Mitigating the Risk of Early Age Cracking in Fly Ash Blended Cement-Based Concrete Using Ferronickel Slag Sand

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Abstract

A concrete mix (FNS25) including 50% natural sand replacement by ferronickel slag (FNS) sand and 25% ordinary portland cement (OPC) substitution by fly ash (FA) was considered to mitigate the risk of early-age cracking in fly ash blended cement-based concrete. Experiments were carried out to accurately quantify early-age shrinkage and tensile creep and assess their influence on early-age cracking in reinforced concrete members. The results show the free shrinkage strain is not influenced by either fly ash or FNS significantly, whereas the tensile creep of FNS25 is significantly larger than that of both OPC100 and FA20. Both restrained ring test and simulations on reinforced concrete members confirm that partly replacing conventional sand by FNS sand reduces the risk of early-age cracking. Micro-structural analysis of the Interface Transition Zone (ITZ) of FNS sand shows that excess in Portlandite is absent in FNS members which confirm that partly replacing conventional sand by FNS sand reduces the risk of early-age cracking. Micro-structural analysis of the Interface Transition Zone (ITZ) of FNS sand shows that excess in Portlandite is absent in FNS members which confirm that partly replacing conventional sand by FNS sand reduces the risk of early-age cracking.

1. Introduction

In the first few days after casting, concrete undergoes significant time-dependent deformation resulting from the cement hydration (heat of hydration and autogenous shrinkage) and water evaporation (drying shrinkage). This early age deformation of concrete members in the field is always restrained leading to the development of tensile stresses. Restraint to this early age deformation can be characterized as either internal or external restraint. Compared to the external restraint, the internal restraint discussed in this paper, which occurs when the strain is non-uniform over the depth of a cross-section or the deformation is restrained by embedded reinforcement in concrete, cannot be avoided in reinforced concrete (Khan et al. 2018). When the tensile stress is larger than the development of early-age tensile strength, unexpected excessive cracking takes place in reinforced concrete structure, and may lead to serviceability and/or durability problem. The development of tensile stresses due to the restraint in concrete depends on various factors, including the heat of hydration, degree of restraint, modulus of elasticity, free drying and autogenous shrinkage, and tensile creep/relaxation (Khan et al. 2018).

Fly ash (FA), which is a by-product of other industrial processes, has been used successfully as a pozzolan for many years in concrete to partly replace ordinary portland cement (OPC). The inclusion of fly ash in concrete affects significantly the early-age concrete properties. Some influences are beneficial in reducing the risk of cracking at the early ages, including a decrease in heat of hydration (De Rojas and Frias 1996; Ballim and Graham 2009), a reduction in shrinkage (Tikalsky et al. 1988; Day 1990), and a slight increase in the tensile creep of concrete. Currently, most of studies have been focused on the effect of fly ash on the compressive creep of mature concrete and the results have shown that the compressive creep of mature concrete is reduced due to addition of fly ash (Li and Yao 2001; McCarthy and Dhir 2005; Gu et al. 2019). For the early-age tensile creep of concrete, a few studies reported that fly ash led to a slightly higher tensile creep (Ji et al. 2013; Klausen et al. 2017; Khan et al. 2018). In restrained concrete members, the development of tensile stresses is slowed due to relaxation afforded by tensile creep. The other influences, such as the slower tensile strength development at early age and the increase in elastic modulus cured under a realistic temperature considering the hydration heat, increase the risk of cracking (Klausen et al. 2018; Ji et al. 2018; Ji and Kanstad 2018). Therefore, the effect of fly ash on the risk of early age cracking of concrete is still a question.

This paper explores the possibility of using ferronickel slag (FNS) fine aggregate to reduce the risk of early age...
cracking in fly ash blended cement-based concrete. Indeed, previous studies showed that mortar compressive strength increases with the increase in natural sand replacement by FNS sand, reaching an optimum performance for 50% natural sand replacement (Saha and Sarker 2017). A similar improvement in early age tensile strength development of fly ash concrete incorporating FNS sand could contribute to reduce the risk of early age cracking. Additionally, Saha and Sarker (2016) investigated the risk of alkali-silica reaction (ASR) in mortars using FNS fine aggregate. The accelerated mortar bar test (AMBT) results obtained using OPC mortar revealed that FNS fine aggregate is potentially reactive according to Australian Standard AS 1141.60.1 (2014), which is similar to ASTM C1260-14 (2014). However, ASR was not observed in fly ash blended cement-based mortars.

