion due to ASR (Choi and Choi, 2015). It has been observed in the authors' ongoing study that the use of a class F fly ash could successfully mitigate the potential ASR expansion of FNS aggregates (Saha and Sarker, 2016). However, FNS aggregates did not have any notable impact on the drying shrinkage, carbonation and permeability properties of concrete (Sakoi *et al*., 2013; Shoya *et al*., 1999).

It was found that some important durability-related properties such as porosity, sorptivity, chloride permeability and resistance to wet–dry cycles of FNS aggregate concrete had not been studied in the past. Resistance against wet–dry cycles is an important aspect of the durability of concrete. Previous studies have shown that electric arc furnace (EAF) slag concrete exhibits a strength loss of about 30% due to exposure to alternate wet–dry cycles (Manso *et al.*, 2006; Pellegrino and Gaddo, 2009). Other studies (Andrade *et al.*, 2009; Kadam and Patil, 2015; Yüksel *et al.*, 2007) have shown that concrete containing manufactured aggregates, such as CBA and BFS, exhibit higher sorptivity as compared to the natural aggregate concrete. However, the use of fly ash as a supplementary cementing material was shown to reduce the sorptivity of concrete by pozzolanic reaction (Dragaš *et al.*, 2016; Soutsos *et al.*, 2017). Chloride permeability of concrete was also affected by the use of manufactured aggregate. The use of high-volume CBA was shown to increase the chloride permeability of concrete (Ghafoori and Bucholc, 1996; Kou and Poon, 2009). Supplementary cementing material such as fly ash was also shown to improve the chloride permeability of concrete (Silva *et al.*, 2017). These studies have shown that it is important to evaluate the durability characteristics of concrete when an industrial by-product is considered for use as a replacement for natural aggregate. Therefore, this paper focuses on the durability-related properties of FNS aggregate concrete.

Research significance

This study evaluates the durability properties of concrete containing FNS aggregates. The FNS used was a by-product of the smelting of garnierite nickel ore found in New Caledonia. The smelter produces about 1·7 million tonnes of FNS annually (Rahman *et al.*, 2017), which is granulated using seawater cooling. The slag has been used by the local construction industries as a landfill material as well as a replacement for natural sand in concrete. Despite its broad application, about 25 million tonnes of slag has been accumulated in the premises of the plant. This paper presents the volume of permeable voids (VPV), sorptivity, chloride permeability and the resistance against wet–dry cycles of concrete containing FNS aggregate with or without fly ash as a partial cement replacement. Investigations of porosity and microstructures were conducted by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) in order to gain an insight into the effects of FNS and fly ash on the properties of concrete.

Experimental work

Materials

Commercially available Portland cement (PC) was used as a primary binder and class F fly ash was used as a supplementary cementing material. Natural silica sand and FNS were used as fine aggregates and crushed granite with a maximum size of 20 mm was used as coarse aggregate. Table 1 presents the chemical compositions of the binders and the FNS aggregate. It can be seen that the FNS was mainly composed of silicon, magnesium and iron. The main components of the fly ash were silica and alumina; the calcium content was very low.

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

Material	PC	Fly ash	FNS
Silicon dioxide (SiO_2)	20·29	76·34	53·29
Aluminium oxide (Al_2O_3)	5·48	14·72	2·67
Iron oxide (Fe_2O_3)	2·85	3·69	11·9
Magnesium oxide (MgO)	1·24	0·54	31·6
Sulfur trioxide (SO_3)	2·49	0·11	—
Calcium oxide (CaO)	63·11	0·60	0·42
Sodium oxide (Na_2O)	0·29	0·19	0·11
Potassium oxide (K_2O)	0·45	0·96	—
Chromium oxide (Cr_2O_3)	0·02	—	1·08
Phosphorus pentoxide (P_2O_5)	0·17	0·10	—
Strontium oxide (SrO)	0·05	—	—
Titanium dioxide (TiO_2)	0·27	0·61	—
Manganese oxide (Mn_2O_3)	0·08	0·07	—
Zinc oxide (ZnO)	0·04	—	—
Nickel oxide (NiO)	—	—	0·1
Cobalt oxide (Co_3O_4)	—	—	0·01
LOI	3·39	0·53	—

The physical appearance of the natural sand and the FNS aggregate is shown in Figure 1. It can be seen that FNS consisted of angular particles of varying sizes, as compared to the round, sand particles of relatively smaller sizes. The FNS aggregate consisted of larger particles with a porous structure. The physical properties of the sand, FNS and coarse aggregates are given in Table 2. It is noticeable that the FNS aggregates have a higher density and water absorption as compared to natural sand. The properties of FNS aggregate are within the allowable limits recommended by the Australian standard AS 2758·1 (SA, 1998).

