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A New Method for Direct Tensile Testing of Concrete

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Abstract

Different testing methods were used in previous studies to measure the direct tensile strength of concrete. However, these methods experienced several major deficiencies such as stress concentration at the end of the specimens because of inadequate gripping and loading eccentricity and nonuniform fracture plane because of difficulties in aligning and centering the specimens during testing. This study presents the details of a new method of testing concrete under uniaxial tension. The method was developed to overcome the difficulties associated with testing methods adopted in the previous research studies. A full description of the wooden molds used in casting the specimens and the loading arrangements including the end grips, universal joints, and frame in which the specimens were tested under uniaxial tension are presented. As expected, all the tested specimens were fractured at the middle where the cross-sectional area was reduced by 20 %. Also, no crushing failure or slippage was observed at the ends of the tested specimens.

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A New Method for Direct Tensile Testing of Concrete

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Abstract

Different testing methods were used in previous studies to measure the direct tensile strength of concrete. However, these methods experienced several major deficiencies such as stress concentration at the end of the specimens due to inadequate gripping and loading eccentricity and non-uniform fracture plane due to difficulties in aligning and centering the specimens

during testing. This study presents the details of a new method of testing concrete under uniaxial tension. The method was developed to overcome the difficulties associated with testing methods adopted in the previous research studies. A full description of the wooden molds used in casting the specimens and the loading arrangements including the end grips, universal joints and frame in which the specimens were tested under uniaxial tension are presented. As expected, all the tested specimens were fractured at the middle where the cross-sectional area was reduced by 20%. Also, no crushing failure or slippage was observed at the ends of the tested specimens.

Keywords: Direct tensile testing; concrete; uniaxial tension; stress-strain behavior; strain rate.

Introduction

Tensile strength is one of the critical properties of concrete, because it influences the cracking, bonding and shear behaviors of reinforced concrete members. Many research studies attempted to use direct tensile, indirect tensile (splitting tensile) and flexural testing methods to investigate the properties of concrete under tension. However, it was reported that the direct tensile testing method provides more reliable and rational uniaxial tensile strength of concrete compared to the splitting tensile and flexural testing methods [1, 2].

The correlations between the direct tensile strength and the compressive, flexural and splitting tensile strength were investigated in several research studies. Wee et al. [3] carried out an experimental study to investigate the tensile strength of concrete. It was found that the tensile strength of the concrete was about 5.5-8.5% of the compressive strength of concrete. It was also found that the tensile strength of concrete obtained from the direct tensile testing

was two-thirds of the flexural strength of the concrete. Swaddiwudhipong et al. [1] studied the tensile behavior of concrete at early ages. It was found that with curing age the direct tensile strength of the concrete increases at a lower rate compared to the compressive strength. Wu et al. [4] conducted experimental investigations on the tensile strength of the concrete under static and intermediate strain rate using three different testing methods: direct tensile, splitting tensile and flexural testing methods. It was reported that specimens tested under flexural loads obtained greater tensile strength than the specimens tested under direct tensile and splitting tensile loads. Choi et al. [2] performed a direct tensile testing on lightweight concrete specimens with different dimensions (lateral depth) and aggregate sizes. It was reported that the effect of the size of the tested specimens on the direct tensile strength of the concrete became greater with a decrease in the unit weight of the concrete. Also, it was observed that the effect of the aggregate interlocking capacity on the tensile strength of the concrete slightly increased with an increase in the lateral depth of the tested specimen. The influence of the end grips of the specimens on the tensile strength of concrete was investigated in Wille et al. [5], Li et al. [6] and Zijl et al. [7]. It was reported that rotational and non-rotational end conditions influence the crack formation and strain distribution in the cross-section of the tested specimens [8].