Ferronickel slag, which is also known as electric arc furnace slag, is a by-product of the production of ferronickel alloy. This slag is produced from the smelting of laterite ore in an electric arc furnace at high temperature with a reducing agent and then cooled in water or air. The manufacture of one tonne of ferronickel alloy discharge around four tonnes of FNS, which is described as an amorphous material due to the cooling process in water. Katsiotis et al. (2015) studied the hydration process and the leachability of blended cement containing ground FNS. Importantly, the heavy metal concentrations in leachates from FNS specimens were below the limits proposed by the United States Environmental Protection Agency (EPA). As a result, FNS is classified as non-hazardous waste and is suitable for use in the construction industry. FNS has also been categorized as non-hazardous waste according to the European Catalogue for Hazardous Wastes (Katsiotis et al. 2015; Dourdounis et al. 2004; Lemonis et al. 2015). The non-hazardous characteristic of FNS provides opportunities to develop new applications for FNS in the construction industry allowing recycling this industrial by-product and reducing the consumption of natural resources such as natural sand. The production of FNS at SLN (Société Le Nickel) in New Caledonia is around 2 million tonne per year with an existing stockpile of 25 million tonnes, which presents an excellent potential for concrete applications in the Pacific region.

In this paper, 50% natural sand replacement by FNS and 25% fly ash blended cement is considered as recommended by previous research outcomes (Saha and Sarker 2016, 2017). The concrete grade investigated is 30 MPa compressive strength. Two control concrete mixes were considered including OPC and fly ash blended cement using only natural sand. The experimental program is organized in two parts. In the first part, the tensile creep and free shrinkage of each concrete were directly measured using plain dog-bone shaped specimens. In the tensile creep tests, the specimens were subjected to sustained axial tension for several weeks. In the second part, tests were performed on concrete ring specimens restrained by inner steel ring in order to measure the time to cracking due to restrained shrinkage. The slender shape of both dog bones and ring specimens as well as the time when restrained shrinkage and creep tests were started (two days after casting) allow to assume that the heat of hydration of cements did not affect significantly early age cracking and, as a result, is not discussed in this paper. The Interfacial Transition Zone (ITZ) between FNS sand and the matrix has been analysed using scanning electron microscope and energy dispersive X-ray spectrometry aiming to understand the fundamental mechanisms responsible of the improvement in the performance of concrete containing FNS sand. Moreover, the test results are then used in a stress analysis to evaluate the risk of cracking due to restraint in two typical reinforced concrete members.

2. Experiment

2.1 Materials and mix design

(1) Aggregates
For all concretes tested, coarse aggregate is crushed basalt supplied from Dunmore quarry in New South Wales, Australia with a maximal nominal size of 10 mm and a water absorption of 1.6%. Two types of fine aggregate are used: natural aggregate and FNS aggregate. Natural aggregate is Sydney sand with a specific gravity of 2650 kg/m³ and water absorption of 3.5%. The characteristics of FNS sand are given in Table 1, obtained based on Australian Standard AS 1141.5-2000 (2016) recommendations.

In comparison with Sydney sand, specific gravity of FNS sand is slightly higher but the water absorption is much lower. The particle size distribution of both fine aggregates was assessed by sieving analysis according to AS 1141.11.1 (2009). Figure 1 represents the grading
curves of Sydney sand and FNS sand showing that FNS sand is coarser than Sydney sand. Moreover, Fig. 1 shows the grading curve of the combination by mass of 50% Sydney sand and 50% FNS sand, which is used in the FNS concrete.

(2) Binder
The OPC used is a general purpose (GP) portland cement complying with the Australia Standard AS 3972 (2010). The low-calcium type fly ash branded as Blue Circle Fly Ash by Boral was sourced from Eraring Power Station in New South Wales, Australia. The chemical composition of both cementitious materials measured by X-ray fluorescence (XRF) is summarized in Table 2.

The laser diffraction technique using a Malvern Mastersizer 2000 instrument was conducted to determine particle size distribution (PSD) of the cementitious materials (Fig. 2). The fly ash used is marginally coarser than OPC with 92% passing the 45 µm sieve while almost 100% of OPC powder passed the 45 µm sieve. According to Australian Standard AS 3582.1 (1998), this fly ash is categorised as fine fly ash, which is the best grade for concrete applications.

