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Experimental evaluation of tensile strength test methods for steel fibre-reinforced concrete

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Abstract

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Keywords

experimental, fibre-reinforced, concrete, steel, methods, test, strength, tensile, evaluation

Disciplines

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Experimental Evaluation of Tensile Strength Test Methods for Steel Fibre Reinforced Concrete

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Abstract

This study presents an experimental evaluation of three different methods for determining the tensile strength of steel fibre reinforced concrete (SFRC). The test methods include the splitting test, Double Punch Test (DPT) and direct tensile test (DTT). The compressive strength of the concrete used in this study ranged between 30 and 80 MPa with 0%, 1.5% and 3% steel fibre

by volume of the concrete. In total, 81 concrete cylinders were cast and tested for 28-day compressive strength, splitting tensile strength and double punch tensile strength of the concrete. In addition, 27 concrete prism specimens were cast and tested to determine the direct tensile strength of the concrete. The test results show that, compared to the splitting test, the DPT is more effective in predicting the tensile strength of SFRC, as the tensile strengths obtained from the DPT and the direct tensile test are very close. The DPT is easier to perform and costs less than the splitting test and the direct tensile test.

Keywords: strength and testing of materials, failure, quality control.

Introduction

The use of Steel Fibre Reinforced Concrete (SFRC) in structural applications experienced continuous growth due to its enhanced tensile strength, flexural strength and ductility. Several studies were carried out in the literature to investigate the mechanical properties of SFRC. Although generally neglected in the structural design, the tensile strength of concrete is an important aspect in the design of concrete dams, airport pavement and tunnel lining. This is particularly because the cracking behaviour of concrete is a function of its tensile strength (Zain et al. 2002).

Different test methods have been used to determine the tensile strength of plain concrete and SFRC either directly or indirectly. The direct tensile test (DTT) can be performed to characterize many properties of the SFRC, such as the tensile stress-strain behaviour, post-peak response (softening or hardening), tensile modulus of elasticity and tensile strength. All these properties are essential in the design of SFRC members. However, there is no standard test procedure to determine the direct tensile strength of concrete. Also, there are difficulties associated with the test methods for the direct tensile strength of concrete. The difficulties in

testing the direct tensile strength of concrete include misalignment and concentration of stresses at the gripping devices and the slippage between concrete and the gripping devices (Wee et al., 2000; Van Mier and Van Vliet, 2002; Swaddiwudhipong et al., 2003; Choi et al., 2014).

The indirect tensile strength test of concrete cylinders (splitting test) is the most common test method used in the structural design of concrete members due to the relatively small size of the concrete sample and the availability of the testing machines. Many standards (e.g. ASTM C496, 2004; Australian Standard (AS) 1012.10, 2000) adopted the splitting test to determine the tensile strength of plain concrete. Several research studies (e.g. Folliard and Smith, 2003; Molins et al., 2009; Abrishambaf et al., 2015; Behnood et al., 2015) also used the splitting tests to evaluate the tensile strength of SFRC. Olesen et al. (2006), however, did not recommend splitting test to determine the tensile strength of SFRC due to the random distribution of the steel fibre within the concrete matrix of the SFRC.

Chen (1970) proposed the Double Punch Test (DPT) as an alternative method to determine the tensile strength of concrete indirectly. The DPT method was investigated and assessed in several studies (e.g. Chen and Yuan, 1980; Marti, 1989; Molins et al., 2009; Carmona et al., 2013; Kim et al., 2015) for the tensile strength of plain concrete. According to these studies, the DPT has the advantages of being easier to perform than the splitting test and yields more accurate tensile strength of concrete. Marti (1989) experimentally investigated the effect of the size of the specimen on the tensile strength of plain concrete obtained from DPT. In Marti (1989) the ratio of the diameter of the specimen to the maximum size of the aggregate (d/d_a) was varied from 8 to 128. It was found that the tensile strength of the concrete increased with the increase in the d/d_a ratio. Molins et al. (2009) used the DPT to determine the tensile strength and toughness of SFRC. Molins et al. (2009) concluded that the DPT had economical and technical advantages over splitting tests for the tensile strength of SFRC. Also, a lower

coefficient of variation in the tensile strength of SFRC was observed for the DPT compared to splitting test. Most of the previous studies on SFRC only compared the tensile strength obtained from the splitting test and the DPT. Goaiz et al. (2018) evaluated the tensile strength of the Reactive Powder Concrete (RPC) using three different test procedures: splitting test, DPT and DTT. It was reported that the DPT provided a more representative tensile strength of the RPC compared to splitting tests.