The particle size distributions of fine aggregates such as FNS, natural sand and their combination taking 50% from each type are presented in Figure 2. The allowable limits of fine aggregate gradation recommended by the Australian standard AS 2758·1 (SA, 1998) are also plotted in the figure. It can be seen that FNS aggregate consisted of more large particles when compared to sand. The grading curve for FNS exceeds the lower limit of the Australian standard due to the presence of fewer fine particles. However, the combination of 50% FNS and 50% natural sand provides a well-graded fine aggregate. The flow test was conducted for the sand, FNS and their combination using a sand flow cone. The results are given in Table 3. It can be seen that the flow time for 100% natural sand was 17·20 s, which was increased to 26·20 s by the inclusion of 50% FNS in the fine aggregate. In contrast, the 100% FNS fine aggregate did not flow at all. The angular shape, larger size and rough surface of the FNS particles as compared to smaller, round and smooth sand particles reduced the flow time of the fine aggregate, eventually reaching no flow for 100% FNS.

Figure 1. (a) FNS aggregate and (b) natural sand

Table 2. Physical properties of aggregates

Property	Coarse aggregate	Sand	FNS
Saturated surface dry (SSD) density: t/m^3	2·71	2·16	2·78
Apparent particle density: t/m^3	2·73	2·32	2·85
Fineness modulus	7·6	1·95	4·07
Water absorption	0·48	0·35	0·42

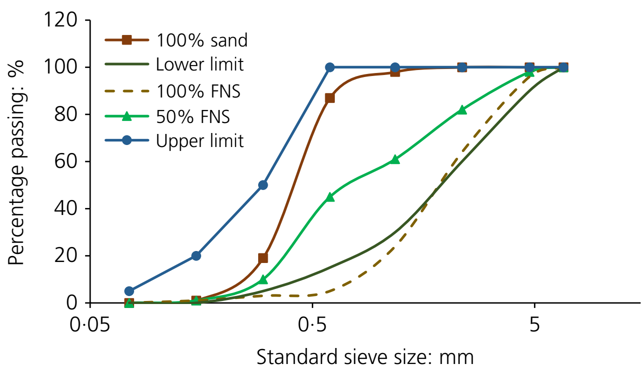

Figure 2. Particle size distribution of sand, FNS and their combination

Table 3. Flow time of the fine aggregates

Sample specification	Time to flow: s
100% sand	17·2
50% FNS and 50% sand	26·2
100% FNS	Did not flow

Mixture proportions and test methods

The concrete mix design was conducted by the absolute volume method and the mixture proportions are shown in Table 4. FNS fine aggregate was used as 50% and 100% volume replacement for natural sand. FNS replacement of 50% in the concrete mixture was selected because this proportion resulted in the maximum compressive strength with good flowability of the mortar mixture (Saha and Sarker, 2017b). The water-to-binder ratio was kept constant at 0·33 for all of the mixtures. The aggregates were prepared to saturated surface dry condition before mixing of the concrete. A naphthalene-based superplasticiser was used to improve the workability of the mixtures. For one group of mixes, 100% PC was used as the binder and for the other group, 30% fly ash was used as a cement replacement. Fly ash (Saha and Sarker, 2016) was adopted as a supplementary cementing material owing to its favourable ASR mitigation mechanism. The mixes are designated as PC-FNS and FA-FNS for without fly ash and with 30% fly ash, respectively. The number at the end of mix identification code represents the percentage of sand replacement by FNS. A standard slump test was carried out in order to determine the workability of the fresh concrete mixtures. The concrete was then placed into 100 mm × 200 mm cylindrical moulds and compacted using a vibrating table. The test specimens were demoulded 24 h after casting and then cured in limewater at 23°C for 28 d. The mean values of the reported results were obtained from the test results of three identical specimens.

Cylinder compressive strengths were determined in accordance with the Australian standard AS 1012·9 (SA, 2014). The porosity of concrete specimens was determined by the VPV test in accordance with the standard ASTM C642 (ASTM, 2006). The test measures the porosity of concrete by absorption of water. Discs that were 50 mm thick were cut from the concrete cylinders after curing for 28 d. The mass of the test sample was recorded after oven drying at 110°C for a period of 24 h. The saturated surface dry weight was then recorded after immersion of the sample in water for 48 h. Finally, the samples were boiled in water for 5 h and weighed after cooling down to room temperature. The volume of the permeable voids was calculated from this recorded weight.