(3) Concrete mix design
Four concrete mixes were initially considered as shown in Table 3. For the three reference concretes, labelled OPC100, FA20 and FA30, only Sydney sand was used as fine aggregate. The water to binder ratio was kept constant as 0.55 for the reference concretes. The binder composition of OPC100 is 100% GP cement. In cases of FA20 and FA30, 20% and 30% of GP cement was replaced by weight with fly ash. For concrete labelled FNS25, 50% of natural Sydney sand was replaced by FNS sand and the binder composition was 25% fly ash and 75% GP cement. The fly ash content in FNS had to be increased compared to FA20 as recommended by Saha and Sarker (2016) to prevent ASR. Initially, the intention was to use 30% fly ash replacement in FNS concrete, but it was difficult to achieve a 30 MPa compressive strength without changing significantly the mix design of the FNS concrete, compared to reference concretes. Indeed, 30% fly ash content affects badly the 28 days compressive strength (see FA30 in Table 3). To achieve 30 MPa, the best compromise was to reduce the fly ash content down to 25% and reduce the water/binder ratio of FNS25 down to 0.45 yielding a 28 days compressive strength of 32.8 MPa, which is close to the compressive strength of OPC100 and FA20 concrete (Table 3). Control concrete FA30 was then disregarded due to its poor performance. Moreover, in comparison with control concretes, the quantity of coarse aggregate was decreased, and the total amount of fine aggregate increased in FNS25, the total mass of aggregate (coarse and fine) in the mixes being constant. The intention was to obtain an overall grading curve including all aggregates similar for all concretes as shown in Fig. 3.

(4) Batching procedure and curing procedures
All aggregates were in the saturated surface dry condition. Aggregates and binder were dry mixed for two minutes. Then, water was added, and mixing was continued for another 5 minutes. Cylindrical moulds were closed.
filled with fresh concrete in two layers and compacted using a vibrating table. After surface finishing, all moulds were covered by using lids to prevent moisture loss. All specimens were demoulded after 24 hours and were stored in the control room at a fixed temperature of 23±2°C and relative humidity of 50% until the testing dates.

2.2 Experimental program

(1) Mechanical properties
A sufficient number of cylinders and prisms were cast and tested to determine the mechanical properties of the concrete at the age of 1, 2, 3, 7 and 28 days. Three specimens were tested in order to assess the mean value for each mechanical property. This practice was repeated for each concrete batch. Compressive strength, elastic modulus and indirect tensile strength tests were conducted on cylinders in accordance with AS 1012.9 (2014) and AS 1012.10 (2000).

(2) Direct tension creep test on dog-bone shaped specimens
As shown in Fig. 4(a), dog-bone shaped specimens were used for direct tension creep tests in a temperature and humidity-controlled room at a constant temperature of 23°C and a relative humidity of 50%. The dog-bone specimens were fixed into the creep rig by means of two steel plates glued to each end of the specimen with high strength epoxy. Two threaded bolts were also cast into the specimens and connected to the steel plates at each end as shown Fig. 4(a). The steel plates were glued to the concrete specimen to ensure an even stress distribution from the applied tensile load. Using the loading setup shown in Fig. 4(b), the specimens were loaded from the top of the creep rig by tightening a nut on a high strength threaded bar and a spring was used to maintain a constant stress level.

In this test, the specimens were loaded 2 days after casting to a sustained stress level of 50% of the tensile strength ftc(t) measured at the age of 2 days. Moreover, unloaded specimens were monitored to measure the free shrinkage strains and loaded specimens were used to measure the initial elastic strain and the time-dependent strains resulting from shrinkage and tensile creep. A total of six dog-bone specimens were cast for each concrete mix, including three loaded specimens and three unloaded specimens.

(3) Restrained ring test
A restrained shrinkage ring test was performed in the control room to assess the risk of restrained shrinkage induced cracking. The dimensions and arrangement of the restrained ring specimens are shown in Figs. 5 and 6.

The specimens were shifted to control room immediately after casting. After 24 hours the outer ring was removed from the restrained shrinkage specimens and a self-adhesive aluminium foil was applied to the outer surface to allow the specimens to shrink uniformly from top and bottom surfaces only [Fig. 6(a)]. In the case of the free shrinkage specimens, both the outer and inner ring was removed and self-adhesive aluminium foil was also applied on both surfaces in order to have similar
shrinkage conditions as for the restrained specimens [Fig. 6(b)]. In order to eliminate the effect of friction between concrete and steel, mold releasing agent was applied at the outer circumferential surface of the steel ring.

(4) Instrumentation
Strain gauges were attached to each 35 mm thick face of the dog bone specimens at mid-height where the width of the specimen is 70 mm. For the restrained ring specimens, three equally spaced strain gauges were attached at the mid height of the inner surface of the steel ring to measure the strains in the steel ring due to concrete shrinkage. For free shrinkage measurement, three strain gauges were applied at the inner surface of the concrete ring. The location of these strain gauges corresponded to the location of the strain gauges on the steel rings. The strains are recorded at regular intervals using a data acquisition system.