The main aim of this study is to examine the reliability of the DPT in evaluating the tensile strength of the SFRC with a wide range of concrete strengths. This study also compares the tensile strengths of SFRC obtained from the splitting tensile test and DPT with those obtained from DTT. However, development of factors to evaluate the tensile strength of SFRC based on the percentage of steel fibres by volume and the compressive strength of concrete is considered beyond the scope of this paper. This study includes plain concrete and SFRC with compressive strengths ranging between 30 MPa and 97 MPa.

Experimental Program

This study experimentally investigates three test methods for the tensile strength of SFRC: the splitting test, the DPT and the DTT. Two types of concrete were used: plain concrete and SFRC with nominal compressive strength ranging between 30 and 80 MPa. In this study, 81 concrete specimens were cast and tested to determine 28-day compressive strength, splitting tensile strength and double punch tensile strength of the concrete. In addition, 27 concrete prism specimens were also cast and tested to determine the direct tensile strength of the concrete.

Materials

A total of nine concrete mixes were prepared with general purpose cement, silica fume, crushed gravel (5-10 mm), coarse sand, fine sand, water, water reducing admixture and straight steel

fibre. The water reducing admixture was Sika-Viscocrete (2016). The steel fibre was 13 mm long and 0.2 mm diameter with a maximum tensile strength of 2500 MPa. The steel fibre was supplied by Ganzhou Daye Metallic Fibres (2015). Table 1 shows the mix proportions of the concrete mixes. For plain concrete, three mixes were designed to have nominal compressive strengths of 30 MPa, 50 MPa and 80 MPa. The SFRC mixes included 1.5% and 3% steel fibre by volume of concrete.

Mixing, casting and curing of specimens

A pan type concrete mixer was used to mix nine concrete mixes. First, all dry materials (cement, silica fume, aggregate and sand) were mixed together for 5 minutes. Then, the water and the water reducing admixture were added to the dry mixture. After 5 minutes of mixing, the plain concrete mix was ready to be cast. To produce SFRC, steel fibres were added to the mix gradually to ensure uniform distribution of fibres. Finally, the mixing continued for 3 minutes. Afterwards, the SFRC was ready to be cast. Each mix was cast to produce three cylinders (100 mm diameter $\times$ 200 mm height) for the compressive strength test, three cylinders (150 mm diameter $\times$ 300 mm height) for the splitting test, three cylinders (150 mm diameter $\times$ 150 mm height) for the DPT and three prism specimens (100 mm width $\times$ 100 mm height $\times$ 500 length) for the direct tensile test. All specimens were taken out of the moulds after 24 hours and cured in water at a temperature of $23\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$ for 27 days.

Labelling system of the concrete mixes

For the purposes of this study, each concrete mix has been identified with an acronym (Table 1). The symbols PC and S stand for plain concrete mix and steel fibre reinforced concrete (SFRC) mix, respectively. The numbers 30, 50 and 80 refer to the nominal compressive strengths of the concrete used in this study. For the SFRC mixes, the numbers afterwards (1.5

and 3) refer to the percentages of steel fibre by volume of concrete. For example, PC50 refers to plain concrete mix with a nominal compressive strength of 50 MPa and S30-1.5 refers to SFRC mix containing 1.5% steel fibre by volume of concrete with a nominal compressive strength of 30 MPa.

Test setup and procedure

Splitting test (ST)

In this study, splitting tests were performed according to AS 1012.10 (2000). Three concrete cylinders (150 mm diameter $\times$ 300 mm height) were tested from each concrete mix to determine the splitting tensile strength. For each test, two timber strips (400 mm long $\times$ 25 mm wide $\times$ 5 mm thick) were placed between the loading plates and the specimen surfaces along the full length of the specimen as supplementary bearing bars. A conventional compression testing machine at a loading rate of 1.5 MPa/min was used to perform the splitting test. The splitting tensile strength was calculated using Equation (1):

$$ST = \frac{2000P}{\pi LD} \quad (1)$$

Where ST is the splitting tensile strength in MPa, P is the maximum applied load in kN, L is the length of the specimen in mm, and D is the diameter of the specimen in mm.