Different methods were adopted to determine the direct tensile strength of the concrete in the previous studies. Based on the techniques used in gripping the specimen in the testing machine, four main direct tensile testing methods were identified: direct tensile test using truncated cone concrete samples [9], direct tensile testing using embedded steel bars [10], direct tensile testing by gluing gripping technique [11] and direct tensile test by means of lateral gripping [12]. However, the above methods suffered several technical deficiencies including non-uniform fracture plane, stress concentration and slippage at the end of the

specimens and flexural loads due to the imperfect alignment of the specimen during testing. As a result of the aforementioned problems associated with direct tensile testing methods, the tensile strength of the concrete has been mainly measured using the splitting tensile testing method and flexural testing method.

In this study, a new direct tensile testing method was designed, based on the embedded bar method, considering the following requirements:

1. The testing arrangements need to be suitable for different types of concrete;
2. The tensile load must be perfectly axial in order to obtain a uniform stress across the specimen section;
3. The end grips need to be simple and easy to fix to avoid the stress concentration and the failure due to fracture at the ends of the specimens;
4. The strain-measurement system has to be steady during the test; and
5. The cost of preparing the specimens should not be high.

The feasibility of using the developed method in testing concrete samples under uniaxial tension was assessed through testing different types of concrete samples: normal-strength concrete (NSC), high-strength concrete (HSC), self-consolidating concrete (SCC) and steel fiber reinforced high-strength concrete (SFHSC) having compressive strengths ranging between 39 and 93 MPa. The developed method of preparing and testing the concrete specimens makes the direct tensile testing of the concrete more reliable and cost-effective.

Description of the Developed Direct Tensile Testing Method

Formwork and Embedded Threaded Rod

Molds of 100 mm × 100 mm in cross-section and 500 mm in length made from non-absorbing wood were used as formwork for the tested specimens (Fig. 1). The cross-section

of each specimen was reduced at the middle to 80 mm × 100 mm in order to induce the failure to occur in the middle of the tested specimen. The reduced cross-section at the middle of each specimen was achieved by gluing two timber prisms vertically at the middle of the inner faces of the 100 × 500 mm (long) sides of the wooden molds. The timber prisms were 100 mm long having a triangular cross-section with a base of 20 mm and a height of 10 mm (Fig. 1).

A couple of threaded steel rods were embedded at the ends of each specimen to be used as grips for the specimens. The embedded threaded steel rods were 20 mm in diameter and 200 mm in length and were embedded inside the specimen for a distance of 125 mm (Fig. 1). In order to reduce the stress concentration at the ends of the tested specimens and to increase the bond between the embedded threaded steel rods and the concrete, four steel pins of 8 mm in diameter and 30 mm in length were welded at each threaded rod. The steel pins were spaced at 20 mm from the tip of the threaded steel rod (located inside the tested specimens) and the steel pins were welded in a way that the angles between the steel pins were 90 degree (Fig. 1). In order to align the embedded threaded steel rods in the center of the tested specimens, two holes of 20 mm diameter were drilled in the 100 × 100 mm sides (ends) of the wooden molds. Besides, a washer was welded to the threaded rod from the inside of the wooden molds and a nut and a washer were used on the outside to fix the threaded steel rods to the ends of the wooden molds. The nuts and the washers further ensured a perfect alignment of the embedded threaded steel rods within the wooden molds (Fig. 1). The completed formwork with the embedded threaded steel rods of the tested specimens is shown in Fig. 2.

