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Short communication

A new test method for determining the fracture toughness of concrete materials

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ABSTRACT

The Spiral Notch Torsion Test (SNTT) determines the intrinsic fracture toughness (K_{IC}) of structural materials by applying pure torsion to cylindrical specimens having a notch line that spirals around the specimen at a 45° pitch. K_{IC} values are obtained with the aid of a three-dimensional finite-element computer code, TOR3D-KIC. The SNTT method is suitable for testing a wide variety of materials used extensively in pressure vessel and piping structural components and weldments, as well as ceramic and graphite materials. One important characteristic of SNTT is that neither a fatigue precrack nor a deep notch is required for evaluation of brittle materials, significantly reducing the sample size requirement. Results are reported for a Portland cement-based mortar demonstrating applicability of the SNTT method to cementitious materials. The estimated K_{IC} of the tested mortar samples with compressive strength of 34.45 MPa was found to be 0.360 ± 0.017 MPa √m.

1. Introduction

The size effect of concrete is well-known and accounting for such an effect in codes of practice for the design of reinforced concrete structures, such as how to reconcile differences between laboratory test data and the properties of full-scale structures, remains a great challenge. Since 1961 when Kaplan initiated the study on the size effect on concrete fracture [1], many researchers have reported experimental observations of the size effect on concrete fracture properties [2,3]. The size effect law by Bazˇant [4] and the specific fracture energy G_F proposed by RILEM [5] have further provided insight into size effects. However, it has been found that fracture energy also depends on the test specimen geometry. Experimental and theoretical studies have been conducted to understand the size effect mechanisms [6]. Hu and Wittmann [7] showed that local fracture energy varies with the width of the fracture process zone. As the crack front approaches the back of a specimen, the fracture process zone becomes more and more confined and the local fracture energy decreases. A local variation of the fracture energy leads to a size dependence of the global specific fracture energy. In general, experimental results reveal that the size effect of concrete testing has two phenomena: (1) for geometrically similar specimens, concrete strength decreases with increasing specimen size, and (2) both the specific fracture energy and fracture toughness increase with increasing specimen size and un-broken ligament length [1–3,8]. Furthermore, it has been noted that the specimen thickness also influences the fracture behavior of concrete. Thick specimens have higher constraint than thin specimens. In general, large, thick specimens are required to obtain a valid plane-strain fracture toughness of metallic materials because for small specimens a large portion of the fracture energy is attributed to plastic deformation (such as shear lip formation) resulting in a large stress intensity factor that is highly non-conservative. For concrete materials, limited results have shown that the specific fracture energy increased with increasing specimen thickness and reached a plateau when the specimen thickness increased to about four times the maximum aggregate size [9] (this seems to contradict the fracture toughness characteristic of metallic materials). Others showed no thickness effect if specimen thickness was much larger than the maximum grain size [10].

2. Spiral notch torsion test (SNTT) system

An unconventional mode of fracture test is proposed herein for determining the fracture toughness of concrete materials. This method applies a pair of opposing pure torsion forces on the ends of a cylindrical test specimen, so that the stress distribution on every cross section normal to the axis is identical, and the maximum tensile stress can be calculated unambiguously as in the case of pure tension. Only a shallow surface notch is required for testing brittle materials thus significantly reducing the specimen size as compared to the conventional test method requiring a deep notch configuration. Mode-I fracture toughness is obtained when a cylindrical specimen having a shallow spiral groove (pitch angle of 45°) on the surface is tested; thereby, the spiral notch torsion test (SNTT). In typical fracture toughness tests the direction of crack propagation is unpredictable and often deflects in zigzags or a thumbnail pattern, resulting in large data scatter. When a cylindrical specimen is twisted, the spiral notch provides the location for crack initiation, and the pure torsion load ensures that the crack will advance perpendicularly toward the central axis of the test specimen. Therefore, the SNTT methodology is

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expected to significantly reduce uncertainty in fracture toughness evaluation. Furthermore, the SNTT test method has advantages relative to bend-beam testing, because (1) the size effect is minimized, (2) inherited high stress gradients from pure torsion (pure shear stress) field, (3) no free surface (normal to specimen axis) exists in the SNTT specimen geometry under the pure torsion loading, and (4) mixed-mode fracture toughness values can be easily obtained by changing the pitch angle of the spiral line. The ability of SNTT to confine plastic deformation within a thin plane provides the opportunity to investigate interfacial material properties, such as investigating interfacial bonding between the cement paste and the aggregate or thin film interface fracture toughness [11]. Reference [12] provides a more detailed description of the SNTT methodology.

3. Experimental test results

3.1. Material properties of SNTT mortar samples

The 40.6-mm-diameter by 177.8-mm-long SNTT test samples were made from a Portland cement-based mortar prepared by first blending the cement and sand together followed by addition of water. Mixing was by hand until the mix assumed a uniform consistency (minimum period of five minutes). Following mixing, the SNTT test samples and 50.8-mm cubes for evaluating the compressive strength were cast in three layers with rodding used to consolidate each layer prior to addition of the next layer of material. Following casting, the specimens were sealed with plastic until they were removed from the molds the following week and placed into a water bath. Approximately 2 months after casting, the specimens were removed from the water bath and air dried until tested. The cement used to fabricate the specimens was ASTM C150 Types II and V. The sand, having a maximum particle size of about 4 mm, was primarily a siliceous material with a specific gravity of 2.62. Weights of cement, sand, and water were 2.72 kg, 10.89 kg, and 1.63 kg, respectively. The mortar compressive strength was 34.45 MPa (5000 psi).