Double Punch Test (DPT)

In this study, the test procedure in Chen (1970) was followed to perform the DPT. For effective evaluation of the tensile strength of concrete specimens, the following test procedure was adopted:

1. Concrete cylinder specimens with a diameter of 150 mm and a height of 150 mm were tested vertically in a compression testing machine.

2. Two cylindrical steel punches were used to transfer the axial compressive load from the testing machine to the concrete specimen. The cylindrical steel punches were 37.5 mm in diameter and 25 mm in height.
3. The top and bottom surfaces of the specimens were ground to have smooth surfaces in order to ensure fully uniform contacts between the steel punches and the surfaces of the specimens.
4. The steel punches were located at the centre of the specimen using a dimensional guide to avoid any loading eccentricity.
5. The concrete specimen was tested at a loading rate of 1.4 MPa/min.

It is noted that Chen (1970) investigated the influence of punch diameter on the tensile strength of concrete. The influence of three different punch diameters of 25 mm, 37.5 mm and 50 mm for 150 mm diameter specimens was investigated. It was found that the punch diameters of 37.5 mm and 50 mm provided more consistent results than the punch diameter of 25 mm. Hence, the punch diameter of 37.5 mm was adopted in this study.

Figure 1 shows the setup of the DPT, where a concrete cylinder specimen was shown to be under applied compressive load. The tensile strength obtained by the DPT was calculated using Equation (2), as suggested in Chen (1970):

$$DPT = \frac{P}{\pi(0.6dh - 0.25x^2)} \quad (2)$$

where, DPT is the double punch tensile strength in MPa, P is the maximum applied load in kN, d is the diameter of the specimen in mm, h is the height of specimen in mm, and x is the diameter of steel punch in mm.

Direct tensile test (DTT)

Several test setups were used in the literature for testing the direct tensile strength of concrete. The test setup used in this study was proposed in Alhussainy et al. (2016). The direct tensile test was performed on concrete prism specimens with a cross-section of 100 mm × 100 mm and a length of 500 mm. A wooden formwork was used as a mould for the specimens, as shown in Figure 2. To apply the direct tensile force on the concrete specimen, two steel gripping claws were used at the ends of the specimen. These claws were made of a 20 mm diameter threaded steel bar and embedded in the specimen to 125 mm. Four steel pins with 8 mm diameter and 30 mm length were welded to the threaded bar at an angle of 90° at 20 mm spacing to provide adequate anchorage between the steel claw and the concrete.

The gripping claws were fixed to the wooden mould by a nut and a washer from the outside of the formwork and a washer from the inside of the formwork. The washer inside was welded to the threaded bar to ensure an accurate alignment of the claws, as shown in Figure 2. In order to prompt the failure to occur in the middle of the specimen, the cross-sectional area of the specimen was reduced by using a timber triangle in the middle from two sides. To avoid any misalignment of the claw during the testing, two universal joints as shown in Figure 3 were designed by Alhussainy et al. (2016). The universal joints were used to grip the ends of the specimen by the testing machine to apply axial tensile forces to the specimen. As illustrated in Figure 3, the specimen aligned vertically between the jaws of the testing machine due to the free movement provided by the joints at the ends of the specimen.

All specimens were axially loaded up to failure with a displacement controlled loading at 0.1 mm/min and the data (tensile load and displacement) were recorded at every two seconds. It is noted that the direct tensile strength was calculated as the maximum tensile load divided by the reduced sectional area of the specimens (100 mm × 80 mm).

