Concrete is the most widely manufactured construction material. The addition of carbon nanofibres (CNFs) to concrete has many advantages in terms of mechanical and electrical properties (e.g. higher strength, higher Young’s modulus and improved fatigue resistance) and self-monitoring behaviour due to the high tensile strength and high conductivity. In this work, the pulse velocity method was used to characterise the properties of concrete containing CNFs. Concrete strength correlations between pulse velocity, electrical resistance variation and destructive tests were analysed for different mix proportions. The test results indicate that the compressive strength, pulse velocity and percentage reduction in electrical resistance while loading concrete containing CNF differ from those of plain concrete. Based on the pulse velocity results, a reasonable concentration of CNFs was determined for use in concrete, which not only enhances compressive strength, but also improves the electrical properties required for strain monitoring, damage evaluation and self-health monitoring of concrete.

Introduction

Concrete has been used as a major construction material for many years in the field of civil engineering because of its high compressive strength and constructability. During casting and loading, cement (the binding component of concrete) develops microcracks, which weaken the final concrete structure. Microcracks, which range in size from picometres to micrometres, eventually lead to abrupt failure if not detected and repaired. In order to restrict the growth of microcracks, carbon nanofibres (CNFs) have been added to concrete mixes. CNFs have tensile strengths over 7.0 GPa (1015 ksi) and an average length of 20 μm. These characteristics enable the nanofibres to bridge microcracks and absorb the energy normally released during crack propagation. The addition of CNFs into concrete increases its strength and ductility, making the material more robust.

Carbon fibre concrete has gained in acceptance over recent years due to a decrease in the cost of the fibres (Newman, 1987) and increased demand for superior structural and fundamental properties such as strength, ductility, creep, shrinkage and ductility. The strength of the cement concrete increases with the development of nanoscale bonding between calcium silicate hydrate (CSH) and the nanofibre, with the nanofibre having the ability to hold the cement matrix more strongly than the CSH (Ji, 2005). Makar and Beaudoin (2003) noted that nanofibres fill voids in the CSH gel structure and make the binding paste matrix denser. The addition of nanofibre improves the integration and stability of the hydration product structure and increases the long-term mechanical properties and durability of the concrete. Li et al. (2007) indicated that the addition of nanofibre also improves the flexural fatigue performance of concrete.

Short carbon fibres enhance the sensing capability of concrete because the electrical conductivity of the fibres allows the DC electrical resistivity of the composites to change in response to strain, damage or temperature (Chen and Chung, 1993, 1996). Chung (1995) pointed out that the length of the carbon fibres relative to the aggregate size decreases as aggregate size increases, so that the effectiveness of the carbon fibres in improving the flexural strength of concrete decreases as aggregate size increases. Concrete containing 0.2–1.1% by volume of carbon fibres is capable of providing non-destructive structural health monitoring by way of electrical probing and, without the nanofibre, no smart behaviour was observed. Chung (1995) also reported that by using carbon fibre together with a water reducing agent and accelerating admixture at 28 d of curing, flexural strength increased by about 85%, flexural toughness increased by about 205% and compressive strength increased by 22% while aggregate size had little effect on the effectiveness of the results. Park and Lee (1993) noted that reinforcing Portland cement with carbon fibres decreased the flow values linearly with an increase in carbon fibre volume, but increased the tensile, compressive and flexural strengths.

Concrete mixed with CNFs acts as a sensor – without CNFs, its sensing ability becomes poor. The CNFs bridge the microcracks and improve the sensing capability upon straining the concrete, and hence act as a strain sensor. Strains and stresses are
proportional to one another in the elastic range, which means CNFs also facilitate stress sensing.

