Development of a Double-Torsion Fracture Test for Bituminous Materials

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ABSTRACT: Fracturing of asphalt concrete paving surfaces and overlays is a significant cause of premature pavement deterioration. Fracture mechanics and the proper handling of crack propagation are much needed for longer pavement life and it is a wide-open area of investigation in the field of asphalt pavement design and analysis. This paper shows an experimental development of double-torsion fracture test and predicts fundamental fracture properties of bituminous materials. Double-torsion test specimens were prepared by an automatic French slab compactor. Double-torsion tests were performed at low temperatures to investigate the brittle and/or quasi-brittle behavior of bituminous materials. A constant displacement control method was applied to obtain reliable fracture properties of bituminous materials. Test geometry with different notch lengths was considered to obtain a standard specimen configuration without any unexpected failure. Characteristic fracture properties from double-torsion tests were determined based on the linear elastic fracture mechanics theory and the relationship of creep compliance. Experimental results showed that the notch length was not a significant factor in the determination of fracture properties from double-torsion fracture tests.

KEY WORDS: Asphalt concrete, fracture, double-torsion, figures.

1 INTRODUCTION

Asphalt concrete is a quasi-brittle composite material, which is composed of brittle aggregates and viscous asphalt. Asphalt concrete becomes more brittle at low temperatures, especially with high frequency loading conditions. There have been some previous studies on the fracture behavior of asphalt concrete at low temperatures with different test methods. Three-point bending beam tests were the popular application for investigating the fracture mechanism of asphalt concrete (Wagoner et al. 2005, Kim et al. 2009(a)). Also, disk-shaped compact tension tests and semi-circular tests were applied to study the fracture toughness of asphaltic materials (Xue and Marasteanu 2005, Kim et al. 2008, Kim et al. 2009(b)). The double-torsion (DT) test has been a fracture mechanics approach used for investigating both critical crack growth (fracture toughness measurement) and subcritical crack propagation. Crack can start from a critical defect, growing very slowly at first, and then accelerating under further load until the part finally fails. This behavior is known as subcritical crack propagation. A wide range of materials have been characterized by double-torsion tests. These include ceramics (McHenry et al. 1976, Ebrahimi et al. 2000, Gremillard et al. 2002,), glasses (Bhaduri, 1991), composites (Frassine, 1992), cement concrete (Hill and Styles 1992), polymers (Williams and Evans 1973, Kulawansa et al. 1992), steels (Egan and Delatycki 1995), and rocks (Ciccotti et al. 2001, Nara and Kaneko 2005). The advantages of DT tests are following: (1) the test configuration consists of simple specimen geometry and inexpensive experimental set-ups; (2) the obtaining fracture property, the stress intensity factor, is the first approximation and independent of crack length for a range of crack lengths in DT specimens; (3) comprehensive crack measurements may not be needed when the constant loading techniques; and (4) DT tests can characterize both the crack channeling, which is a typical pavement longitudinal crack behavior, and fatigue cracking under repeated traffic loads. In this study, a DT fracture test for bituminous materials was developed and implemented to predict the crack channelizing and to obtain the fracture properties. In the beginning of study, there were many trial test configurations and specimen geometries to obtain the reliable test results at low temperatures. DT tests were performed with different notch lengths and loading speeds to obtain the fracture properties of asphalt concrete and to investigate the response dependencies of fracture behavior.

2 MATERIALS AND SPECIMENS

Asphalt binder 70/100 based on the penetration grade system according to the European standard EN 12591 (1991) and common Swiss asphalt mixtures was selected for this study. According to European Standard EN 13108-1 (2006), asphalt mixture, AC4, with relatively small nominal maximum aggregate size was used to obtain homogeneous and repeatable test results. The aggregate gradation curve of asphalt mixture is shown in Figure 1. Table 1 shows material properties of the asphalt mixture and Marshall test results following the series of European standards EN 12697-34 (2004) and EN 12697-35 (2004).