The sorptivity test was conducted to evaluate the capillary suction of concrete as per ASTM C1585 (ASTM, 2004). After the 28 d of the curing period, the concrete cylinders were cut into 50 mm thick discs. The samples were oven dried to achieve a constant weight before beginning the sorption by

Table 4. Concrete mix proportions

Mix ID	Binder: kg/m³		Fine aggregate: kg/m³		Water: kg/m³	Coarse aggregate: kg/m³	Superplasticiser: kg/m³
	Cement	Fly ash	Sand	FNS			
PC-FNS0	390	0	710	0	129	1194	4
PC-FNS50	390	0	355	435	129	1194	4
PC-FNS100	390	0	0	870	129	1194	4
FA-FNS0	273	117	710	0	129	1194	4
FA-FNS50	273	117	355	435	129	1194	4
FA-FNS100	273	117	0	870	129	1194	4

keeping only the bottom surface in contact with water. The sides of the specimen were sealed by duct tape and the top surface by a plastic sheet. As a result, water movement was allowed only from the bottom surface. The mass increments were measured for a period of 9 d, with the designated time intervals as suggested in the standard. The sorptivity coefficient was measured from the slope of the plot of absorption against the square root of time.

The rapid chloride permeability test (RCPT) was conducted in accordance with ASTM C1202 (ASTM, 1997). Although the RCPT may give high variability of results and may not be considered as a direct measure of durability, it is used as an indication of chloride ingress into concrete. Concrete cylinders were cut to 50 mm thick discs after 28 d of curing and kept in a vacuum desiccator for 3 h at a pressure of 50 mm Hg, followed by 18 h of immersion in water. The saturated samples were then subjected to a direct current of 60 V for a duration of 6 h, keeping one side of the specimen in contact with 3% sodium chloride (NaCl) solution and the other side in contact with 0·3 M sodium hydroxide (NaOH) solution. During the test period, the total charge passing through the specimens in coulombs was recorded.

In order to evaluate the resistance of concrete to wet–dry cycles, the samples were exposed to cycles of alternate immersion in water and drying at a temperature of 110°C. This exposure condition was considered in order to evaluate the effects of adverse environmental conditions on concrete with age. The exposure to wet–dry cycles started after initial curing of the samples for 28 d. The samples were kept in an oven at 110°C for 8 h, after which they were immersed in water at 23°C for 15 h to complete one cycle of drying and wetting. After 28 cycles of alternate wetting and drying, the changes in compressive strength and mass of the specimens were measured. In order to understand the effect of wet–dry cycles, microstructural observations were conducted using SEM and EDS.

Results and discussion

Workability and compressive strength

The workability of the freshly mixed concrete was determined by a slump test. The slump values were 120 mm, 140 mm and 110 mm for the PC-only (PC-FNS) mixtures for 0, 50 and 100% FNS, respectively. The slump values of the mixtures with 30% fly ash were 130 mm, 155 mm and 125 mm for 0, 50 and 100% FNS content, respectively. Although all of the mixtures had good workability, it can be seen that slump increased with the use of fly ash and 50% FNS fine aggregate. This is attributed to the well-known ball-bearing effect of fly ash particles and relatively large particles of FNS aggregate as compared to sand. The use of 50% FNS reduced the total surface area of the fine aggregate and thus there was more paste available to increase the workability. However, workability then decreased with the use of 100% FNS aggregate because all the fine aggregate particles were angular, which increased the friction against movements among the particles.

The mean density of the hardened concretes of all the mixtures was 2486 kg/m³ with a coefficient of variation of 1·05%. The compressive strength results are given in Figure 3. It can be seen that the compressive strengths of the PC-FNS mixes were 61, 66 and 44 MPa for 0, 50 and 100% FNS, respectively. Thus, it can be seen that compressive strength increased by 8% for 50% sand replacement by FNS aggregates and then decreased by 26% for 100% replacement of sand by FNS. This is because 50% FNS produced a well-graded aggregate and 100% FNS produced a relatively poorly graded aggregate, as shown in Figure 2. Besides, there was a gradual reduction of compressive strength due to the use of 30% fly ash as a cement

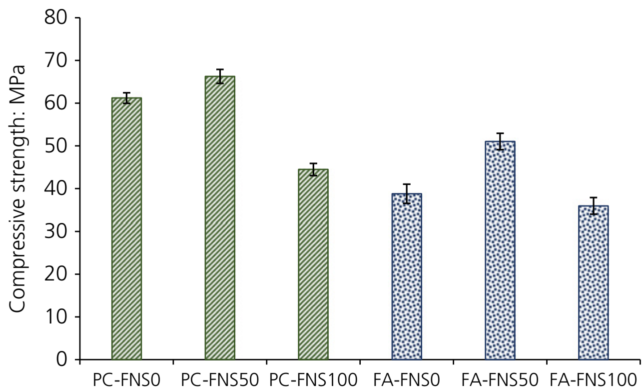

Figure 3. Compressive strength after 28 d of curing

replacement. The compressive strengths of the mixtures with 30% fly ash were 39, 51 and 36 MPa for 0, 50 and 100% FNS, respectively. Although compressive strength is reduced by fly ash, it is considered necessary to use fly ash as an ASR mitigating measure for the FNS aggregate.