However, because of the large van der Waals forces between CNFs, their uniform dispersion throughout a cement matrix is difficult to achieve. In order to improve the dispersal of CNFs, self-consolidating concrete (SCC) has been used to increase flowability throughout wet concrete (Dhonde et al., 2007). Xiao et al. (2003) indicated that the nanofibre acts as a semiconductor and is useful for self-monitoring up to failure of the specimen. The fractional change in resistance linearly decreases with increasing compressive force up to failure. In this work, self-consolidating concrete with CNFs (CNFSCC) was therefore studied. Gao et al. (2009) indicated that some mechanical and electrical properties of CNFSCC were improved under compression stress, which is the most basic force acting on concrete in reinforced concrete structures. With particular regard to the electrical properties, relationships between electrical resistance variation (ERV) and strain and ERV and stress can be established. Therefore, damage evaluation and self-health monitoring of concrete structures might be easier to carry out since the concrete itself acts as a sensor, resulting in much lower costs of infrastructure maintenance and repair. The development of smart high-performance CNF concrete is thus a feasible and attractive prospect.

In recent years, many researchers have used the ultrasonic pulse velocity non-destructive technique to test materials because the method is easier and more economical than traditional tests. The pulse velocity method was used to evaluate the properties of the CNF concrete in this work. Lamb (1904) analysed surface wave propagation for the case of impulse vertical point load with a solution valid for a point far from the source. Lamb’s solution was later extended by Nakano (1925) for cases close to the source.

Pulse velocity changes with many concrete variables, including water content, mixing proportions, aggregate type and size, and concrete age. Several researchers have previously used the pulse velocity method to characterise the properties of concrete (Ak-kaya et al., 2003; Jones, 1949; Lawson et al., 2011; Tanigawa et al., 1984; Yaman et al., 2001). However, to the best of the authors’ knowledge, concrete containing CNFs has not been investigated using the pulse velocity method.

Okamoto and Whiting (1994) studied the maturity and pulse velocity method to predict the strength of concrete. Mantrala and Vipulanandan (1995) used the pulse velocity method for an evaluation of differences between polyester polymer and polymer. Frearson (1995) conducted non-destructive testing and discussed problems with concrete tests and test results in adverse weather conditions. Ohdaira and Masuzawa (2000) studied the effect of water content on pulse velocity and found that a 7% increase in water content can lead to a 12.5% increase in velocity. Hernandez et al. (2000) conducted pulse velocity tests to evaluate concrete deterioration caused by environmental damage. They concluded that previous knowledge of the concrete composition is important and that the concrete should be elastic and isotropic with a random distribution of pores. Sutan and Jaafar (2003) studied crack locations and compared pulse velocity measurements and impact echo methods. Abo-Qudais (2005) conducted pulse velocity tests and found that the velocity changes with different types of concrete mixtures, water content and aggregate sizes. Pulse velocity tests were also conducted by Popovics et al. (2000), who studied the effect of an uneven moisture distribution inside the concrete.

Mixing with CNFs allows for the greatest ERV of concrete with increasing strain and stress and, consequently, may be used in applications that require strain monitoring, making concrete itself a sensor for damage evaluation and self-health monitoring. The notion of CNF concrete as a smart material is thus feasible. With the knowledge acquired from this study, it is hoped that researchers can further develop an understanding of the correlation between pulse velocity, ERV and compressive strength of CNF concrete. In this research, at least three samples of each mixture were prepared to evaluate the properties of the CNFSCC. Because of the constraints on the number of samples tested in this research, the results might be further validated in the future.

**Experimental procedure**

**Material properties**

The following three types of CNF (from Pyrograf Products, Inc.) were used in this study.

- PR-19-XT-PS, produced by pyrolytically stripping the produced fibre to remove polyaromatic hydrocarbons from the fibre surface.
- PR-19-XT-PS-OX, an oxidised version of PR-19-XT-PS, which is more conductive.
- PR-19-XT-LHT-OX, which is produced by heat-treating the fibre at 1500°C. Heat treatment converts any chemical vapour deposited carbon present on the surface of the fibre to a short-range ordered structure. The inherent conductivity of the fibre is increased following heat treatment and it is the most conductive of the three types of fibres (www.pyrografproducts.com).