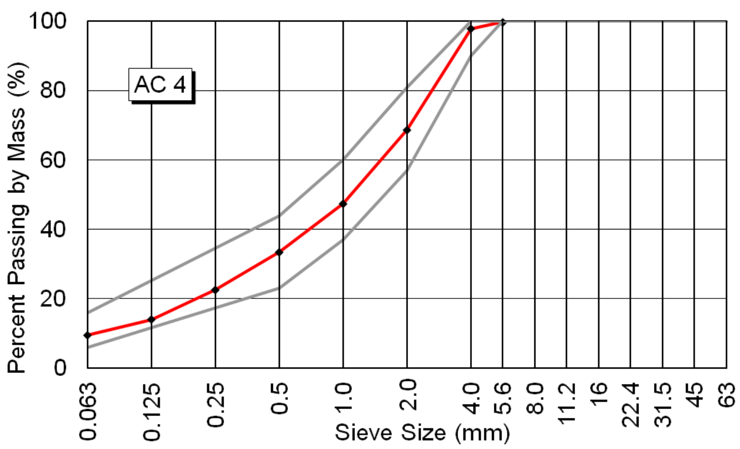

Figure1: Aggregate gradation of asphalt mixture.

Table 1: Marshall properties of AC4

Asphalt mixture (AC4)	Percentage of binder	8.0	Mass %
	Density	2407	kg/m^3
	Area density (SSD)	2296	kg/m^3
	Percentage of air void	4.6	Vol.%
	Voids in the mineral aggregate (VMA)	22.5	Vol.%
	Voids filled with asphalt (VFA)	79.4	Vol.%
Marshall properties	Marshall stability	11.1	kN
	Marshall flow	2.7	mm

Asphalt concrete slabs were compacted by an automatic steel roller compactor, developed by Laboratoire Central des Ponts et Chaussées (LCPC) in France (LCPC, 1995). The asphalt slabs were 500mm long with a rectangular cross section of 180 width and 20mm. The constant load magnitude of steel roller was 5kN. The bottom plate of steel mould is gradually lifted during compaction such that the contact surface of the steel roller with the specimen always remains at a constant level during the roller passing. For compacting asphalt specimens, the hot asphalt concrete mixture was firstly filled into a pre-heated steel mould with an aluminum plate and compacted until obtaining the targeted 20mm specimen thickness.

There have been some studies for finding proper DT specimen geometries. Evans et al. (1974) and Atkinson (1979) showed experimentally that W should be 12 times greater than d. Pletka et al. (1979) suggested that the specimen length L should be greater than twice the value of W. Therefore, the size of the DT specimen must be

$$12d < W < L/2 \tag{1}$$

In addition, Trantina (1977) used a finite element analysis to show that K_I was independent in an operational range with 5% deviations of K_I. The operational range was

$$0.55W < a < L-0.65W \tag{2}$$

According to the above constraint, the experimental study of Shetty and Virkar (1978) determined as operational the following ranges of crack lengths:

$$0.50W < a < L-1.0W \tag{3}$$

$$0.4W < a < L-0.8W \tag{4}$$

Most recently, Ciccotti et al. (2000) performed detailed three-dimensional finite element analyses for various range of DT test specimens (170mm < L < 250mm and 60mm < W < 100mm). They analyzed both the range determined by Trantina (1977) and the dimension proposed by Shetty and Virkar (1978). Based on their investigations, the operational ranges were not consistent due to different loading conditions and different thickness. Also, they concluded that appreciable deviations can be occurred form the classical analytical predictions of strain energy release rate (g). A guide groove is necessary to control the crack path in DT specimens due to the heterogeneity of materials. There were some studies related to the notch shape effects in DT fracture tests (Pabst and Weick 1981, Atkinson, 1984, Ciccotti et al. 2001). Swanson (1984) mentioned that the guide groove geometries (sizes and shapes) had no significant effects of reducing the scatter of DT test on rocks. However, Nara and Kaneko (2005) later tested rock DT specimens with three different groove shapes using rectangular, semi-circular, and the triangular section grooves. They concluded that the level of reproducibility was highest for the rectangular guide groove specimens.