Volume of permeable voids

The VPV (Vicroads, 2007) test is used to determine the total porosity of concrete that consists of capillary pores, gel pores, air voids and microcracks. Thus, the VPV indicates the ease of penetration of fluids into concrete from the surroundings. The changes of VPV of concrete with the percentage of FNS content are plotted in Figure 4. It can be seen that the porosity of the samples gradually increased with the increase of FNS aggregate for both of the binder groups, with and without fly ash. The VPV values of the concrete specimens without fly ash in the binder were 5·79, 7·80 and 11·23% for 0, 50 and 100% FNS content, respectively. The increase of porosity is attributed to the increase of voids in concrete due to the larger size and angular shape of the FNS particles. The durability classifications according to the VPV value of concrete by VicRoads (2007) are also shown in Figure 4. As shown in the figure, concretes with a VPV value below 11% are classified as 'excellent' and those between 11 and 13% are classified as 'good'. Thus, the mixtures containing 0 and 50% FNS are classified as 'excellent' whereas the mixture containing 100% FNS is marginally classified as 'good' concrete in terms of the VPV.

It can be seen from Figure 4 that the VPV of concrete generally reduced by the use of fly ash as a cement replacement for both types of aggregate. The trend of the change of VPV with the increase of FNS aggregate was similar for the concretes with or without fly ash. The VPV values were 5·23, 7·18 and 9·76% for 0, 50 and 100% FNS content, respectively, in the concrete containing 30% fly ash as cement replacement. The reduction of porosity by the inclusion of fly ash is attributed to its higher fineness than cement and its pozzolanic reaction. The reduction of permeability by the addition of fly ash (Bijen, 1996; Shehata *et al.*, 1999) has been well documented in previous studies. As shown in Figure 4, the concrete specimens containing 30% fly ash and up to 100% FNS are classified as 'excellent' according to the VPV values.

Sorptivity coefficient

The sorptivity coefficients of the samples of both binder groups are plotted in Figure 5. The sorptivity coefficients of the concrete specimens without fly ash were 0·085, 0·153 and 0·219 mm/min$^{1/2}$ for 0, 50 and 100% FNS, respectively. It is noticeable that the sorptivity value of concrete with 100% FNS aggregate exceeded the allowable limit of 0·21 mm/min$^{1/2}$ suggested by Cement Concrete & Aggregates Australia (CCAA, 2009). The higher sorptivity coefficient was due to the higher internal voids associated with the addition of FNS aggregates. The larger size and higher angularity of the FNS particles increased the internal voids, which eventually increased the absorption of concrete. The relatively larger size and angular shape of the FNS particles can be seen in the grading curve (Figure 2) and in Figure 1(a), respectively.

The sorptivity coefficients of the specimens using 30% fly ash were 0·061, 0·092 and 0·123 mm/min$^{1/2}$ for 0, 50 and 100% FNS, respectively. Thus, sorptivity was significantly reduced by the use of fly ash. The sorptivity values of the specimens of this group are well below the allowable limit of 0·21 mm/min$^{1/2}$ suggested by CCAA. There are two primary reasons contributing to the reduction of sorptivity of the fly ash concrete. First, fly ash contains a high volume of amorphous silica (Saha and Sarker, 2016), which reduced the capillary pores by the products of pozzolanic reaction with portlandite. Second, fly ash particles are generally finer than cement particles (Kuroda *et al.*, 2000), and reduced the interconnecting voids by acting as nucleation sites and their pore filling effect.