The high-range water reducer Glenium 3200 HES, a polycarb-oxylate admixture from BASF Chemical Co., was used to decrease the viscosity of the concrete (www.masterbuilders.com). The amphiphilic detergent sodium dodecyl sulfate (SDS) from Fluka was used to disperse the non-oxidised CNFs (such as PR-19-XT-PS) in water (www.sigmaaldrich.com). Antifoam 2210, a silicone–glycol emulsion (polypropylene glycol and polydi-methylsiloxane) from Dow Corning (www.dowcorning.com), was used for all three types of CNFs to reduce the amount of foam produced during mixing and after detergent addition. Low-alkali type I/II cement was used in all specimens. Crushed limestone with a maximum size of 19 mm was used as coarse aggregate in...
all specimens. Natural river sand with a fineness modulus of 2.71 was used as fine aggregate in all specimens.

**Mixture proportions**

As shown in Table 1, 13 CNFSCC mixtures were studied (binder weight is the total weight of cement and CNF)

- four mixes (0.25%, 0.5%, 1.0% and 1.5% by volume of binder) of PR-19-XT-PS
- four mixes (1.0%, 1.5%, 2.0% and 2.5% by volume of binder) containing PR-19-XT-PS-OX type fibres
- five mixes (0.7%, 1.0%, 1.5%, 2.0% and 2.5% by volume of binder) containing PR-19-XT-LHT-OX.

The samples were named according to the following convention. CNFSCC025-S identifies self-consolidated concrete containing 0.25% CNF type PR-19-XT-PS. Similarly, CNFSCC10-PO denotes 1.0% CNF type PR-19-XT-PS-OX and CNFSCC07-LO denotes 0.7% CNF type PR-19-XT-LHT-OX.

**Testing methods**

**Destructive testing**

The CNF/water/SDS/antifoam mixture was slowly poured into a mixer and stirred for several minutes to achieve good workability. The fresh concrete was poured into moulds to form cylinders of 200 mm height and 100 mm diameter. The specimens were demoulded after 1 d and then allowed to cure at room temperature until tested. Compression tests were conducted on the cylinders using a Tinius Olsen universal material tester with a maximum load capacity of 2700 kN according to ASTM rates of 1300 N/s in load-control mode and 0.0013 mm/s in strain-control mode. A compressometer Standard C 39M-05 load with a digital dial gauge was used to detect strain. After the compression tests, some pieces of crushed specimens were selected for scanning electron microscopy (SEM).

**Electrical resistance variation (ERV) testing**

The four-probe method was used to determine the volume electrical resistance of the specimens (Figure 1). The surface of each specimen was ground in order to expose higher densities of CNFs and remove dust from the surface where the wires contacted the specimen. Conductive silver epoxy was spread along the wires to hold them in place and ensure continuous contact with the concrete surface. Current was measured across