Results and Discussion

Concrete compressive strength

The compressive strength test of concrete was conducted according to AS 1012.9 (1999). The 28-day compressive strengths of plain concrete (0% of steel fibre) and SFRC with 1.5% and 3% steel fibre by volume of concrete are presented in Table 1. The average 28-day compressive strength of the nine concrete mixes varied from 30 MPa to 97 MPa. It can also be observed that the compressive strength of concrete increased with the increase in the percentage of steel fibre by volume of concrete. The S30-1.5 and S30-3 showed 17% and 24% higher average compressive strength, respectively, than PC30. The average 28-day compressive strength of S50-1.5 and S50-3 was higher than PC50 by 21% and 28%, respectively. The S80-1.5 and S80-3 also showed 10% and 17% higher average 28-day compressive strength, respectively, than PC80.

Splitting test (ST)

Figure 4 shows typical failure modes of concrete specimens with 0%, 1.5% and 3% steel fibre by volume of concrete. As shown in Figure 4, the concrete specimens with 0% steel fibre by volume of concrete (PC30, PC50 and PC80) experienced one failure surface located at the centre of the concrete cylinder. The failure surface was along the line of the loading strip. The specimens failed in a brittle manner and split into two halves, as shown in Figure 4a. For SFRC specimens, however, a different failure mode was observed where the failure surface was not clearly visible and the specimens remained nearly intact after the maximum load was reached. This ductile failure mode is attributed to the effect of steel fibre. The applied stress was distributed along the failure surface and prevented complete splitting failure. A compressive zone appeared under the loading strip which distributed the load non-uniformly in the direction of the load.

Figure 5 presents the test results of the average tensile strength of plain concrete and SFRC with 1.5% and 3% steel fibre by volume of concrete. The average splitting tensile strength of S30-1.5 and S30-3 was increased by 57% and 135%, respectively, compared to PC30. The average tensile strength of S50-1.5 and S50-3 was also higher than PC50 by 100% and 163%, respectively. The results of the splitting test show that the tensile strength increases as the content of steel fibre and the compressive strength of concrete increase. The highest splitting tensile strength (11.2 MPa) was achieved for S80-3, which contained the highest compressive strength and the highest amount of steel fibre by volume of concrete. The effect of the amount of steel fibre on the splitting tensile strength was more noticeable with high strength concrete (concrete compressive strength > 50 MPa).

Double punch test (DPT)

The typical failure modes of the concrete specimens with 0%, 1.5% and 3% steel fibre by volume of concrete tested under DPT are shown in Figure 6. The typical failure mode of plain concrete specimens (0% steel fibre) is presented in Figure 6a. As shown in Figure 6a, three radial failure surfaces were observed at an angle of nearly 120° between each failure surface. This failure mode was reported as a common failure mode according to previous studies (e.g. Chen, 1970; Chen and Yuan, 1980; Marti, 1989; Molins et al., 2009; Carmona et al., 2013). By increasing the percentage of the steel fibre into the concrete mixture, the failure mode was changed to an increased number of the radial cracks, as shown in Figure 6b and 6c. Thus, by increasing the percentage of steel fibre in the concrete, more radial cracks are expected to be observed in the failure surface.

The test results of the DPT are presented in Figure 7. It can be seen that the average tensile strength of S30-1.5 and S30-3 was increased by 23% and 61%, respectively, compared to PC30. The average tensile strength of S50-1.5 and S50-3 was also higher than PC50 by 45%

and 86%, respectively. The highest DPT tensile strength (6.48 MPa) was achieved by S80-3, where the compressive strength of concrete and the percentage of steel fibre by volume were the highest. Similar to the splitting test, the effect of the percentage of steel fibre by volume on the DPT tensile strength was also higher with high strength concrete (concrete compressive strength > 50 MPa). It can be observed that the DPT was able to detect changes in fibre content and compressive strength of SFRC (Figure 7).

Direct tensile test (DTT)

Figure 8 illustrates the typical failure mode of the DTT for concrete specimens with 0%, 1.5% and 3% steel fibre by volume of concrete. As expected, all specimens failed in the middle. For all plain concrete and SFRC specimens tested under direct tensile load, only one failure crack surface was observed. No claw slippage was observed at the ends of the specimens, which indicated that adequate alignment was provided to the specimens under the direct tensile test. As shown in Table 2, by increasing the compressive strength of the concrete and the percentage of the steel fibre, the direct tensile strength is also increased. As can be seen in Figure 9, the minimum tensile strength of 2.06 MPa was obtained by PC30 and the maximum tensile strength value of 6.32 was achieved by S80-3.