In this paper, authors determined the proper specimen dimension from previous DT studies but the specimen dimension was not limited to the definition from because of different material characteristics, e.g. different level of heterogeneity like the relatively large aggregates embedded in asphalt mixtures and the large creep behavior from viscous binder. Figure 2 shows the specimen geometry for DT fracture tests. DT specimens were cut from asphalt slabs compacted by French roller compactor with a dimension as shown in Table 2. The thickness of 20mm was chosen because the double-torsion fracture test concept was based on the thin plat theory and DT specimens should have enough thickness, more than three times than the maximum aggregate size, to reduce the aggregate dependency on test results. The beam length of 300mm, twice than the width and more than six times than the thickness, was chosen to produce reasonable bending conditions within the size limitation of the temperature chamber. In this study, the rectangular guide groove was made on the bottom surface of DT specimen and the notch lengths (*a*) were varied with 0, 30, 60, and 85mm.

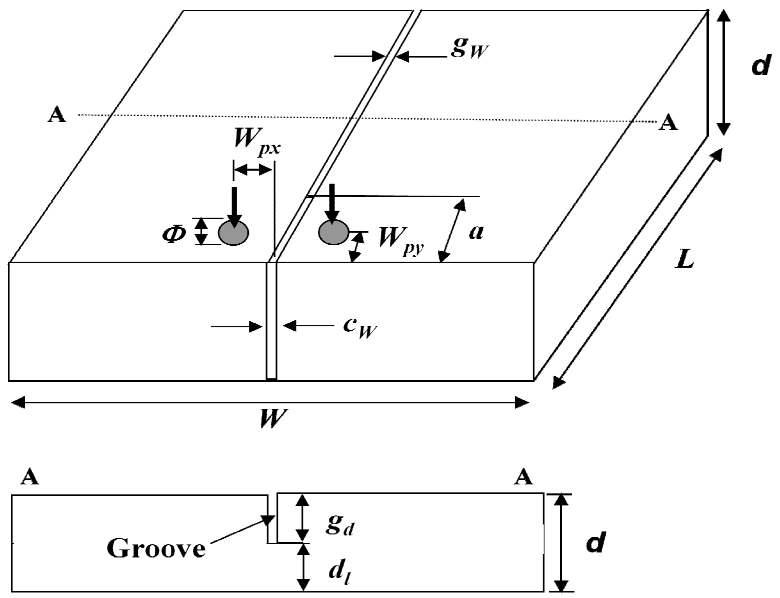

Figure 2: Double-torsion specimen geometry.

Table 2: Dimension of double-torsion specimen (unit: mm)

W	L	d	g_W	c_W	g_d	d_l	W_{px}	W_{py}	Φ	a
150	300	20	3	3	3	17	20	20	10	0, 30, 60, 85

3 EXPERIMENTAL PROCEDURES

DT asphalt specimens were placed on simple supported bars inside of a temperature chamber under the mechanical loading frame and round-shape point loading pins with 10mm diameters applied on the top of DT specimens with 1mm/min monotonic loading speed. The span length of supporting bars was 130mm and the two loading bars were 40mm apart. The distance between point loading positions and the outer edge of DT specimen was 20mm. The diameter of supporting steel rollers was 10mm. In most cases, two to four replicates were used for experiments. Mechanical loading was applied and monitored using a 10kN load cell and the loading was controlled by the crosshead movement. The beam deflection was measured by the linear variable differential transducer (LVDT) placed on the top surface in the middle of steel loading plate as shown in Figure 3(a). Figure 3(b) shows the details of DT loading point area and small pieces of rectangular steel plates on the bottom of loading positions, which was used for avoiding punching effects at the loading positions. The test was conducted in a refrigerated environmental chamber capable of maintaining air temperature within ±0.2°C during the test. The test temperature was at -10°C. The groove surface was located at the bottom surface of DT specimens because the critical cracking starts from the crack tip of bottom surface.