---

**Table 1. Mix proportions (Gao et al., 2009)**

<table>
<thead>
<tr>
<th>Mix</th>
<th>Carbon nanofiber: vol% binder</th>
<th>Water: kg/m³ concrete</th>
<th>Cement: kg/m³ concrete</th>
<th>Coarse aggregate: kg/m³ concrete</th>
<th>Fine aggregate: kg/m³ concrete</th>
<th>High-range water reducer: ml/kg</th>
<th>Sodium dodecyl sulfate (SDS): kg/m³</th>
<th>Antifoam: ml/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC</td>
<td>0.00</td>
<td>191</td>
<td>480</td>
<td>901</td>
<td>1005</td>
<td>7·17</td>
<td>0·00</td>
<td>0·00</td>
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<tr>
<td>CNFSCC025-S</td>
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<td>191</td>
<td>480</td>
<td>901</td>
<td>942</td>
<td>7·17</td>
<td>0·18</td>
<td>7·17</td>
</tr>
<tr>
<td>CNFSCC05-S</td>
<td>0·50</td>
<td>191</td>
<td>448</td>
<td>838</td>
<td>877</td>
<td>9·13</td>
<td>0·36</td>
<td>15·65</td>
</tr>
<tr>
<td>CNFSCC10-S</td>
<td>1·00</td>
<td>191</td>
<td>448</td>
<td>838</td>
<td>877</td>
<td>9·13</td>
<td>0·77</td>
<td>28·04</td>
</tr>
<tr>
<td>CNFSCC15-S</td>
<td>1·50</td>
<td>191</td>
<td>448</td>
<td>838</td>
<td>877</td>
<td>10·43</td>
<td>1·15</td>
<td>40·42</td>
</tr>
<tr>
<td>CNFSCC10-PO</td>
<td>1·00</td>
<td>191</td>
<td>478</td>
<td>902</td>
<td>1008</td>
<td>7·17</td>
<td>0·00</td>
<td>7·17</td>
</tr>
<tr>
<td>CNFSCC15-PO</td>
<td>1·50</td>
<td>191</td>
<td>478</td>
<td>902</td>
<td>1008</td>
<td>12·39</td>
<td>0·00</td>
<td>7·17</td>
</tr>
<tr>
<td>CNFSCC20-PO</td>
<td>2·00</td>
<td>191</td>
<td>478</td>
<td>902</td>
<td>1008</td>
<td>15·00</td>
<td>0·00</td>
<td>7·17</td>
</tr>
<tr>
<td>CNFSCC25-PO</td>
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<td>191</td>
<td>478</td>
<td>902</td>
<td>1008</td>
<td>22·82</td>
<td>0·00</td>
<td>7·17</td>
</tr>
<tr>
<td>CNFSCC07-LO</td>
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<td>191</td>
<td>478</td>
<td>902</td>
<td>1008</td>
<td>4·56</td>
<td>0·00</td>
<td>7·17</td>
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<td>478</td>
<td>902</td>
<td>1008</td>
<td>7·17</td>
<td>0·00</td>
<td>7·17</td>
</tr>
<tr>
<td>CNFSCC15-LO</td>
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<td>191</td>
<td>478</td>
<td>902</td>
<td>1008</td>
<td>12·39</td>
<td>0·00</td>
<td>7·17</td>
</tr>
<tr>
<td>CNFSCC20-LO</td>
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<td>478</td>
<td>902</td>
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<td>15·00</td>
<td>0·00</td>
<td>7·17</td>
</tr>
<tr>
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<td>191</td>
<td>478</td>
<td>902</td>
<td>1008</td>
<td>22·82</td>
<td>0·00</td>
<td>7·17</td>
</tr>
</tbody>
</table>
the top and bottom wires using an ammeter with ±0.01 μA accuracy and voltage was measured across the two middle wires using a voltmeter with ±1.0 μV accuracy so that the electrical resistance between the two central wires could be calculated using Ohm’s law. Figure 2 shows the failed cylinder. A 1.5 V AA battery was used as the voltage source. The original voltage and current readings were recorded as $V_0$ and $A_0$, and the original electrical resistance $R_0$ was calculated. Subsequent voltage and current values were recorded each time the load and strain were recorded during the compressive test. Each strain value $\Delta_i$ at every time point $i$ had corresponding values of voltage and current recorded as $V_i$ and $A_i$. The electrical resistance $R_i$ and ERV ($\Delta R_i$) were calculated using:

1. $R_i = V_i/A_i$

2. $\Delta R_i = (R_i - R_0)/R_0$

Ultrasonic pulse velocity (UPV) testing

The device used for testing was the ultrasonic pulse velocity meter V-meter (http://www.ndtjames.com), which conforms to ASTM C 597 (ASTM, 2003). The V-meter can generate compressive waves travelling along materials and record the shortest travel time. The wave travel depends upon the concrete mix. The transit time can be measured with three methods – direct, semi-direct and indirect. The direct transmission method was used in this study because it is more reliable than the other two methods.

Pulse velocity was measured using two methods. First, it was measured along the longitudinal axis of the cylinder before destructive testing and was then correlated with the compressive strength at different ages of the concrete. Second, pulse velocity was measured continuously along the two transverse directions (across the cylinder diameter) at the middle of the cylinder (Figures 3) throughout the destructive testing. Since pulse velocity was measured continuously along the transverse direction, it could be correlated with several other parameters, such as ERV, concrete strength and deformation at different loading stages.