(5) Microstructural analysis of ITZ
SEM-EDS analysis was performed to investigate the aggregate-matrix interface, the so-called Interfacial Transition Zone (ITZ). Specimens were sampled from the bulk of a 28 days concrete cylinder by using a slow-speed diamond cutter. After being dried at 50 degrees, they were impregnated with low-viscosity epoxy in a vacuum chamber. The impregnated specimens were first lapped on the diamond-coated wheels with progressively smaller grit (45 µm, 30 µm, and 15 µm). Finally, each specimen was polished using polishing cloth and diamond paste with progressively smaller grit (9 µm, 6 µm, 3 µm, 1 µm, and 0.25 µm). Carbon coating was applied to obtain a better surface conductivity prior to the microstructural analysis. A Hitachi S3400 scanning electron microscope (SEM) coupled with Quantax 400 energy dispersive X-ray spectrometer available at the Electron Microscope Unit at the Mark Wainwright Analytical Centre, UNSW Sydney, Australia was used under backscattered image to observe the ITZ microstructure and assess the elemental composition of the matrix close to both Sydney sand and FNS sand-matrix interface. The SEM-EDS analysis was carried out at 20 kV beam strength with a 10 mm working distance.

3. Test results and discussions

3.1 Mechanical properties
Tables 4, 5, and 6 show the time-dependent average compressive strength, tensile strength and elastic modulus of concrete respectively. The statistical variation of mechanical characteristics of concrete for all the batches was less than 10%. Results show that the increase in fly ash content resulted in a remarkable reduction in both compressive and tensile strength gain at

| Table 4 Time-dependent average compressive strength (MPa) of concrete. |
|-----------------|--------|--------|--------|--------|
| Age (days)      | OPC100 | FA20   | FA30   | FNS25  |
| 1               | 15.00  | 11.00  | 6.00   | 12.00  |
| 2               | 21.55  | 16.00  | 11.00  | 16.00  |
| 3               | 25.00  | 18.00  | 13.00  | 22.30  |
| 7               | 32.00  | 23.50  | 18.00  | 26.30  |
| 28              | 35.00  | 30.50  | 22.00  | 32.80  |

| Table 5 Time-dependent average tensile strength (MPa) of concrete. |
|-----------------|--------|--------|--------|--------|
| Age (days)      | OPC100 | FA20   | FA30   | FNS25  |
| 1               | 1.35   | 1.25   | 0.70   | 1.05   |
| 2               | 2.10   | 1.70   | 1.20   | 1.70   |
| 3               | 2.55   | 2.05   | 1.40   | 2.50   |
| 7               | 2.95   | 2.50   | 1.80   | 2.65   |
| 28              | 3.50   | 2.90   | 2.10   | 3.40   |

| Table 6 Time-dependent average elastic modulus (GPa) of concrete. |
|-----------------|--------|--------|--------|--------|
| Age (days)      | OPC100 | FA20   | FA30   | FNS25  |
| 1               | 20.10  | 16.10  | 15.50  | 20.50  |
| 2               | 22.00  | 21.30  | 16.70  | 22.80  |
| 3               | 24.00  | 22.50  | 20.00  | 25.10  |
| 7               | 27.80  | 25.00  | 21.50  | 25.30  |
| 28              | 28.60  | 26.80  | 21.90  | 27.10  |
early-age. The measured compressive strengths of FA20 and FA30 one day after casting were 73% and 40% of that of OPC100. At the age of 28 days, the measured compressive strength of FA20 and FA30 were 82% and 63% of that of OPC100 respectively. Similarly, after one day, the tensile strength of FA20 and FA30 were 93% and 52% of that of OPC100 respectively. The measured tensile strength of FA20 and FA30 at 28 days was 83% and 60% of that of OPC100 respectively. Compared to compressive strength and indirect tensile strength, the elastic modulus was not as much affected by the replacement of OPC by fly ash. At the age of 28 days, the elastic moduli of FA20 and FA30 reached 94% and 77% of that of OPC100 respectively. The development of the compressive strength of FNS25 is similar with the performance of FA20. The lower water to binder ratio of FNS25 concrete might have contributed to the increase of the compressive strength. At the age of 28 days, the compressive strength of FNS25 concrete was slightly higher than that of FA20 concrete but by only 7% which seems not to be relevant. Regarding the tensile strength, except after one day, the performance of FNS25 is closer to that of OPC100 and better than that of FA20. At the age of 28 days, the tensile strength of FNS25 was about 20% higher than that of FA20, which could be due to not only the lower water to binder ratio but also the contribution of the FNS sand in improving concrete strength (see section on microstructural characterisation).

Considering the mechanical properties of all concrete mixes tested, the tensile creep and restrained shrinkage tests were carried out only using OPC100, FA20, and FNS25. Indeed, the performance of FA30 was not suitable to carry out the creep test. The tensile strength of FA30 was too low at the early age (at 2 days). Moreover, the tensile specimens were loaded at the age of 2 days as the tensile strengths of all specimens were too low at the first day.