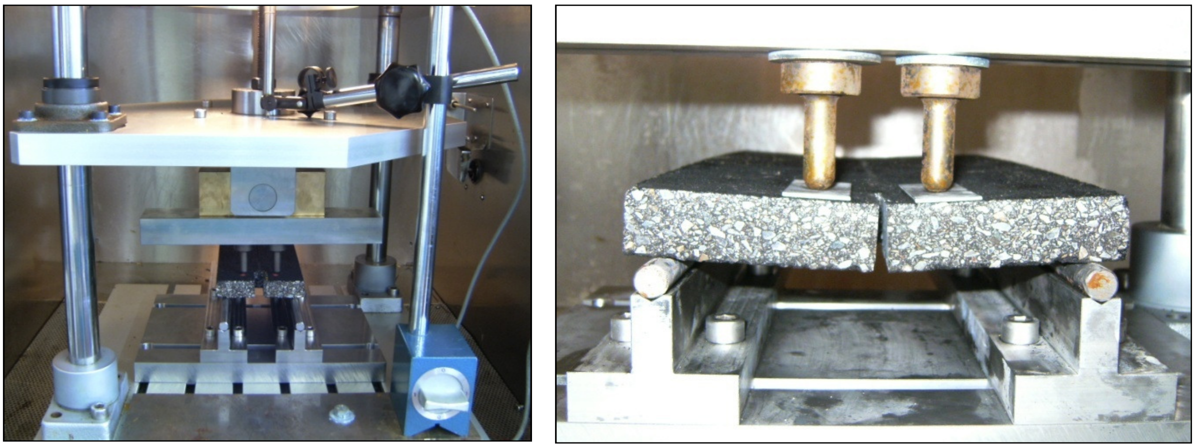

Figure 3: DT test configurations: test set-ups and measurement (left) and an example of point loading configuration (right).

The DT fracture tests have received considerable attention as a direct method to determine the fracture toughness and the behavior of subcritical crack growth due to its simplicity and the possibility of conducting extensive crack propagation in a wide range of crack propagation rates under constant loading conditions or load relaxation tests (Outwater et al. 1974). A compliance analysis of DT fracture test indicates that the stress intensity factor, K_I, is independent of the crack length a (Williams and Evans 1973). The compliance C of a linear elastic solid, defined as the ratio of load point displacement (Δ) to the load (P), varies linearly with crack length:

$$C = Ba + D \tag{5}$$

Where, B and D are constants empirically depending on materials.

The expression for stress intensity factor takes the following form:

$$K_I = PW_m\left(\frac{3(1+\nu)}{Wd^3 d_l \psi(d/W)}\right)^{1/2} \tag{6}$$

Where, P is the applied force, ν is Poisson's ratio, d_l is the ligament length after subtracting the groove depth from d, and $\psi(d/W)$ is a correction factor for the plate thickness (Virkar and Johnson 1976). This factor can be significant for thick beams relative to width. The function of correction factor is

$$\psi(d/W) = 1 - 0.6302\left(\frac{2d}{W}\right) + 1.20\left(\frac{2d}{W}\right)\exp\left(\frac{\pi}{d}\right) \tag{7}$$

The instantaneous crack length (a_i) can be obtained then by the following equation:

$$a_i = a_0 + \Delta a_i = a_0 + \frac{C_i - C_0}{B} \tag{8}$$

Where, a_0 is the initial notch length, C_0 was calculated for each test from the initial slope of P-Δ curve in its elastic portion, C_i was obtained from lines radiating from the origin.

4 RESULTS AND DISCUSSION

From DT fracture test results, the applied force versus displacement curves represent the region of elastic deformation in the beginning of curve and the region of stable crack propagation where the points begin to deviate from the straight line of elastic region including the plateau and the failure. Figure 4 shows the applied force versus displacement curves for tested DT specimens with different notch lengths. In general, the length of stable cracking plateau becomes shorter as the notch length increases. It is understandable that specimens with longer ligaments can resist more against the applied force and have more displacement at the displacement measurement or loading position. Also, the behavior of initial slope from Figure 4 showed that DT specimens with longer notches can have larger compliance or smaller stiffness. However, the notch length did not significantly or systematically contribute the behavior of maximum force.