3.2. SNTT fracture toughness testing and evaluation

Pure torsion tests (with zero axial load) were performed in a closed-loop, electrohydraulic, biaxial testing system with shear strain measured using a biaxial strain extensometer with a Rosette strain gage used for cross calibration. A full lobe of a 45-pitch angle spiral-shallow groove was engraved into the 40.6 mm (1.6-in) diameter specimens. The SNTT sample and the associated end-grip assembly are shown in Fig. 1(a) prior to being placed into the adapters of the torsion testing frame. A typical fractured surface profile of a tested SNTT mortar sample is shown in Fig. 1(b). The notch depths and fracture–torque results are listed in Table 1. The fractured surface of tested SNTT samples shows a classical tensile brittle fracture feature, shown in Fig. 2. Fig. 3 presents the pure torsion test results of SNTT mortar samples that failed at 46.9 N-m (415 lb-in.) and 53.1 N-m (470 lb-in.) torques, for notch depth of 2.6-mm and 1.9-mm, respectively. The initial low-load rotation, up to 204 N-m (150 lb-in.), was due to initial gaps between the square-torque ends of the SNTT assembly and the torque-coupling adapter-ends of the loading frame. All SNTT samples showed sudden (brittle) failure at peak fracture torque. This normally was revealed as a sharp drop in torque to zero as registered by the biaxial extensometer within the gage length. While using an RVDT for grip-ends (SNTT mortar sample assembly) rotation measurement, due to continuing rotation of the grip/stage upon fracture a slightly declined slope was observed, see Fig. 3. Therefore, the post crack-initiation data registered by RVDT does not represent a true material response, but is an artifact of the test method.

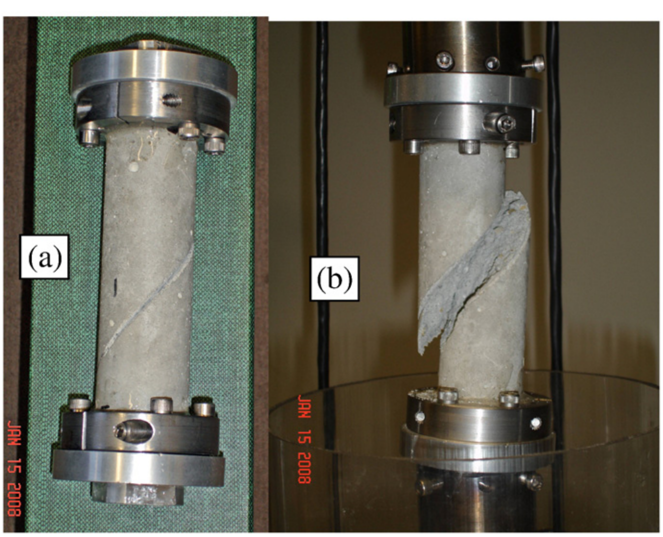

Fig. 1. SNTT test assembly and fractured SNTT sample.

Table 1
Test results of mortar fractured by SNTT method.

SNTT sample	1	2	3	4	5	6	7
Fracture torque [N-m]	62.2	53.1	51.9	50.9	47.4	46.9	40.7
Notch depth range [mm]	0.762 ~0.254	1.905 ~1.524	2.159 ~1.905	2.286 ~1.905	2.667 ~2.032	2.667 ~2.337	3.264 ~3.175
K_{IC} [MPa√m]		0.341				0.376	0.364
J_{IC} , G_c [N/m]		3.467				4.210	3.952

The variation of the fracture torques observed from the tested SNTT mortar samples appears to be consistent with the associated notch depth variation. With Young's modulus of 32.2 GPa [13] and Poisson's ratio of 0.2, the estimated Mode-I fracture toughness, K_{IC}, based on three SNTT mortar samples, was 0.360 ± 0.017 MPa√m. This K_{IC} value is compatible with results presented in the literature [10] and appears to provide a lower bound. The associated J-integral value (J_{IC} or G_c) is 3.876 ± 0.377 N/m, which was obtained of using *Contour Integral of ABAQUS's routine [12]. Due to sharp drop of SNTT load-displacement curve at crack initiation, G_c is expected to be very close to G_f.

4. Conclusions

The SNTT system represents a practical and effective approach for testing fracture toughness of concrete materials by applying pure

Fig. 2. Fractured SNTT mortar sample shows.

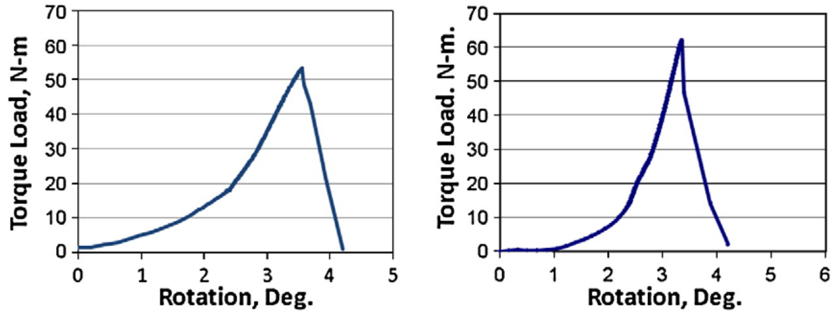

Fig. 3. SNTT torsion test results with notch depth (left) at 1.9-mm and (right) at 0.7-mm.

torsion to a cylindrical sample that is notched with a groove that spirals around the sample at a 45° pitch. The SNTT overcomes many of the limitations inherent in traditional techniques and introduces new possibilities for improved fracture toughness testing: (1) It conforms to the classical theory of fracture mechanics; (2) it allows miniaturization of test specimen to appropriate sizes, which makes the test method economically attractive and test equipment portable for on-site testing; and (3) for brittle material only a shallow notch is needed, thus further reducing the specimen size required for generating a valid K_{IC} test.

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