3.2 Direction tension test

The free shrinkage strains were measured on the unloaded companion dog-bone specimens. The results are shown in Fig. 7. The measured free shrinkage strains were not influenced by either fly ash or FNS sand, significantly. At the age of 21 days, the measured free shrinkage strain of FA20 was -523 $\mu$e, which was 96% of the shrinkage strain measured on OPC specimens (-546 $\mu$e). The shrinkage strain of the FNS25 specimens at age 21 days was -535 $\mu$e.

The total strain $\varepsilon(t)$ at age $t$ in a uniaxially loaded specimen at constant temperature may be expressed as the sum of the instantaneous (or elastic) strain $\varepsilon(t)$, the creep strain $\varepsilon_c(t)$ and the shrinkage strain components $\varepsilon_s(t)$:

$$\varepsilon(t) = \varepsilon(t) + \varepsilon_c(t) + \varepsilon_s(t)$$ (1)

In this test, the total strain was measured on the specimens by using the strain gauges attached to the surface of the specimens. A constant stress $[\sigma(t) = \sigma_r(t)]$ was applied at the age of $r = 2$ days, and the instantaneous strain at time $t$ can be calculated by

$$\varepsilon(t) = \frac{\sigma(t)}{E(t)}$$ (2)

where $E(t)$ is the elastic modulus of concrete at age $t$. The creep strain $\varepsilon_c(t)$ can be deduced from the experimental data using Eq. (1) and Eq. (2). The creep coefficient for the dog-bone specimens can be calculated as

$$\phi(t, r) = \frac{\varepsilon_c(t)}{\varepsilon_c(r)} = \frac{\varepsilon(t) - \varepsilon_c(t) - \sigma_r(t)}{\sigma_r(t)} E_c(t)$$ (3)

Figure 8 shows the average tensile creep coefficient of the dog-bone specimens cast using concrete OPC, FA20, and FNS25. The tensile creep coefficient in FNS25 specimens [i.e. $\phi(21.2) = 2.29$] is larger than OPC100 [i.e. $\phi(21.2) = 1.16$] and FA20 [i.e. $\phi(21.2) = 1.78$] concretes. High tensile creep is helpful to relax undesirable stresses in concrete caused by restrained shrinkage, thermal gradient, support-restraint, and so on (Gilbert and Ranzi 2010).

3.3 Restrained ring test

Ring specimens cast by using OPC100, FA20, and FNS25 were tested and results are plotted in Fig. 9. The replacement of cement by fly ash raises the risk of early-age cracking. As shown in Fig. 9(b), the steel strain on FA20 suddenly dropped down to zero at the age of 10 days as soon as a crack occurred in the concrete as shown.
in Fig. 9(d). Meanwhile, the OPC-based concrete specimen (OPC100) cracked much later than FA20 at the age of 15 days as shown in Fig. 9(a). The replacement of natural sand by FNS can significantly improve the performance of fly ash blended cement-based concrete. Compared to FA20, FNS25 specimens, which used 5% more fly ash, cracked at the age of 15 days (the same day with OPC100).

The tensile stress, which led to cracking, resulted from the shrinkage of the concrete ring restrained by the steel ring. The average tensile stress $\sigma_{\text{act}}(t)$ of concrete in restrained ring specimens, taking into account both the shrinkage strain and the relaxation due to tensile creep, can be calculated as follows (Hossain and Weiss 2004):

$$\sigma_{\text{act}}(t) = -\varepsilon_s(t)E_sC_{3k}C_{4k}$$  \hspace{1cm} (4a)

$$C_{3k} = \frac{r_{oc}^2 + r_{in}^2}{r_{oc}^2 - r_{in}^2}$$  \hspace{1cm} (4b)

$$C_{4k} = \frac{r_{oc}^2 - r_{in}^2}{2r_{in}^2}$$  \hspace{1cm} (4c)

where $\varepsilon_s(t)$ is the measured strain in the inner steel ring; $E_s$ is the modulus of elasticity of the steel (200 GPa), $r_{oc}$ and $r_{in}$ are the outer radius of the steel and concrete rings respectively, $r_{in}$ is the internal radius of the steel ring. Figure 10 shows the calculated tensile stress resulting from restrained shrinkage for OPC100, FA20 and FNS25. According to Altoubat and Lange (2001), the direct tensile strength of concrete is approximately 80% of the indirect tensile strength at ages greater than about 100 hours. Due to the uncertainties of mechanical properties of concrete, the cracking occurred when the tensile stress was slightly lower than the direct tensile strength. As shown in Fig. 9(a) and 9(b), the direct development of tensile stress of FA20 was lower than that of OPC100 and FNS25. Hence, the ring specimens cast with F20 cracked much earlier than OPC100 ring (at the age of 10 days). Compared to FA20, FNS25 has a higher tensile strength (Table 5) after three days and a significantly higher creep coefficient (Fig. 8). As a result, FNS25 ring cracked 5 days later than FA20 ring. Regarding to OPC100 and FNS25, they had a similar free shrinkage. FNS25 had a high creep coefficient (Fig. 8), whereas the tensile strength of FNS25 was lower than that of OPC100 (Table 5). Hence, OPC100 and FNS25 cracked at the same day.