Universal Joints

The tested specimens were mounted to the testing machine using a couple of reusable universal steel joints manufactured at the University of Wollongong, Australia. The schematic of the universal joints is presented in Fig. 3. Each universal joint consisted of two main parts: eye terminal and toggle terminal. One end of the eye terminal of each universal joint had a Ø30 mm steel rod to be gripped by using the jaw of the 500 kN Instron testing machine, whereas the other end had a Ø18 mm hole. The toggle terminal of each universal joint consisted of two main components: clevis holder and clevis. One end of the clevis holder had a Ø18 mm hole and the other end was fabricated to hold the clevis. Also, the clevis of the toggle terminal had two different ends: one end had a fixed pin to be held by using the clevis holder and the other end had a Ø16 mm threaded rod. The eye terminal and the toggle terminal of each universal joint were connected to each other thorough Ø18 mm holes using a Ø16 mm steel pin (Fig. 3). For each universal joint, the threaded rod end of the clevis was screwed onto the threaded steel rod embedded in the end of the specimen using a Ø20 mm to Ø16 mm reduced nut. In order to avoid any loose connection in the reduced nut, a locked nut was used to hold the reduced nut firm during the test. The universal joints were used to avoid any bending moments that might be experienced by the specimens during testing as a result of an eccentricity in the applied load. This is because the universal joints allowed movement at both ends of each tested specimen (Fig. 4), which ensured a perfect alignment for the specimen between the jaws of the Instron testing machine. Moreover, the universal joints overcame any defects in misalignment of the threaded steel rods that might occur during the casting of the specimen.

Strain Rate and Strain Measurement

Concrete is considered a sensitive material to the applied strain rate. Considerable efforts have been dedicated in the previous research studies to investigate the effect of the strain rate on the tensile properties of the concrete under uniaxial tension. Körmeling and Reinhardt [13] studied the effect of strain rate on the fracture energy and the tensile strength of concrete specimens with and without steel fibers. It was observed that using high strain rates in testing the specimens resulted in a substantial increase in the fracture energy and the tensile strength of the plain and the steel fiber reinforced concrete specimens. Yan and Lin [14] carried out an experimental investigation on the strain rate dependent response of the concrete in tension. Strain rate of 10^{-5} ϵ/s to $10^{-0.3}$ ϵ/s was used in testing the concrete specimens. It was observed that the strain rate influenced the direct tensile strength of the concrete more than it influenced the modulus of elasticity. Chen et al. [15] investigated the effect of four different strain rates (10^{-6} ϵ/s , 10^{-5} ϵ/s , 10^{-4} ϵ/s , 10^{-3} ϵ/s) on the direct tensile strength of the concrete. It was found that the peak stresses decrease with the decrease in the strain rate. In this study, the strain rate used in testing all the specimens was 6×10^{-6} ϵ/s , which is considered within the intermediate strain rates suitable for testing of concrete under uniaxial tension [15].

Concrete strain gauges with a length ranging between 30 mm to 120 mm were used in the previous research studies to measure the axial tension strain in the tested specimens [1, 4, 16]. Short strain gauges are considered more susceptible to several forms of measurement errors especially error caused by the open cracks distributed along the face of the monitored material where those strain gauges attached. Hence, strain gauges with a long sensor length are need for inhomogeneous materials such as concrete [17]. In this study, two concrete strain

gauges of 120 mm length were attached at the middle of long non-notched sides of the tested specimens to measure the axial tension strain during the tests (Fig. 5).

Specimen Preparation and Testing Setup

A total of 12 concrete specimens were cast and tested under uniaxial tension in order to validate the direct tensile testing method developed in this study. Four different types of concrete were used in casting the tested specimens: normal-strength concrete (NSC); high-strength concrete (HSC), self-consolidating concrete (SCC) and steel fiber reinforced high-strength concrete (SFHSC). Three specimens (S1, S2 and S3) were tested for each type of concrete. The ready mixes of NSC, HSC and SCC were provided by a local concrete company. The mix proportions of the NSC, HSC and SCC mixes are presented in Table 1. The SFHSC was prepared using a small lab concrete mixer having the maximum volume capacity of 0.2 m³. The HSC ready mix, provided by a local company, was firstly placed in the lab mixer and then brass coated steel fibers with 1% by volume were added gradually inside the HSC mix. The steel fibers were straight in shape with 0.2 mm diameter and 13 mm length (aspect ratio = 65) having maximum tensile strength of 2500 MPa [18]. The maximum size of the aggregate used in the NSC, HSC, SCC and SFHSC was 10 mm. For NSC, HSC and SFHSC specimens, the concrete was placed into the formwork in two stages. After each stage, concrete was vibrated using an electrical concrete vibrator. No vibration was needed for the SCC specimens.