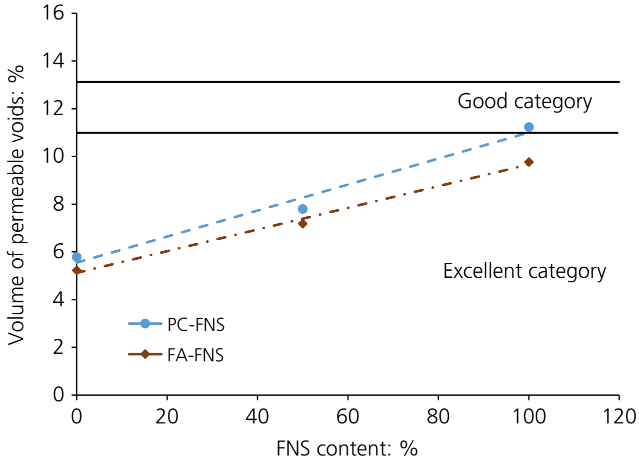

Figure 4. Variation of the VPV with FNS content in concrete

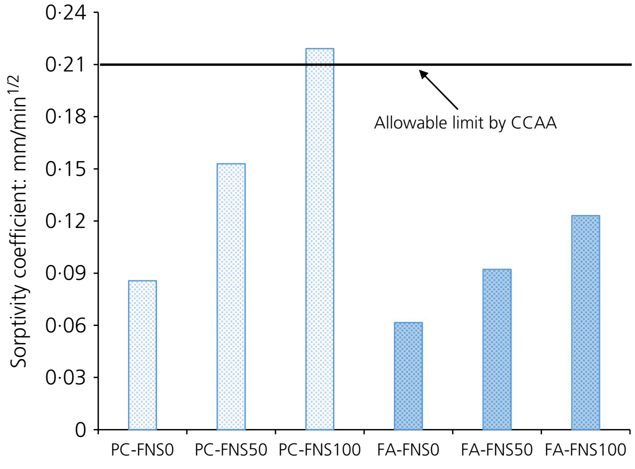

Figure 5. Variation of sorptivity with FNS content

Chloride permeability

Chloride permeability of the concrete samples was determined by RCPT. The test is based on the principle that the total charge passing through a concrete sample is an indicator of the chloride ion penetration. This test is relatively quick and gives reliable data to compare the chloride permeability values for different specimens. The total charge passed through the concrete samples of two binder groups is presented in Figure 6. The ASTM C1202 (ASTM, 1997) classifications of concrete from 'very low' to 'high' values of charge passed are also shown in this figure. It can be seen that the charge passed through the samples with no fly ash (PC-FNS) was within a range of 2066–3335 C. The value of charge increased gradually with the increase of the percentage of FNS aggregate. The chloride permeability of the specimens of PC-FNS series has been classified as 'moderate level' by the ASTM C1202 (ASTM, 1997) standard. The FNS aggregates increased the permeable voids in concrete, as discussed in the previous two sections, which is the primary reason for the increase of chloride permeability with the increase of FNS aggregates.

In contrast, the concrete specimens with 30% fly ash in the binder exhibited lower chloride penetration for all the three fine aggregates. The charges passed through the samples were 698, 1030 and 1074 C for 0, 50 and 100% FNS, respectively. Thus, the specimens are classified as 'very low' chloride permeability for 100% natural sand and 'low' for using 50 and 100% FNS aggregate. It was shown that fly ash reduced the pore size (Kuroda *et al.*, 2000) by reducing the thickness of the interfacial transition zone between the binder matrix and the aggregates. Furthermore, fly ash also reduces the hydroxyl ion (Shehata *et al.*, 1999) in the pore solution of concrete, thus reducing the charge passed through the concrete. Overall, while the use of FNS aggregate increased the pore volume, fly ash helped to reduce the porosity and the alkalinity of the pore solution to reduce the chloride permeability of the concrete.

Effect of wet–dry cycles

Strength and mass variations due to wet–dry cycles

The concrete samples were exposed to alternate wetting and drying for 28 cycles and each cycle consisted of 8 h of oven drying at 110°C followed by 15 h of immersion in water at room temperature. The samples were visually observed before and after the wet–dry exposures. The specimens of mixture PC-FNS100 are shown in Figure 7 as the typical appearance of the specimens after the wet–dry cycles. No visible crack or damage was observed in the specimens after 28 cycles of the wet–dry conditions. However, there was a thin layer of whitish substance over the surface of the samples. This surface deposition is attributed to slow migration of the hydrated product from inside the concrete by the alternate wetting and drying conditions.

The compressive strengths of the specimens after the cycles of wet–dry exposures are presented in Figure 8. The figure also shows the compressive strength of corresponding mixtures at 58 d of age without exposure to wet–dry cycles. The strength reduction of the specimens is considered to be due to the minor internal damage at the microstructural level by the alternate expansions and contractions because of the alternate changes of temperature between 110°C and 23°C. In addition, the moisture movement and drying shrinkage due to the variation of humidity condition are also considered to play a role in the strength reduction of concrete.