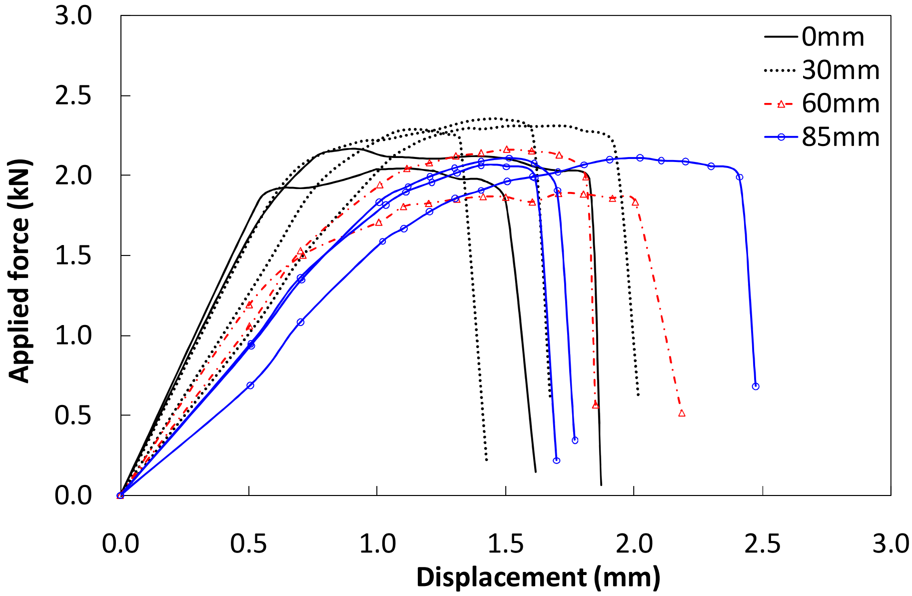

Figure 4: Applied force versus displacement curves for asphalt concrete at -10°C.

Figure 5 shows typical crack propagation through the guide grove made on the bottom surface of DT specimen and also the side view through the crack path of cracked specimens. The subcritical crack growth was not investigated in this paper because of using relatively thin specimens. From Figure 5, the channelized crack in DT specimens well followed the guide groove path but was not a straight line. The crack propagation still showed the arbitrary crack path along the guide groove line to avoid the aggregates and/or to follow the weakest material points. In future, some crack detection or measurement approaches will be applied to determine the crack velocity and investigate the behavior of subcritical crack growth in thick DT specimens.

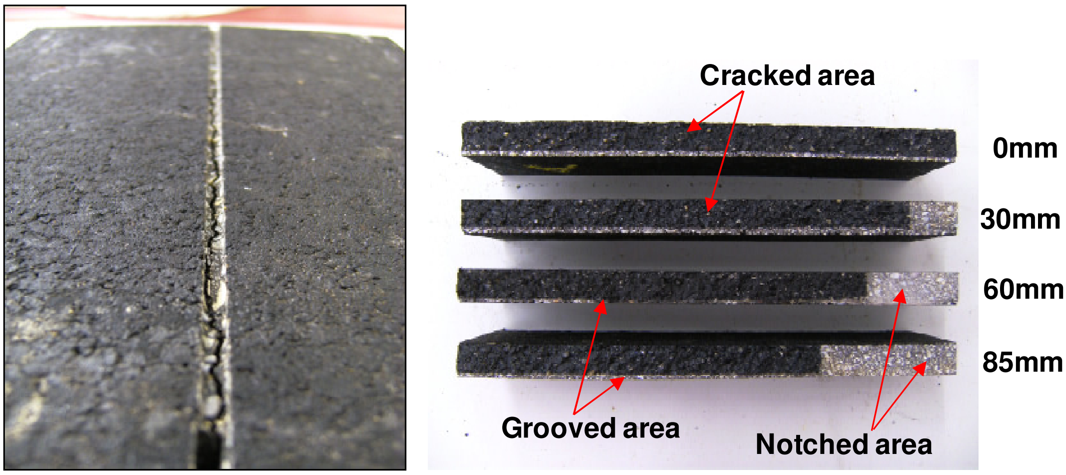

Figure 5: Cracked DT specimens: crack path through the guide groove (left) and cracked area surface along groove lines (right).