The properties of fresh SCC were tested according to ASTM [19-21] and the results were found to be satisfactory. The standard mechanical properties including compressive strength, splitting tensile strength, flexural strength, direct tensile strength and the modulus of elasticity of the NSC, HSC, SCC and SFHSC were determined. The compressive strengths of the

concrete were determined by testing three 100 mm × 200 mm cylinder-specimens according to ASTM C39 [22]. The splitting tensile strengths of the concrete were determined by testing three 150 mm × 300 mm cylinder-specimens according and ASTM C496 [23]. The flexural strengths of the concrete were determined by testing three 100 × 100 × 500 mm beam-specimens with third-point loading according to ASTM C78 [24]. The direct tensile strength and the modulus of elasticity of the concrete in tension were determined from the tensile stress-strain behavior of three specimens tested by using the direct tensile testing method developed in this study. The modulus of elasticity of the concrete in compression was determined from the slope of the stress-strain behavior obtained from testing three 150 mm × 300 mm cylinder-specimens under axial compression according to ASTM C469 [25].

The universal Instron testing machine at the laboratory of School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia was used in testing the specimens under uniaxial tension. First, the universal joints were fixed to the embedded threaded steel rods of the tested specimen. Afterwards, the specimens were mounted to the Instron testing machine. During the tests, a strap was used to slightly hold the lower part of tested specimens in order to avoid any sudden fall of any part of the specimen during the fracture of the specimen (Fig. 5). Fig. 6 shows a typical testing setup of the tested specimens.

Results and discussion

Failure modes

All the tested specimens fractured once the specimens reached their maximum tensile strength. The fracture occurred in the middle of each specimen where the cross-sectional area of the specimens was reduced by 20%. Fig. 7 shows the failure modes of the tested specimens. The reduced cross-sectional area in the middle of the specimens prevented the

fracture to occur at undesirable locations along the length of the specimens. Furthermore, the reduced cross-sectional area contributed in concentrating the stresses in the middle of the specimens resulting in a uniform fracture plane at this location. None of the tested specimens experienced either a slippage or a crushing failure at the ends, which was an indication that the embedded threaded steel rods provided a strong and evenly distributed bond with the surrounding concrete. Moreover, no secondary flexural-related failure was observed, confirming that proper alignment was provided by the universal joints.

Stress-strain behavior of tested specimens

In this study, the axial tensile stress for the tested specimens was determined from dividing the axial tensile load recorded by the load cell of the Instron testing machine by the reduced cross-sectional area (80×100 mm) of the specimens. Two strain gauges were attached at the middle of long non-notched sides of each tested specimen to measure the axial tensile strain. Fig. 8 presents the elastic phase of the stress-strain behavior of the SCC specimen (S1), in which the axial strains were recorded by the two strain gauges attached on both sides of the SCC specimen (S1). Since the strain gauges were not able to provide accurate readings after the specimens were fractured in the middle (notched zone), especially for SFHSC specimens, the stress-strain behaviors of the specimens were drawn, based on strain gauge readings, until the fracture occurred. Afterwards, the axial strains were calculated by dividing the axial deformation captured by the Instron testing machine by the overall length of the tested specimens in order to draw the post-fracture behavior of the tested specimens. It is noted that the proposed testing configuration in a servo-hydraulic testing system with closed loop may reasonably capture the post-cracking stress-strain behavior of the concrete.

Figure 9 shows the stress-strain behavior of the tested specimens under uniaxial tension. All the tested specimens experienced an almost linear stress-strain behavior up to the peak stress. Similar observations were reported in Ref. [5, 15]. After the peak stress, the NSC, HSC and SCC specimens (plain concrete) failed immediately once they reached their peak tensile stresses. The immediate failure of the plain concrete specimens under uniaxial tension was attributed to the complete fracture failure exhibited by the tested specimens in the middle. As expected, the fracture failure occurred at the weakest section (notched zone) of the tested specimens. On the other hand, the failure of the SFHSC specimen started with a partial crack in the middle of the specimens which resulted in a drop of about 50% of the peak tensile stress followed by a gradual reduction in the stress-strain behavior until failure. Similar stress-strain behavior was reported for SFHSC in Ref. [5, 13, 26].