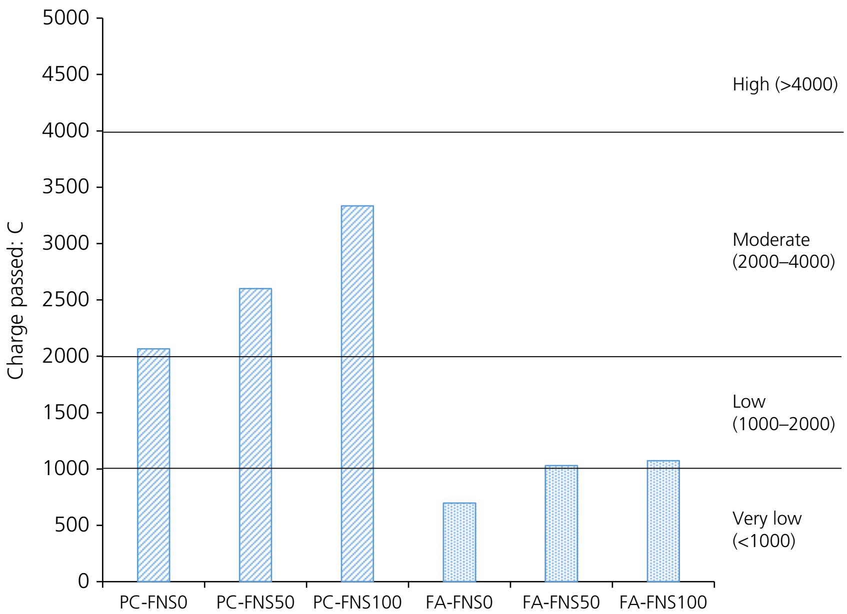

Figure 6. Charge passed during rapid chloride permeability test

Figure 7. Physical appearance of PC-FNS100 samples after wet–dry cycles

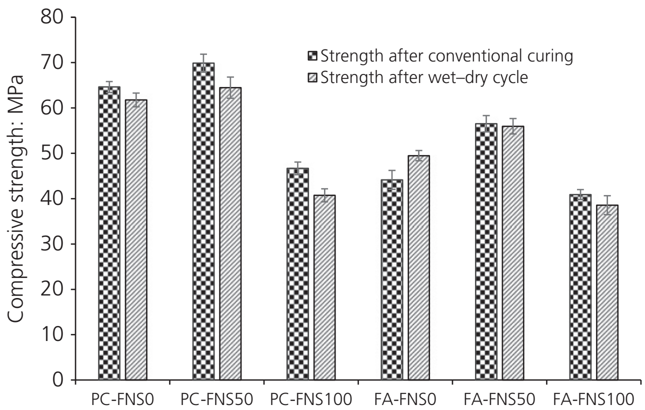

Figure 8. Comparison of compressive strength following exposure to wet–dry cycles

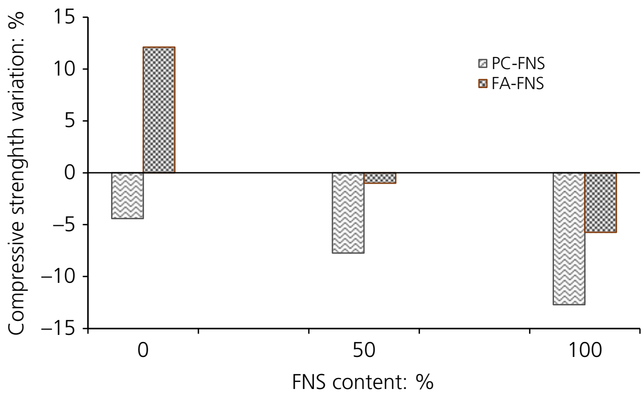

Figure 9. Percentage of strength change by the wet–dry cycles

The percentages of changes in compressive strength after the wet–dry cycles are presented in Figure 9. It is noticeable that the specimens without fly ash (PC-FNS0) exhibited a strength loss of 4·42% after the exposures to wet–dry cycles. The strength loss gradually increased for the PC-FNS specimens with the increment of FNS content in concrete. The strength loss was 7·73 and 12·71% for 50 and 100% FNS content, respectively. Manso *et al.* (2006) and Pellegrino and Gaddo (2009) used similar wet–dry conditions for concrete using steel slag aggregates and reported a strength loss of about 30%. Therefore, FNS aggregate used in this study showed comparatively lower strength loss than the steel slag aggregate concrete. The use of FNS aggregates increased the permeability and absorption of concrete, as shown in Figures 3–5. Thus, it is possible to have higher water penetration during the wetting cycles, which may result in an increased vapour pressure in the specimens containing FNS aggregate during the drying cycle. Therefore, there are three principal reasons for the strength reduction of concrete caused by the internal damage due to wet–dry cycles: (*a*) the simultaneous wetting and drying at elevated temperature causing sudden thermal expansion and contraction; (*b*) water vapour pressure during the drying cycle; and (*c*) the leaching out of some hydrated product. The combined effect of these aspects is considered to cause strength losses of the specimens.

As shown in Figure 8, the concrete specimens with 30% fly ash as cement replacement showed relatively lower strength loss after the wet–dry cycles. The compressive strength of samples containing 100% natural sand and 30% fly ash increased by 12% after the wet–dry cycles. There were 1 and 6% strength losses in the samples with 50 and 100% FNS aggregate, respectively. The increment of compressive strength is attributed to the pozzolanic reaction of fly ash. The alternate wetting and drying cycles at elevated temperature accelerated the pozzolanic reaction of fly ash, which caused the smaller strength loss for the concrete containing FNS aggregate. Furthermore, the effect of water vapour depends on the porosity and water absorption of the samples. The inclusion of fly ash increases the density of the paste matrix and reduces the concrete porosity and absorption, which has been discussed in earlier sections. As a result, the compressive strength of the samples with 30% fly ash and 50% FNS aggregate suffered only marginal strength loss (1%), whereas samples with 100% PC as the binder and 50% FNS aggregate suffered a strength loss about 8%.