The equation for the compliance of test specimens extracted from the corresponding calibrations curves is shown Figure 6 and equation (9). It is interesting that the comparison between the theoretical and experimental determination of B will be interesting. Also, the critical crack length can be determined from combining experimental data and compliance approach but was not included in this paper due to the limitation of time and paper length. As already discussed, the critical stress intensity factor, K_{IC}, can be determined from equation (6) and (7). Figure 7 shows the critical stress intensity factor versus notch length plots with the average value of 1.351MPa.m$^{1/2}$. The averaged deviation from K_{IC} was 5% from the averaged K_{IC}.

$$C = 3.2 \cdot 10^{-6} a + 3.609 \cdot 10^{-7} \tag{9}$$

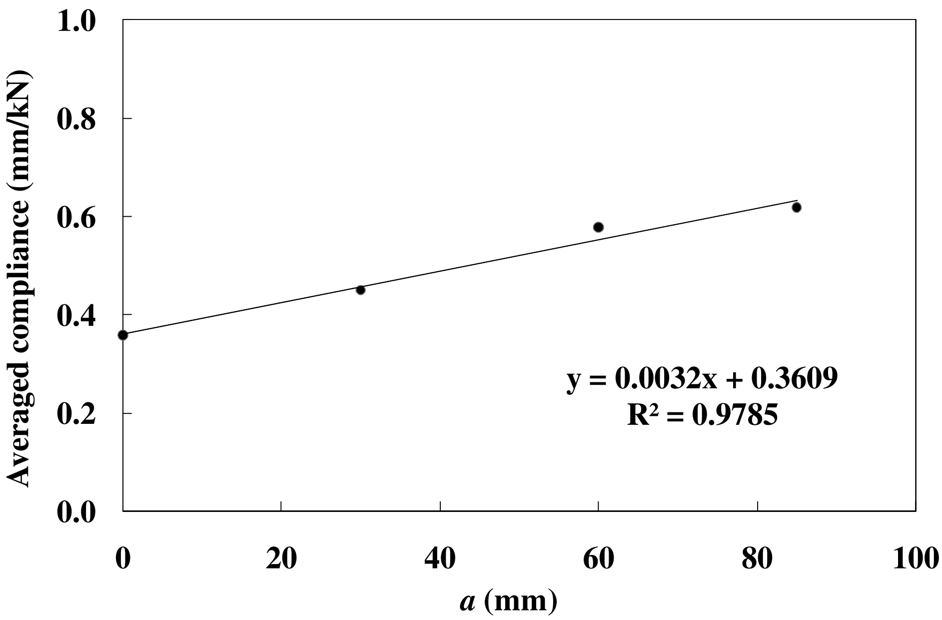

Figure 6: Averaged compliance versus notch length for asphalt concrete at -10°C.

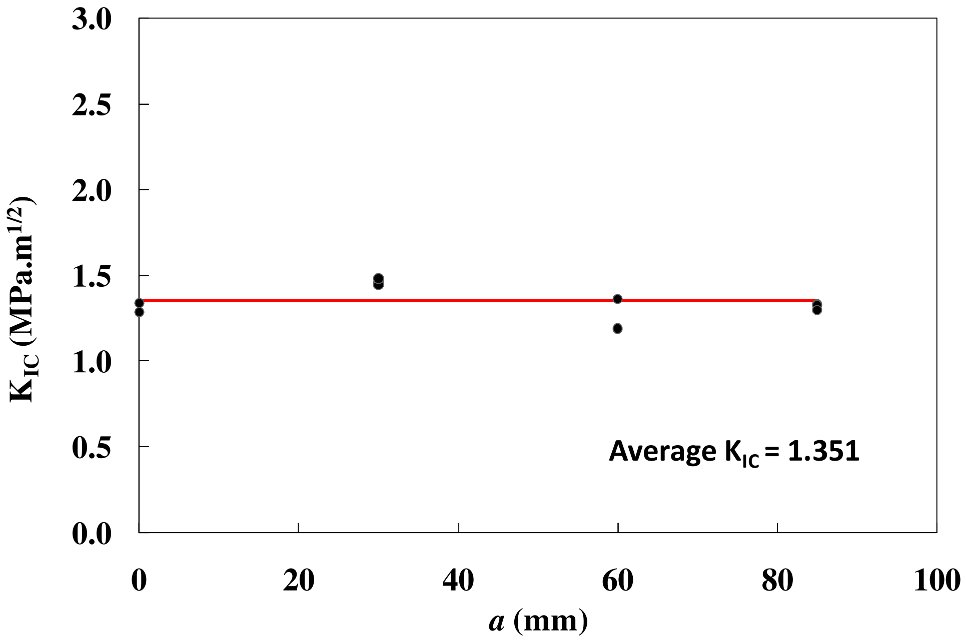

Figure 7: Mode-I stress intensity factor (K_{IC}) versus notch length.