3.4 Microstructural characterisation of ITZ

The characteristic of the interfacial transition zone (ITZ) between aggregate and cement paste is an important factor governing the mechanical and durability properties of concrete. The geometrical arrangement of cement grains is disturbed in concrete by the presence of aggregates. This involves a wall effect creating a gradient for water concentration in the cement paste (Ollivier et al. 1995). This perturbation is most significant over a thickness of 15 to 20 µm around aggregates, leading to several consequences on the microstructure of the hydrated cement paste in the vicinity of aggregates such as greater water to cement ratio and higher porosity. As a result, ITZ is mechanically less resistant than the bulk cement paste. The first microcracks resulting from me-
mechanical or hydrothermal actions will appear in this zone. In terms of hydration products, previous studies showed that calcium hydroxides (Portlandite) is mainly crystallizing in the ITZ with a preferential orientation weakening the ITZ (Ollivier et al. 1995; Tang et al. 2015; He et al. 2014; Gao et al. 2018). Ollivier et al. (1995) also observed a very significant increase in Ca/Si ratio of hydrated cement paste in the ITZ (up to 6) compared to that of the bulk matrix (around 3) due to both excess in Portlandite and low C-S-H content. A detailed analysis by SEM and EDS analysis was conducted to compare the geometrical shape and the ITZ properties of FNS aggregate and Sydney sand, aiming to explain the improvements observed in FNS25 performance compared to reference concretes in terms of both mechanical and durability properties.

The typical particle shapes of FNS and Sydney sand are displayed in Fig. 11. FNS aggregate shape is mostly angular whereas the shape of Sydney sand is mostly rounded. The irregular shape of FNS sand may...
strengthen the bond between the aggregate and the cement matrix and certainly contribute to enhance the mechanical properties of concrete. It is worth noticing that the water absorption of FNS sand is very low, around 0.79%, compared to that of Sydney sand (3.5%) leading to much less interference with cement hydration in the ITZ by either absorbing or releasing water. The low water absorption of FNS sand can contribute in the improvement of the ITZ. Importantly, no sign of ASR gel formation could be observed anywhere at the interface between FNS sand and cement paste in the specimens tested.

Beyond the potential improvement in physical bond between FNS sand and cement paste, the chemical interactions between FNS sand and the cement paste were investigated as well by EDS analysis. Line profile analysis was carried out through the ITZ of both Sydney sand and FNS sand. Figure 12 shows typical results obtained for Sydney sand ITZ including Ca, Si, Al and Mg. Figs. 13 and 14 present the results obtained at two different locations for FNS sand ITZ.

As shown in Fig. 12, the cement paste in Sydney sand ITZ over about 20 µm is mainly composed of Ca and Si. The ratio Ca/Si is very high (around 6.13) and consistent with results obtained by Ollivier et al. (1995), showing that hydrates in Sydney sand ITZ are mostly Portlandite. However, according to Figs. 13 and 14, FNS sand ITZ matrix composition is fundamentally different compared to that of Sydney sand. The ratio Ca/Si measured is drastically lower as a result of the Si sourced by FNS sand due to its amorphous nature. The average ratios Ca/Si in Figs. 13 and 14 were equal to 0.90 and 1.49 respectively. The presence of Al in significant quantity is observed as well in the ITZ. Importantly, the level of Mg in the ITZ remains very low. As a result, Mg from FNS sand does not interfere with the cement paste hydration in the ITZ. The low Ca/Si ratio in FNS ITZ shows that the matrix composition in mainly calcium silicate alu-
minate hydrates. Further investigations are required to identify in detail the nature of the hydrates forming in FNS sand ITZ. However, the excess in Portlandite weakening the ITZ of natural aggregate (Ollivier et al. 1995; Bourdette and Revertegat 1994) is absent in the FNS sand ITZ providing an explanation for the increase in early compressive and tensile strength observed in concrete with FNS sand.

4. Simulations of reinforced concrete members

In this section, several simulations are proposed in order to compare the performance of FA20 and FNS25 in reinforced concrete structures.