Pulse velocity is calculated from known distance and time. The pulse velocity along the longitudinal axis of the cylinder was calculated before destructive testing using

$$V_{PL} = L/T$$
Along the transverse direction of the cylinder, it was calculated during destructive testing from

\[ V_{PD} = \frac{D}{T^4} \]

where \( V_{PL} \) and \( V_{PD} \) are the pulse velocities (km/s) along longitudinal and transverse directions respectively, \( L \) and \( D \) are the length (km) and diameter (km) of the cylinder respectively and \( T \) is the travel time (s) between source and receiver transducers (Figure 3).

**Results and discussion**

**Strength and pulse velocity variations before destructive loading**

The pulse velocity \( V_{PL} \) was measured in the longitudinal axis of the cylinder at 3, 7, 14 and 28 d before destructive testing and these velocities were correlated with the corresponding compressive strengths after destructive testing. For all of the mixtures, pulse velocity \( V_{PL} \) increased with the age of the concrete. For all of the mixtures, the concrete compressive strength increased with the curing time of the mixture and the pulse velocity test results exhibited similar trends with compression test results. Because of this, the pulse velocity test results could be used to predict the compressive strengths of the specimens.

Compressive strength (\( f'_c \)) results are plotted against pulse velocity \( V_{PL} \) for the three types of mixes (CNFSCC-S, CNFSCC-PO and CNFSCC-LO) with a single regression line in Figure 4. The results show that linear correlations could be established for the concrete mixtures. The correlation was determined with simple regression analysis based on the least-squares method. The coefficient of determination \( r^2 \) was found to be above 0.80, indicating that the model represents well the relationship between the two variables \( f'_c \) and \( V_{PL} \). The linear equation for CNFSCC concrete mix

\[
f'_c = 42.150V_{PL} - 159.150
\]

is capable of predicting strengths of 25.0–56.5 MPa for the pulse velocity range 4.4–5.0 km/s with a maximum error of 17% (Figure 4). From Figure 4 it is evident that an increase in pulse velocity increases the compressive strength.

**Strength and pulse velocity variations during destructive loading**

The pulse velocity \( V_{PD} \) was measured at the middle of the cylinder along the transverse direction throughout loading. The stress–strain relations and variation of \( V_{PD} \) with stress and strain for plain SCC and the SCCCNF mixes are shown in Figures 5–13. As loading increases, compressive strain along the longitudinal direction increases along with an increase in concrete compressive stress. After reaching the peak stress of the concrete, the compressive stress reduces with an increase in compressive strain (Figures 5, 8 and 11). With an increase in compressive strain of the concrete along the longitudinal axis of the cylinder, tensile strain along the transverse direction increases because of Poisson’s effect, which causes damage to the cylinder. The pulse

![Figure 4. Concrete compressive strength and pulse velocity correlation for CNFSCC-S, CNFSCC-PO and CNFSCC-LO mixtures](image)

![Figure 5. CNFSCC-S: stress–strain relation](image)

![Figure 6. CNFSCC-S: pulse velocity–stress relation](image)
velocity $V_{PD}$ reduces steadily until reaching a compressive strain of about 0.001; after that, it reduces rapidly because of the increased in damage of the specimen. Each fibre mix was cast using at least three cylinder samples and the results were averaged from each experiment. The maximum observed variability between different experiments is below 10%.

Table 2 shows the compressive strength of SCC and the 13
CNFSCC mixtures at age 28 d. From Table 2 and Figures 5–7 for CNFSCC containing PR-19-XT-PS and SDS, the compressive strength and pulse velocity $V_{PD}$ varies as follows: CNFSCC05-S > SCC > CNFSCCC20-PO > CNFSCC15-LO > CNFSCC07-LO > CNFSCC25-LO > CNFSCC20-LO and is increased by 21-4% compared with plain SCC when the CNF concentration is 1-0%. This indicates that the concentration threshold is around 1-0% and corresponds to higher energy dissipation. From Figures 9 and 10 it is evident that the pulse velocity $V_{PD}$ and ductility of CNFSCC20-PO are 20% higher than those of SCC.