5 CONCLUSIONS

In this study, a double-torsion (DT) fracture test was developed and implemented to investigate the fracture behavior of asphalt concrete. DT test was initiated for understanding the channelized crack propagation and for obtaining various fracture parameters. One selected asphalt mixture, AC4, was tested with different notch lengths at -10°C to testify the developed DT fracture test set-ups and to find the proper DT specimen geometry and test configurations. Some conclusive remarks are:

- Double-torsion fracture test was a suitable method to characterize the crack propagation along the longitudinal dimension of thin plate asphalt specimen.
- The compliance approach with different notch lengths showed the strong benefits for obtaining characteristic material parameters from DT fracture tests without comprehensive measurements. The material constants for AC4 were 3.2×10^{-6} for B and 3.609×10^{-7} for D.
- The constant fracture toughness K_{IC} was obtained from DT specimens tested with different notched lengths. In other words, the fracture property obtained from DT tests was independent on the initial notch length of DT specimen. The averaged critical stress intensity factor of AC4 was 1.351 MPa.m$^{1/2}$.
- DT specimens with shorter notch lengths showed longer lengths of stable crack propagation in the force versus displacement curves.

There are more research topics related to DT fracture tests, which are done already for some features and will be conducted for future such as determination of critical crack length, dependency of loading speed, investigation of crack velocity, the consumption of fracture energy, DT fatigue fracture tests, crack measurements, and the determination of the correction factor function for asphalt concrete. Definitely, various types of asphalt mixtures should be testified with DT test method in future.

REFERENCES

Atkinson, B. K., 1979. Fracture Toughness of Tennessee Sandstone and Carrara Marble Using the Double Torsion Testing Method. *International Journal of Rock Mechanics and Mining Science,* 16, 49-53.

Atkinson, K., 1984. Subcritical Crack Growth in Geological Materials. *Journal of Geophysical Research,* 89, 4077–4114.

Bhaduri, S. B., 1991. Direct Measurement of Subcritical Crack Growth Rate in Magnesium Aluminosilicate Glass by the Indentation Technique. *Materials Letters,* 12(5), 373-375.

Ciccotti, M., Gonzato, G., Mulargia, F., 2000. The Double Torsion Loading Configuration for Fracture Propagation: An Improved Methodology for the Load Relaxation at Constant Displacement. *International Journal of Rock Mechanics and Mining Sciences,* 37(7), 1103-1113.

Ciccotti, M., Negri, N., Gonzato, G., Mulargia, F., 2001. Practical Application of an Improved Methodology for the Double Torsion Load Relaxation Method. *International Journal of Rock Mechanics and Mining Sciences*, 38(4), 569-576.

Ebrahimi, M. E., Chevalier, J., Fantozzi, G., 2000. Slow Crack-growth Behavior of Alumina Ceramics. *Journal of Materials Research*, 15(1), 142-147.

Egan, B. J., Delatycki, O., 1995. Evaluation of the Crack Shape and Activation Energy for Fracture in Double Torsion Fracture Tests of High Density Polyethylene. *Journal of Materials Science Letters*, 14(5), 340-343.

European Standard EN 12591, 1999. *Bitumen and Bituminous Binders Specifications for Paving Grade Bitumens.* European Committee for Standardization (CEN), Brussels.

European Standard EN 13108-1:2006/AC, 2008. *Bituminous Mixtures - Material Specifications - Part 1: Asphalt Concrete.* European Committee for Standardization (CEN), Brussels.

European Standards EN 12697-34, 2004. *Bituminous Mixtures - Test Methods for Hot Mix Asphalt - Part 35: Laboratory Mixing.* European Committee for Standardization (CEN), Brussels.

European Standards EN 12697-35, 2004. *Bituminous Mixtures - Test Methods for Hot Mix Asphalt - Part 34: Marshall Test.* European Committee for Standardization (CEN), Brussels.

Evans, A. G., Linzer, M., Russell, L. R., 1974. Acoustic Emission and Crack Propagation in Polycrystalline Alumina. *Materials Science and Engineering,* 15(2-3), 253-261.