The typical axial tension-axial deformation response of all mixes is shown in Figure 10. For all specimens (plain concrete and SFRC), a linear axial tension-deformation behaviour up to the maximum load was observed. As can be observed in Figure 10, the axial tension dropped to zero immediately after reaching the maximum load in plain concrete specimens (Mixes PC30, PC50 and PC80). The post-peak behaviour, however, changed by including 1.5% steel fibre by volume of concrete (Mixes S30-1.5, S50-1.5 and S80-1.5). In this case, the axial tension dropped to nearly one-third of the maximum load followed by a descending axial tension-axial deformation curve. For SFRC specimens with 3% steel fibre by volume (Mixes

S30-3, S50-3 and S80-3), the vertical drop in the post-peak axial tension was reduced due to the influence of increase in the percentage of steel fibre by volume of concrete, as can be seen in Figure 10. Thus, direct tensile test results showed that the tensile strength of the concrete could be enhanced by increasing the percentage of steel fibres by volume in the concrete mix.

Comparison of tensile test methods

Table 2 and Figure 11 show comparisons between the tensile strength results from three different test procedures: ST, DPT and DTT. The test methods used in this study have a low ratio of the diameter of the specimen to the maximum aggregate size (d/d_a). For ST and DPT, the d/d_a was equal to 15 and for DDT, the d/d_a was equal to 10. Marti (1989) conducted an experimental study to investigate the influence of d/d_a ratio which ranged from 8 to 128 for the tensile strength of concrete. It was found that the low d/d_a ratio had a minor effect on the tensile strength of the DPT. Rossi et al. (1992) found that the influence of the size of the specimen on the tensile strength of the concrete was highly dependent on the compressive strength of concrete. The influence is relatively minor for high strength concrete. Thus, the effect of the size of the specimen may not be highly significant in this study. The results presented in Figure 11 show that the ST overestimates the tensile strength of the plain concrete and SFRC. This overestimation is increased as the concrete compressive strength and percentage of steel fibre in the concrete increase. The splitting tensile strength of Mix PC30 was 32% higher than the direct tensile strength, whereas the splitting tensile strength of Mix S80-3, which has the highest compressive strength and highest percentage of steel fibre by volume of concrete, was 77% higher than the direct tensile strength (Table 2). This is because of the ductile behaviour of the SFRC, which forms a large compressive zone under the loading strip during the ST, as shown in Figure 8c.

Figure 11 also shows that the tensile strength obtained from DPT was close to those obtained from the DTT. The DPT tensile strength of PC30, PC50 and PC80 was higher than direct tensile strength by 10%, 20% and 25%, respectively (Table 2). For SFRC mixes, the DPT tensile strengths were within $\pm 10\%$ difference from the direct tensile strength, as shown in Table 2. It can be seen that the increase in the content of steel fibre in the concrete mixes leads to more accurate tensile strengths of the DPT (Figure 11). Chen (1970) also stated that the accuracy of the DPT increased with the increase of the number of radial cracks. This is because of the fact that the greater the number of the radial cracks, the more even the stress distribution in the test specimen. In the same way, introducing steel fibre to the concrete mixes can result in more even stress distribution, as shown in Figure 6c. According to the test results presented above, for the tensile strength of SFRC, the DPT is more representative than the ST when compared with the DTT. The DPT also has the advantages of being easier to perform and costs less than both the ST and the DTT.

Conclusions

The aim of this study was to experimentally evaluate three different methods for determining the tensile strength of plain concrete and SFRC. Based on the results of the experimental program presented above, the following conclusions can be drawn:

- The splitting test overestimated the tensile strength of concrete. The overestimation was increased with the increase in the concrete strength and the percentage of steel fibre in the concrete mix.
- Tensile strengths of plain concrete and SFRC obtained from DPT were close to those obtained from the direct tensile test.