For CNFSCC containing PR-19-XT-PS-LHT-OX, the peak compressive strength and pulse velocity $V_{PD}$ varies as follows (Figures 11–13): CNFSCC10-LO > CNFSCC15-LO > SCC > CNFSCC07-LO > CNFSCC25-LO > CNFSCC20-LO and is increased by 21-4% compared with plain SCC when the CNF concentration is 1-0%. This indicates that the concentration threshold is around 1-0% and corresponds to higher energy dissipation. From Figures 12 and 13 it is clear that the pulse velocity $V_{PD}$ and ductility of CNFSCC10-LO are 20% and 45% higher than plain SCC respectively. From Figures 5–13 it is also clear that the ductility of SCC containing PR-19-XT-LHT-OX or PR-19-XT-PS-OX is greater than that of plain SCC or SCC containing PR-19-XT-PS.

The addition of amphiphilic detergent SDS used in the non-oxidised CNFs (PR-19-XT-PS) decreases the bond strength between cement and aggregate and hence an increase in fibre concentration beyond 0.5% decreases the strength. The oxidised types of fibres (19-XT-PS-OX and PR-19-XT-LHT-OX) improved the sensing capabilities of the concrete but decreased the strength with an increase in CNF concentration beyond the optimum value. This is attributed to the difficulty in distributing large concentrations of polar CNFs in a hydrophilic cement matrix.

It is thus evident that the pulse velocity has a direct correlation with strength and energy dissipation of CNF concrete. In the next section, the pulse velocity is correlated with the ERV.

**Pulse velocity and ERV during loading**

Concrete under increasing compressive load improves the contact between CNFs and transmits more current due to the tunnel effect (meaning that electrical charges can transfer between two CNFs without any direct contact if the distance between them is sufficiently small). The resistance decreases with an increase in current if the voltage remains constant. The resistance changes with strain until reaching the peak load; after that, microcracks increase in magnitude and propagate to more areas, which breaks the contact between the CNFs. A higher CNF concentration increases the contact between fibres and further decreases the resistance. Excess fibre addition causes clumps (observed during SEM studies), which increase microcrack formation.

Figures 14–22 show the relationships between ERV ($\Delta R_i$), pulse velocity $V_{PD}$, stress and strain for the plain SCC and SCCCNF mixtures. Figures 15 and 16 show the results for plain SCC and SCC containing CNF PR-19-XT-PS. Resistance did not change much at CNF concentrations of 0.5 and 1-0%, meaning that the minimum concentration of CNF is 1.5%, otherwise ERV cannot be measured.
be detected. From Figures 15 and 16, with an increase in strain and stress, the value of the pulse velocity \( V_{PD} \) was reduced. The ERV is increased with an increase in stress and strain. Figures 17–19 shows the results for plain SCC and SCC containing the PR-19-XT-PS-OX. Comparatively, a steady ERV can be detected when the fibre concentration is 1–2% (Figure 17); the minimum ERV across this range of concentrations varies between 0.2 and 0.25. The ERV decreases for all fibre concentrations and the minimum ERVs are inversely related to CNF concentration. The ERV does not change much when the concentration of CNF varies between 1% and 2%, but decreases significantly when the concentration of CNF is higher than 2%. Figures 20–22 show the results for plain SCC and SCC contain-
ing CNF PR-19-XT-LHT-OX. The resistance decreases for all fibre concentrations. At 1.0% CNF concentration, CNFSCC10-LO exhibits the highest electrical sensitivity with an 80% reduction in electrical resistance (Figure 20). ERV decreases rapidly when the concentration of CNFs is increased from 1.0 to 1.5%. This trend continues at a slower rate for CNF concentrations greater than 1.5%. When the concentration of PR-19-XT-LHT-OX fibres exceeds 2.0%, the reduction in electrical resistance is less than 10%. From Figures 19 and 21 it is evident that an increase in strain and stress reduces \( V_{\text{PD}} \) and ERV. Compared to the other mixes, CNFSCC10-LO exhibits the highest \( V_{\text{PD}} \) and the lowest ERV. For SCC, a sudden change in ERV is observed. This is because, after reaching a certain compressive strain, microcracks propagate throughout the concrete; without CNFs, no contact channels will be formed and hence the resistance will suddenly increased.