4.1 Symmetrically reinforced concrete short column

A symmetrically reinforced concrete short column of length \( L \) is considered for the first simulation (Fig. 15). Both width and height of the column are 200 mm, and the area of concrete and reinforcement are \( A_c \) and \( A_s \) respectively. The total strain of concrete can be expressed by Eq. (1). In this case, if an early-age shrinkage \( \varepsilon_{cs} \) commencing \( \tau \) days after casting is considered, the restrained shrinkage gradually leads to an increase in tensile stress. According to the age-adjusted effective modulus method (Trost 1967; Dilger and Neville 1971; Bazant 1972), the creep strain of concrete can be calculated as follows:

\[
\varepsilon_c(t) = \frac{\Delta \sigma(t, \tau)}{E_s} \chi(t, \tau) \phi(t, \tau) \tag{5}
\]

Neglecting the effect of gravity, the increase in tensile stress in concrete \( \Delta \sigma(t, \tau) \) can be derived on the basis of equilibrium and compatibility of strains assuming that perfect bond exists between the concrete and steel:

\[
\varepsilon_c(t)E_s A_s + \Delta \sigma(t, \tau) A_c = 0 \tag{6a}
\]

\[
\varepsilon_c(t)E_s = \varepsilon_s(t) \tag{6b}
\]

where \( \varepsilon_c(t) \) is the strain in the reinforcing bar (and \( \varepsilon_s(t)E_s A_s \) is the force carried by the steel bar), \( E_s \) is the elastic modulus of steel.

By substituting Eqs. (1), (2), (5), and (6b) into Eq. (6a), the increment in tensile stress of concrete can be calculated by

\[
\Delta \sigma(t, \tau) = \frac{-\varepsilon_{cs}(t)E_s}{1/\rho + E_s/E(t) + E_s/E(\tau)\chi(t, \tau)\phi(t, \tau)} \tag{7}
\]

where \( \rho \) is the reinforcement ratio (\( \rho = A_s/A_c \)).

It is assumed that the column is exposed to a dry environment similar to the exposure conditions of the dog-bone and ring specimens. In order to calculate the creep and shrinkage strains of the column from the measured results on the dog-bone specimens, despite their different dimensions, the ratio of their hypothetical thickness \( t_h \) as defined by Eq. (8) as in AS3600 (2009) was used as follows:

\[
t_h = \frac{2A}{u} \tag{8}
\]

where \( A \) is the cross-sectional area of the specimen and \( u \) is the perimeter of the specimen exposed to the atmosphere.

The creep coefficient of the column \( \phi(t, \tau) \) was calculated as follows:

\[
\phi(t, \tau) = \frac{k_2(t_h, \phi)}{k_2(t_h, c)} \phi(t, \tau)_c \tag{9}
\]

where \( k_2 \) is the development factor of creep with time (AS3600 2009; Gilbert and Ranzi 2010), \( t_{h, \phi} \) is the average hypothetical thickness of the dog-bone specimen, \( t_{h, c} \) is the hypothetical thickness of the RC column and \( \phi(t, \tau)_c \) is the creep coefficient measured from the dog-bone specimen.

The dry shrinkage strain of the column \( \varepsilon_{sh}(t, \tau) \) was calculated as follows:

\[
\varepsilon_{sh}(t, \tau) = \frac{k_1(t_h, \phi)}{k_1(t_h, c)} \varepsilon_{sh}(t, \tau)_c \tag{10}
\]

where \( k_1 \) is the development factor of dry shrinkage with time (AS3600 2009; Gilbert and Ranzi 2010) and \( \varepsilon_{sh}(t, \tau)_c \) is the dry shrinkage strain measured from the dog-bone specimen.

The development of tensile stress in concrete in the symmetrically reinforced concrete short column cast by using FA20 or FNS25 with various reinforcement ratios were calculated and the ratio of tensile stress to tensile strength \( R(t) \) was used as the risk index to evaluate the risk of early-age cracking:

\[
R(t) = \frac{\Delta \sigma(t, \tau)}{f_u(t)} \tag{11}
\]

The calculated values of \( R(t) \) are shown in Fig. 16. Due to the increase in the shrinkage induced tensile stress,
the risk of early-age cracking arises with the age of concrete as shown in Fig. 16(a). Figure 16(b) compares the risk of early-age cracking of the OPC100, FA20 and FNS columns at the age of 21 days. It is an effective approach to mitigate the risk of early-age cracking in fly ash blended cement-based concrete to use FNS. For example, the risk index $R(t)$ of the reinforced concrete columns cast by using OPC100, FA20, and FNS25 with a reinforcement ratio of 4% at the age of 21 days are equal to 64.72%, 72.00%, and 62.89%, respectively.