- For concrete compressive strength ranging from 30 MPa to 97 MPa with 1.5% and 3% steel fibre by volume of concrete, the DPT was able to capture the tensile strength of SFRC within $\pm 10\%$ difference from direct tensile strength.
- Considering that the DPT is easier to perform and less expensive, the DPT can be used instead of the direct tensile test to determine the tensile strength plain concrete and SFRC.

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Notations

D : Diameter of the specimen in mm

DPT : Double Punch Test

DTT : Direct Tensile Test

h : Height of the specimen in mm

L : Length of the specimen in mm

P : Maximum applied Load in kN

RPC : Reactive Powder Concrete

$SFRC$: Steel Fibre Reinforced Concrete

ST : Splitting Test

x : Diameter of steel punch in mm

References

- Alhussainy F, Hasan HA, Rogic S, Sheikh MN and Hadi MNS (2016) Direct tensile testing of Self Compacting Concrete. *Construction and Building Materials* 112: 903-906.
- ASTM (2004) Standard test method for splitting tensile strength of cylindrical concrete specimens. *ASTM C469-04*, West Conshohocken, PA.
- Australian Standards (2000) Methods of Testing Concrete, Method 10: Determination of Indirect Tensile Strength of Concrete Cylinders ('Brazil' or Splitting Test). *Australian Standards 1012.10*, Sydney.
- Australian Standards (1999) Methods of testing concrete, Method 9: Determination of the compressive strength of concrete specimens. *Australian Standards 1012.9*, Sydney.
- Abrishambaf A, Barros JAO, Cunha VMCF (2015) Tensile stress-crack width law for steel fibre reinforced self-compacting concrete obtained from indirect (splitting) tensile tests. *Cement and Concrete Composites* 57: 153-165.
- Behnood A, Verian KP, Gharehveran MM (2015) Evaluation of the splitting tensile strength in plain and steel fiber-reinforced concrete based on the compressive strength. *Construction and Building Materials* 98: 519-529.
- Blaesser RJ, Couls LM, Lee CF, Zuniga JM and Malek MH (2015) Comparing EMG amplitude patterns of responses during dynamic exercise: Polynomial as log-transformed regression. *Scandinavian Journal of Medicine and Science in Sports* 25(2): 159-165.
- Carmona S, Aguado A and Molins C (2013) Generalization of the Barcelona test for the toughness control of FRC. *Materials and Structures* 45: 1053-1069.

366 Chen WF and Yuan R (1980) Tensile Strength of Concrete: Double Punch Test. *Journal of*
367 *Structural Division ASCE* 106(8): 1673-1693.

368 Chen WF (1970) Double punch test for tensile strength of concrete. *ACI Materials Journal* 67:
369 993-1005.

370 Choi S, Yang K, Sim J and Choi B (2014) Direct tensile strength of lightweight concrete with
371 different specimen depths and aggregate sizes. *Construction and Building Materials* 63: 132-
372 141.

373 Folliard K, and Smith C (2003) Evaluation of Alternative Materials to Control Drying
374 Shrinkage Cracking in Concrete Bridge Decks. *Technical Report, Texas Department of*
375 *Transportation, Austin*: 44-45.

376 Ganzhou Daye Metallic Fibres Co (2015) [cited 2016;
377 http://www.gzdymf.com/product/WSF_Steel_Fiber.html].

378 Goaiz HA, Yu T and Hadi MNS, (2018) Quality Evaluation Tests for Tensile Strength of
379 Reactive Powder Concrete. *ASCE Journal of Materials in Civil Engineering*, 30(5):1-9.
380 [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0002257](https://doi.org/10.1061/(ASCE)MT.1943-5533.0002257)

381 Kim J, Kim DJ, Park SH and Zi G (2015) Investigating the flexural resistance of fiber
382 reinforced cementitious composites under biaxial condition. *Composite Structures* 122: 198-
383 208.

384 Marti P (1989) Size effect in double-punch tests on concrete cylinders. *ACI Materials Journal*
385 86: 597-601.

386 Molins C, Aguado A and Saludes S (2009) Double punch test to control the tensile properties
387 of FRC (Barcelona Test). *Materials and Structures* 42: 415-25.

388 Olesen JF, Østergaard L and Stang H (2006) Nonlinear fracture mechanics and plasticity of the
389 split cylinder test. *Materials and Structures* 39: 421-432.