The strong trends with respect to fibre dosage rates have been studied by several researchers (e.g. Chen and Chung, 1996). Poor CNF dispersal is the greatest problem encountered during CNFSCC fabrication. Clusters of nanofibres in the cement matrix limit Ca(OH)\(_2\) crystal formation in the CSH gel, while good dispersion facilitates uniform CSH gel formation. The test results show significant improvement in the sensitivity of concrete containing an optimum percentage of CNF. As the CNF ratio increases over the optimum percentage, no improvement is observed or the concrete is actually harmed. This phenomenon could be attributed to poor dispersal of CNFs where excessive clumps of CNFs cause microcracking and reduction in concrete strength.
Microstructure

Figure 23 shows SEM images of CNFSCC with 1.5% concentration of CNFs by volume of cementitious material. Clumps of CNF at 430× magnification (Figure 23(a)) were found, indicating poor fibre dispersal. For SCC containing CNF PR-19-XT-LHT-OX, the threshold value of the concentration is 1.0% of CNF. Beyond 1.0% concentration, the CNFs formed more clusters and bonding between the CNFs and cement compounds was not effective because of lack of uniform dispersion. Figure 23(b) shows the microcracks at 1900× magnification for the same sample of CNFSCC15-LO. Figure 23(c) shows the presence of large hydrate crystals in combination with the absence of CNFs due to poor dispersal. If an appropriate amount of CNF is uniformly dispersed in the cement paste, the hydration products of cement surround and enclose the CNF because of its great surface energy. Therefore, CNF distributed in the cement paste is tightly bound to the hydration products so that transmission of the CNFs’ high tensile strength and electrical conductivity to the surrounding cement matrix is possible (Hui et al., 2004). Optimising CNF concentration also encourages uniform hydrate crystal growth, which reduces the volume of voids and improves the ultimate strength of the concrete. However, CNFs in excess of the threshold concentration will cause the fibres to attract one another and clump together in localised weak zones that decrease the ultimate strength of the concrete (Colston et al., 2000).

Conclusions

The results presented in this paper indicate that the strength and ductility of CNF concrete can be estimated by the pulse velocity method provided that the CNFs are well dispersed in the mix. It can also be concluded that the strength–pulse velocity relationship can be described by a linear equation for all mixtures. The ERV of plain SCC is random, so it is impossible to establish a relationship between ERV and strain/stress. Adding CNFs decreases the electrical resistance of SCC because it is a semiconductor, but there is a threshold for fibre concentration. If the actual concentration is higher than the threshold, the tunnel conductivity effect of the CNFs will decrease and the electrical resistance will not change with increasing strain. Well-dispersed CNFs in an appropriate concentration allow for determination of the steady pulse velocity and ERV of concrete with increasing strain and, consequently, may be used in applications that require strain monitoring, making the concrete itself a sensor.

Well-dispersed CNFs improve the pulse velocity, strength and stiffness of concrete. However, an excess concentration leads to poorly dispersed CNF clumps inside the concrete, which has a negative effect on pulse velocity, strength and electrical sensitivity. Each type of CNF requires a different concentration for optimum performance. PR-19-XT-PS performs best at concentrations of 0.5% for strength and greater than 1.5% for electrical sensitivity. PR-19-XT-PS-OX performs best at concentrations of around 2% for both strength and electrical sensitivity. PR-19-XT-LHT-OX performs best at concentrations of around 1.0% for both strength and electrical sensitivity. PR-19-XT-LHT-OX performs
better than the other two types of fibres tested, with an 80% reduction in electrical resistance and 20% increase in pulse velocity.

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