The mass losses of the concrete specimens due to wet–dry cycles are presented in Figure 10. It can be seen that weight loss increased with the increase of FNS content for both of the binder types. The weight loss was within a range of 0·45–1·89%. The weight loss was almost doubled for a particular binder group due to the inclusion of 100% FNS aggregate as compared to that with 100% natural sand. The trend of the mass loss is similar to the strength loss for both the binder groups. The reasons for mass changes by the wet–dry cycles are considered to be the same as those for the strength changes, as discussed above.

Microstructural observation after wet–dry cycles

The SEM images and EDS of the concrete microstructures after the wet–dry cycles are used to understand the effects of FNS and fly ash. The SEM image of the specimen containing 100% natural sand and no fly ash (PC-FNS0) is presented in Figure 11(a). It can be seen that there was development of internal cracks due to the aggressive wet–dry cycle exposure. The EDS of the reaction product is presented in spectrum 1. It can be seen that the hydrated product had a high intensity of calcium (Ca) and low intensity of silicon (Si). This is because the binder did not undergo any pozzolanic reaction, as there was no fly ash in this specimen. The SEM image of the specimen with 100% PC as the binder and 100% FNS aggregate (PC-FNS100) is presented in Figure 11(b). The presence of cracks can be seen at the interface of aggregate and binder in this microstructure. The corresponding EDS (spectrum 2) shows a calcium-rich phase that is similar to the EDS (spectrum 1) of specimen PC-FNS0.

The SEM image of the specimen with 30% fly ash and no FNS is presented in Figure 11(c). It can be seen that the hydrated product consisted of a dense structure, some fly ash particles underwent the pozzolanic reaction and some others were initiating the process. Additionally, the fine line of a crack can be seen in the image, which is significantly thinner as compared to those observed in the SEM image of specimen PC-FNS0. The EDS data in spectrum 3 confirm the pozzolanic reaction of fly ash, showing a product of higher intensity of silica and low intensity of calcium. Thus, the wet–dry cycle accelerated the pozzolanic reaction of the amorphous silica of fly ash producing a silica-rich hydrated product, commonly known as calcium–silicate–hydrate gel. Figure 11(d) presents the microstructure of the specimen with 30% fly ash and 100% FNS aggregate. The contribution of the pozzolanic reaction product of fly ash to fill up the pores can be seen in this image. This contributed to increase the density of the binder matrix and improve the bond between the aggregate and binder. Thus, the use of fly ash helped to reduce the strength loss of FNS aggregate concrete after the wet–dry cycles, as shown in Figure 9.

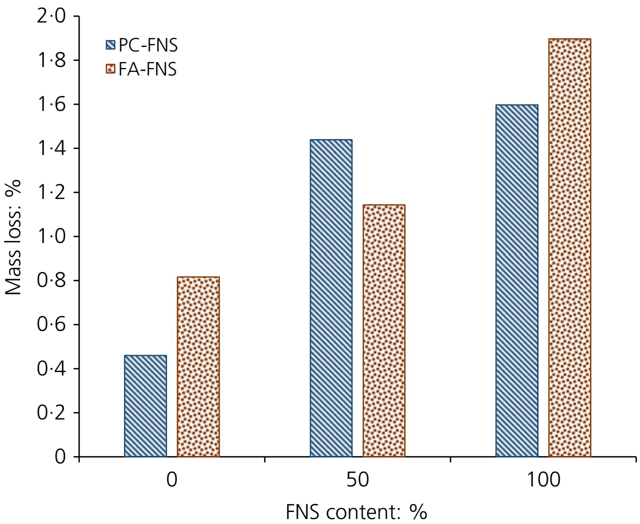

Figure 10. Mass loss attributable to exposure to wet–dry cycles

Conclusions

By-product FNS was used as fine aggregate to replace 50 and 100% natural sand, and a class F fly ash was used as 30% replacement of cement in concrete. The durability characteristics of the concrete specimens were studied by evaluating the VPV, sorptivity, chloride permeability and resistance to exposure to wet–dry cycles. Generally, VPV was found to increase with the increase of FNS aggregates replacing natural sand. Chloride permeability and capillary absorption of concrete were also found to increase with the increase of sand replacement by FNS aggregate. These increases are attributed to the increase of porosity by the relatively large size and angular shape of the FNS particles. The increase of FNS content also showed higher strength and mass losses due to the exposure to alternate wet–dry cycles. However, the pozzolanic reaction of fly ash reduced the permeable voids, as evidenced by the SEM images and EDS data. Thus, the chloride permeability and capillary water absorption were also reduced by fly ash. The concrete samples with fly ash also suffered from lower strength reduction after the wet–dry cycles as compared to the samples without fly ash. The compressive strength of the sample with 50% FNS and 30% fly ash remained almost unchanged after exposure to the wet–dry cycles. The sorptivity coefficient of this mix was well below the recommended value of 0·21 mm/min$^{1/2}$ and the rapid chloride permeability was classified as low. Consequently, the durability performance of the concrete containing 50% FNS fine aggregate and 30% fly ash is considered equivalent to that of the concrete using 100% natural sand and 100% cement. Therefore, combined use of FNS fine aggregate and fly ash is a promising option for environmentally friendly and durable concrete.