390 Rossi, P., Wu, X., Le Maou, F., Belloc, A. (1992). “Effect d'echelle sur le comportement du
391 beton entrainement.” Bulletin de Liaison des Laboratoires des Ponts et Chaussées, 182, 11-20.

392 Sika Australia Pty Limited (2016) [cited 2016; Available from:
393 http://aus.sika.com/en/solutions_products/].

394 Swaddiwudhipong S, Lu H and Wee T (2003) Direct tension test and tensile strain capacity of
395 concrete at early age. *Cement and Concrete Research* 33(12): 2077-2084.

396 Van Mier J and Van Vliet M (2002) Uniaxial tension test for the determination of fracture
397 parameters of concrete: state of the art. *Engineering Fracture Mechanics* 69(2): 235-247.

398 Wee T, Lu H and Swaddiwudhipong S (2000) Tensile strain capacity of concrete under various
399 states of stress. *Magazine of Concrete Research* 52(3): 185-193.

400 Zain MFM, Mahmud HB, Ilham A and Faizal M (2002) Prediction of Splitting Tensile of High-
401 Performance Concrete. *Cement and Concrete Research* 32: 1251-1258.

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Table 1 Mix proportion for plain concrete and SFRC

Material	Mixes								
	Plain Concrete			Steel Fibre Reinforced Concrete					
	PC30	PC50	PC80	S30-1.5	S50-1.5	S80-1.5	S30-3	S50-3	S80-3
	kg/m ³								
Cement	260	360	425	260	360	425	260	360	425
Fly ash	100	100	----	100	100	----	100	100	----
Silica Fume	----	----	75	----	----	75	----	----	75
Fine sand	230	230	170	230	230	170	230	230	170
Coarse sand	530	500	400	530	500	400	530	500	400
10 mm Aggregate	950	1000	500	950	1000	500	950	1000	500
Water	190	170	150	190	170	150	190	170	150
Water reducing admixture	2	5	6.5	2	5	6.5	2	5	6.5
Steel fibre	----	----	----	120	120	120	240	240	240
28-day compressive strength (MPa)	30.6	56.0	81.3	35.8	68.0	89.1	37.8	71.7	95.0

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Table 2 Tensile strength results for plain concrete and SFRC

Mix Label	Tensile strength at the age of 28 days							
	Splitting test (ST) (MPa)		Double Punch Test (DPT) (MPa)		Direct tensile test (DTT) (MPa)		ST/DTT	DPT/DTT
	Individual	Average	Individual	Average	Individual	Average	Average	Average
PC30	2.43	2.71	2.11	2.26	2.08	2.06	1.32	1.10
	2.79		2.07		1.98			
	2.91		2.60		2.12			
PC50	3.28	3.45	2.81	3.06	2.30	2.54	1.36	1.20
	3.46		3.32		2.88			
	3.61		3.05		2.44			
PC80	4.12	4.20	3.51	3.63	3.04	2.95	1.44	1.25
	4.11		3.76		2.89			
	4.37		3.62		2.92			
S30-1.5	4.35	4.26	2.81	2.76	2.51	2.62	1.63	1.06
	4.36		2.68		2.57			
	4.07		2.79		2.78			
S50-1.5	6.65	6.90	4.38	4.43	4.19	4.08	1.69	1.09
	6.97		4.49		4.08			
	7.08		4.42		3.97			
S80-1.5	8.01	7.76	4.91	4.87	4.68	4.55	1.74	1.09
	7.70		4.99		4.62			
	7.57		4.71		4.35			
S30-3	6.61	6.36	3.72	3.63	4.04	3.86	1.68	0.93
	6.30		3.58		3.73			
	6.17		3.59		3.81			
S50-3	8.76	9.10	5.01	5.11	5.42	5.28	1.72	0.97
	8.95		5.19		5.25			
	9.59		5.13		5.17			
S80-3	10.70	11.20	6.49	6.49	6.56	6.32	1.77	1.03
	11.34		6.41		6.22			
	11.56		6.57		6.18

Section A-A

Universal joint

Concrete specimen

Universal joint

Axial Tension (kN)