Comparison of the test results

The experimentally obtained values of direct tensile strengths for NSC, HSC, SCC, and SFHSC were evaluated in order to assess the precision of the developed direct tensile testing method. Table 2 summarizes the mechanical properties of NSC, HSC, SCC and SFHSC including the compressive strength, splitting tensile strength, flexural strength, direct tensile strength and the modulus of elasticity.

The modulus of elasticity of the NSC, HSC, SCC and SFHSC was determined from the slope of the stress-strain behavior of the specimens in tension and compression as mentioned earlier. It was observed that the modulus of elasticity of the NSC, HSC, SCC and SFHSC in tension was about 73%, 55%, 67% and 57% of the modulus of elasticity of the NSC, HSC, SCC and SFHSC in compression, respectively.

The compressive, splitting and the flexural strengths were obtained using standard concrete tests [22-24], whereas the direct tensile strength of the concrete was obtained using the testing method developed in this study. The average direct tensile strength for the NSC, HSC, SCC and SFHSC obtained using the developed direct tensile testing method were found to be 3.19, 3.5, 3.5 and 4.1 MPa, respectively. The average direct tensile strengths of the tested specimens were found to be less than the corresponding average splitting tensile and flexural strengths. The average direct tensile strength of NSC, HSC, SCC and SFHSC specimens were found to be 10%, 33%, 8% and 36% less than the average splitting tensile strengths of NSC, HSC, SCC and SFHSC, respectively. In addition, The average direct tensile strength of NSC, HSC, SCC and SFHSC specimens were found to be 26%, 42%, 46% and 41% less than the average flexural strengths of NSC, HSC, SCC and SFHSC, respectively. The difference between the direct tensile strength and the tensile strengths obtained from the splitting tensile and flexural strengths might be attributed to the distribution of tensile stresses at the failure plane.

The average direct tensile strength of the NSC specimen was equal to 90% of the splitting tensile strength, which is consistent with AS 3600-09 [27] and EC 2 [28]. Similarly, the average direct tensile strength of the SCC specimens was approximately equal to 90% of the splitting tensile strength [29]. In addition, the average direct tensile strength of the HSC and SFHSC, obtained using the developed direct tensile testing method, were found to be close to the direct tensile strengths reported in the previous studies [13, 30, 31, 32].

According to AS 3600-09 [27], the direct tensile strength of the concrete is calculated as 60% of the flexural strength of the concrete. The average direct tensile strength of NSC, HSC, SCC and SFHSC, obtained using the developed direct tensile testing method, were compared

to that calculated from flexural strength according to AS 3600-09 [27]. The ratio of the calculated to the experimental results of the direct tensile strength for NSC, HSC, SCC and SFHSC specimens were found to be 0.8, 1.0, 1.1 and 1.0, respectively.

The previous testing procedures for concrete under uniaxial tension were complicated. Besides, a considerable number of the experimental data reported in some previous research studies for the direct tensile strength of concrete were found to be unreliable due to the technical complications related to the testing procedure. However, the direct tensile testing method developed in this study provides rational and reliable results for the direct tensile strength of the NSC, SCC, HSC and SFHSC using a simple and an effective testing technique.

Conclusions

1. The developed direct tensile testing method was found to be efficient in ensuring that the fracture occurred in the middle of each specimen where the cross-sectional area was reduced by 20%.
2. Due to the use of an adequate gripping technique (embedded threaded steel rods), none of the tested specimens experienced slippage or crushing failure at the ends.
3. Due to the proper alignment provided by the universal joints, no secondary flexural-related failure occurred in the tested specimens.
4. The average direct tensile strengths of the tested specimens were found to be less than the average flexural strength and splitting tensile strength.
5. All tested specimens showed linear stress-strain behaviors under uniaxial tension almost up to the peak stress. The NSC, HSC and SCC specimens (plain concrete) failed immediately once the tensile stress peak was reached. However, the failure of the SFHSC specimen

324 started with a partial crack in the middle of the specimens which resulted in a drop in the
325 tensile peak stress by about 50%.