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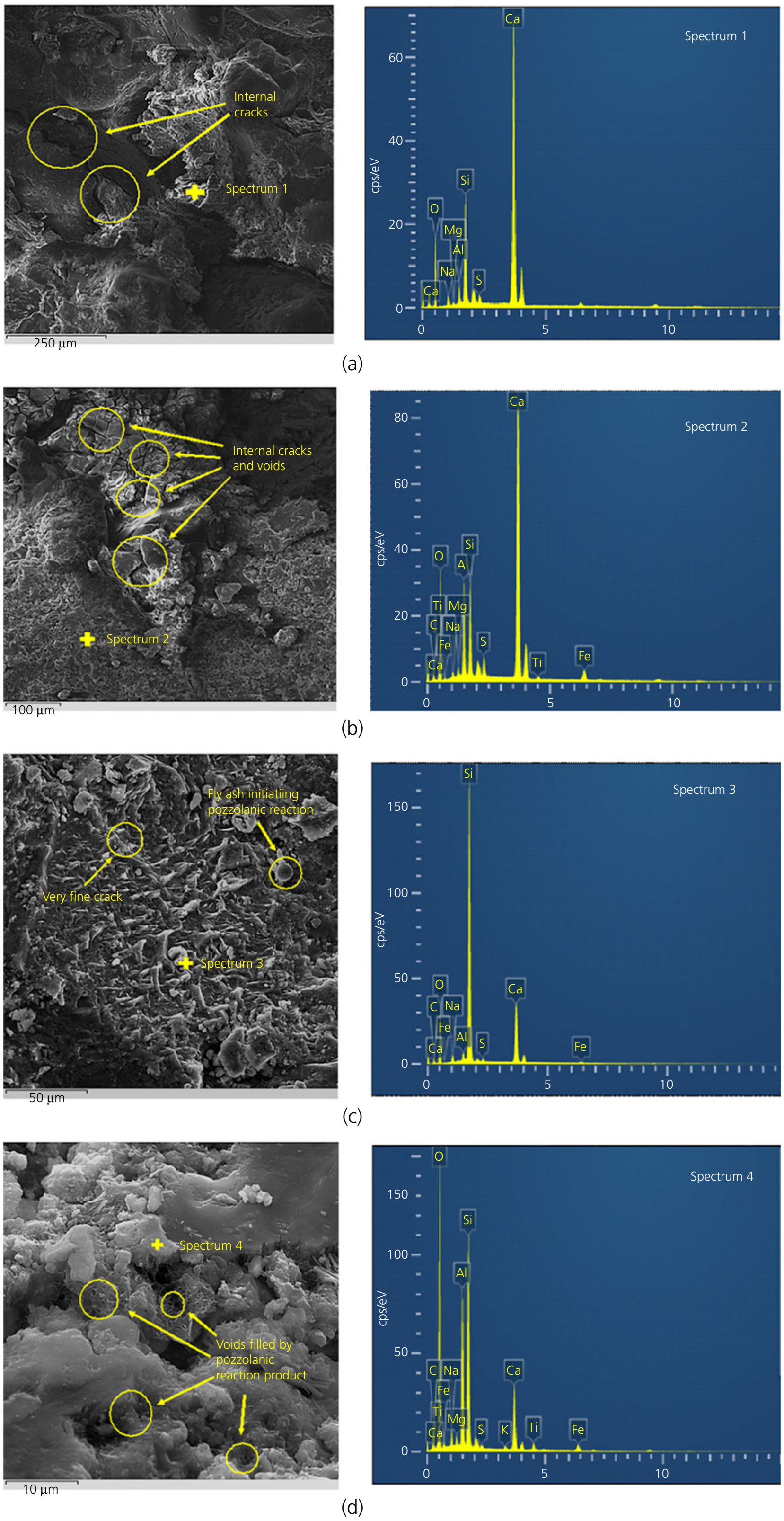

Figure 11. SEM and EDS data of the samples after wet–dry cycles: (a) PC-FNS0; (b) PC-FNS100; (c) FA-FNS0; (d) FA-FNS100 (cps/eV: counts per second)

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