Frassine, R., 1992. The Application of Double Torsion Testing to Unidirectionally Reinforced Composite Materials. *Journal of Composite Materials,* 26(9), 1339-1350.

Gremillard, L., Chevalier, J., Epicier, T., Fantozzi, G., 2002. Improving the Durability of a Biomedical-grade Zirconia Ceramic by the Addition of Silica. *Journal of the American Ceramic Society*. 85(2), 401-407.

Hill, R., Styles, C., 1992. The Influence of Polymer Chain Length on the Fracture Toughness of Polymer-modified Portland Cements. *Journal of Materials Science Letters,* 11(23), 1555-1558.

Kim, H., Wagoner, M. P., Buttlar, W. G., 2008. Simulation of Fracture Behavior in Asphalt Concrete Using a Heterogeneous Cohesive Zone Discrete Element Method. *Journal of Materials in Civil Engineering,* 50 (8), 552–563.

Kim, H., Wagoner, M. P., Buttlar, W. G. Buttlar, 2009(a). Micromechanical Fracture Modeling of Asphalt Concrete Using a Single-Edge Notched Beam Test. *Materials and Structures*, 42(5), 677-689.

Kim, H., Wagoner, M. P., Buttlar, W. G., 2009(b). Numerical Fracture Analysis on the

Specimen Size Dependency of Asphalt Concrete Using a Cohesive Softening Model. *Construction and Building Materials,* 25(5), 2112–2120.

Kulawansa, D. M., Langford, S. C., Dickinson, J. T., 1992. Scanning Tunneling Microscope Observations of Polymer Fracture Surfaces. *Journal of Materials Research*, 7(5), 1292-1302.

Laboratoire Central des Ponts et Chausse´es LCPC, 1995. *Asphalt Mixtures Slabs Compaction Unit (BBPAC).* Nantes, France.

McHenry, K. D., Yonushonis, T., Tressler, R. E., 1976. Low-temperature Subcritical Crack Growth in Silicon Carbide and Silicon Nitride. *Journal of the American Ceramic Society*, 59(5-6), 262-273.

Nara, Y., Kaneko K., 2005. Study of Subcritical Crack Growth in Andesite Using the Double Torsion Test. *International Journal of Rock Mechanics and Mining Sciences*, 42, 521-530.

Outwater, J. O., Murphy, M. C., Kumble, R. G., Berry, J. T, 1974. Fracture Toughness and Slow-stable Cracking, ASTM STP 559, 127-138.

Pabst, R. F., Weick, J., 1981. Double-torsion Measurements With and Without a Guiding Notch. *Journal of Materials Science,* 16, 836–838.

Pletka, B. J., Fuller Jr, E. R., Koepke, B. G., 1979. An Evaluation of Double-torsion Testing - Experimental. ASTM STP, 678, 19–37.

Shetty, D. K., Virkar, A. V., 1978. Determination of the Useful Range of Crack Length in Double Torsion Specimens. *Journal of American Ceramic Society,* 61(11), 93-94.

Swanson, P. L., 1984. Subcritical Crack Growth and Other Time- and Environment-dependent Behavior in Crustal Rocks. *Journal of Geophysical Research,* 89, 4137–4152.

Trantina, G. G., 1977. Stress Analysis of the Double-torsion Specimen. *Journal of American Ceramic Society,* 60, 338–341.

Virkar, A. V., Johnson, D.L., 1976. Fracture Behaviour of ZrO//2-Zr Composites. *Journal of the American Ceramic Society,* 59(5-6), 197-200.

Wagoner, M. P., Buttlar, W. G., Paulino, G. H., 2005. Development of a Single-edge Notched Beam Test for Asphalt Concrete Mixtures. *Journal of Testing and Evaluation*, 33(6), 452-460.

Williams, D. P., Evans, A. G., 1973. Method for Studying Slow Crack Growth. *Journal of Testing and Evaluation*, 1(4), 264-270.

Xue, L., Marasteanu, M., 2005. Cohesive Modeling of Fracture in Asphalt Mixtures at Low Temperatures. *International Journal of Fracture*, 136, 285-308.