326 6. The developed procedure provided rational and reliable results for the direct tensile
327 strength of the NSC, SCC, HSC and SFHSC using a simple and an effective testing
328 technique.

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Table 1. Mix proportions of the concrete used in this study

Mix	Cement (kg/m ³)	Fly ash (kg/m ³)	Slag (kg/m ³)	Silica fume (kg/m ³)	Sand (kg/m ³)	Coarse aggregate (kg/m ³)	Water (kg/m ³)	HRWR ^a (l/m ³)	Steel fiber content (%)
Normal-strength concrete	350	-	-	-	850	1000	185	-	---
High-strength concrete	576	64	-	30	540	990	197	6	---
Steel Fiber high-strength concrete	576	64	-	30	540	990	197	6	1
Self-consolidating concrete	280	120	50	-	950	780	182	3.4	---

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^a HRWR: High range water reducer

438   Table 2. Test results for NSC, HSC, SCC and SFHSC specimens

Type of test	Standard tests	Tested specimens for different types of concrete															
		Normal-strength concrete (NSC)				High-strength concrete (HSC)				Self-consolidating concrete (SCC)				Steel fiber high-strength concrete (SFHSC)			
		S1	S2	S3	Ave	S1	S2	S3	Ave	S1	S2	S3	Ave	S1	S2	S3	Ave
Compressive strength (MPa)	ASTM C39-16 [22]	39	38.5	39.5	39	82.8	86.6	85.5	85	56.5	57	-	57	92.3	94.7	91.2	93
Splitting tensile strength (MPa)	ASTM C496-11 [23]	3.56	3.65	3.42	3.54	5.4	5.3	4.8	5.2	3.7	3.78	3.87	3.8	6.8	6.2	6.1	6.4
Flexural strength (MPa)	ASTM C78-16 [24]	4.2	4.37	4.31	4.3	6.2	6.8	6.1	6.0	6.0	6.39	7.1	6.5	6.9	6.8	7.2	6.9
Direct tensile strength (MPa)	Developed method	3.08	3.29	3.2	3.19	3.6	3.3	3.5	3.5	3.4	3.49	3.6	3.5	4.1	4.0	4.3	4.1
Modulus of elasticity (compression) (GPa)	ASTM C469-14 [25]	30.5	31	30	30.5	40.5	39.3	38.5	39	29.5	30	31	30	42	39.8	41	41
Modulus of elasticity (direct tension) (GPa)	Developed method	21	22.4	23.5	22.3	21.4	21.8	21.6	21.6	19.5	20.4	21	20	21.9	23.5	24.7	23.4

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Fig. 2. Completed formwork with the embedded threaded steel rods of the tested specimens

Each universal joint provides two degrees of freedom: rotation about the x-axis (Joint A) and rotation about the z-axis (Joint B)

Fig. 4. Universal joint designed for direct tensile testing of all specimens

Fig. 5. Schematic setup of the tested specimen

Fig. 6. Typical test setup for direct tensile testing of concrete

Fig. 7. Failure modes of the tested specimens: (a) NSC, (b) HSC, (c) SCC and (d) SFHSC

Fig. 8. Elastic phase of the stress-strain behavior of the SCC specimen (S1)

(a) Normal-strength concrete (NSC)

(b) High-strength concrete (HSC)

(c) Self-consolidating concrete (SCC)

(d) Steel fiber reinforced high-strength concrete (SFHSC)

Fig. 9. Uniaxial tensile stress-strain behavior: (a) NSC, (b) HSC, (c) SCC and (d) SFHSC