4.2 Reinforced concrete beam

In the reinforced concrete beam, the reinforcement is not symmetrically placed in the section as shown in Fig. 17. The shrinkage of the concrete fibre at the level of the reinforcement is restrained. The steel is compressed and an equal and opposite tensile force is imposed to the concrete at the level of the reinforcement. The tensile restraining force is eccentric to the centroid of the concrete cross-section causing a shrinkage induced curvature $\kappa$ on the cross-section and a concrete tensile stress $\rho$.

![Graphs showing time-dependent risk and reinforcement ratio](image_url)

(a) Time-dependent risk of early-age cracking risk in OPC100, FA20 and FNS25 concrete columns

![Graph showing risk of early-age cracking at 21 days](image_url)

(b) Risk of early-age cracking in OPC100, FA20 and FNS25 concrete columns at the age of 21 days

Fig. 16 Risk of early-age cracking in symmetrically reinforced concrete short column.

![Diagram showing cross-section, strain, and stress](image_url)

Fig. 17 Shrinkage-induced deformation and stresses in a simply supported reinforced concrete beam.
at the extreme fibre that may initiate cracking (Gilbert 2017), as shown in Fig. 17.

The extreme concrete fibre tensile stress \( \Delta \sigma(t, \tau) \), caused by a uniform free strain of magnitude \( \varepsilon_{cs}(t) \) may be approximated by (Gilbert 2017):

\[
\Delta \sigma(t, \tau) = \frac{-E_{cs}(t)E_n \rho (1 + \lambda_1 \lambda_2)}{1 + n_{aef} \rho (1 + \lambda_1)} \tag{12a}
\]

\[
\rho = \frac{A}{bh} \tag{12b}
\]

\[
n_{aef} = \frac{E}{E_n} [1 + \chi(t, \tau) \phi(t, \tau)] \tag{12c}
\]

where \( b \) and \( h \) are the width and height of the cross-section respectively; \( n_{aef} \) is the age-adjusted modular ratio; \( \lambda_1 \) and \( \lambda_2 \) depend on the geometry of the cross-section and are given by:

\[
\lambda_1 = 12 \left( \frac{d}{h} - 0.5 \right)^2 \tag{13a}
\]

\[
\lambda_2 = \frac{0.5h}{d - 0.5h} \tag{13b}
\]

where \( d \) is the effective depth of the reinforcement.

Similar to columns, reinforced concrete beams with OPC100, FA20 and FNS were analysed. The beams have a uniform rectangular cross-section 400 mm deep by 300 mm wide, and \( d/h \) is equal to 0.9. The time-dependent extreme fibre concrete tensile stress with various reinforcement ratio were calculated, and the risk of early age cracking was assessed by using Eq. (11). The results are shown in Fig. 18. Similarly to reinforced concrete column, using FNS resulted in less restrained shrinkage induced tensile stress and less risk of early age cracking. The risk index \( R(t) \) of the reinforced concrete beams cast by using OPC100, FA20, and FNS25 with the reinforcement ratio of 4% at the age of 21 days are equal to 76.57%, 84.06%, and 73.26%, respectively.

5. Conclusion

In this paper, the concrete mix with 50% natural sand replacement by FNS sand and 25% ordinary portland cement substitution by fly ash (FNS25) was considered to mitigate the risk of early age cracking in fly ash blended cement-based concrete. Experimental tests were carried out in order to accurately quantify early-age shrinkage and tensile creep of concrete and assess their influence on cracking in reinforced concrete members. The proposed concrete mix and two control concrete mixes (OPC100 and FA20) were tested. The evolution of the tensile creep was measured directly using unrein-
forced dog-bone shaped specimens subjected to sustained axial tension. Restrained shrinkage cracking was assessed through restrained concrete ring tests. Microstructural characterisation of ITZ was carried out to explain the improvements observed in FNS25. In addition, restrained shrinkage induced tensile stress in reinforced concrete column and beam was simulated. No thermal effects due to heat of hydration were considered in this paper.

The following conclusions can be drawn:

1. The free shrinkage strain is not influenced by either fly ash or FNS sand significantly, whereas the tensile creep coefficient of FNS25 is significantly larger than that of both OPC100 and FA20. Experiments are in progress aiming to understand why FNS25 tensile creep is higher than that of control concretes.

2. Both restrained ring tests and simulations on reinforced concrete members show that tensile creep and shrinkage characteristics of FNS25 contribute to relax the restrained shrinkage induced tensile stress in concrete and reduce the risk of early-age cracking compared to conventional fly ash blended cement-based concrete.

3. Microstructural analysis results show that excess in early-age compressive and tensile strength of FNS25 concrete. Additionally, the FNS aggregate shape is mostly angular, which may strengthen the bond between aggregate and cement matrix, leading to the better mechanical properties of concrete.

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