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**Standard Method of Test for**

**Determining the Fracture Energy  
of Asphalt Mixtures Using  
the Semi Circular Bend Geometry  
(SCB)**

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AASHTO Designation: L nnn-YY

**PROVIDED AS AN EXAMPLE ONLY - NOT FOR DISTRIBUTION**

**Proposed Test Method to be reviewed by the FHWA Mixture ETG**

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### 1. SCOPE

- 1.1. This test method covers the determination of the fracture energy ( $G_f$ ) of asphalt mixtures by means of the semi circular bend geometry (SCB). The method also includes procedures for calculating fracture toughness ( $K_{IC}$ ) and stiffness ( $S$ ). The SCB specimen is a half disc with a notch that is  $a$ -mm long and makes an angle  $\alpha$  with the vertical axis of the disc. The SCB test can be used to determine mode I and mixed mode I and II stress intensity factors [Lim et al. 1993]. In this standard, only mode I fracture toughness is addressed ( $\alpha$  is equal to zero).
- 1.2. The procedures described in this standard provide parameters that describe the fracture resistance of asphalt mixtures at low temperatures. These procedures apply to test specimens having a maximum aggregate size of 19 mm or less. Specimens shall be  $150 \pm 9$  mm in diameter and  $25 \pm 5$  mm thick. These procedures are valid at temperatures below  $10^\circ\text{C}$  above the PG lower limit of the asphalt binder used to prepare the asphalt mixture.
- 1.3. *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety concerns associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.*

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### 2. REFERENCED DOCUMENTS

- 2.1. *AASHTO Standards:*
  - AASHTO M 320, Performance-Graded Asphalt Binder
  - AASHTO T 166, Bulk Specific Gravity of Compacted Hot-Mix Asphalt Using Saturated Surface-Dry Specimens
  - AASHTO T 269, Percent Air Voids in compacted Dense and Open Asphalt Mixtures
  - AASHTO T 312, Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor
  - AASHTO T322 Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device
- 2.2. *ASTM Standards:*
  - D 8, Terminology Relating to Materials for Roads and Pavements
  - D 4123, Indirect Tension Test for Resilient Modulus of Bituminous Mixtures
  - D5045, Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials
  - D 5361, Sampling Compacted Bituminous Mixtures for Laboratory Testing
  - E399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials

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### **3. TERMINOLOGY**

- 3.1. *Definitions:*
- 3.1.1. *Crack mouth* — portion of the notch that is on the flat bottom surface of the specimen, that is, opposite the notch tip
- 3.1.2. *Crack mouth opening displacement, CMOD* — relative displacement of the crack mouth.
- 3.1.3. *Load line displacement, LLD* — the displacement measured in the direction of the load application.
- 3.1.4. *Semi circular bend (SCB) geometry* — a geometry that utilizes a semicircular specimen.
- 3.1.5. *Fracture energy,  $G_f$*  — the energy required to create a unit surface area of a crack.
- 3.1.6. *Stiffness,  $S$*  — the slope of the linear part of the ascending load-load line displacement curve
- 3.1.7. *Mode I stress intensity factor,  $K_I$*  — the parameter used to characterize the mode I stress field in the vicinity of the crack tip in the LEFM analysis
- 3.1.8. *Mode I critical stress intensity factor,  $K_{IC}$*  — stress intensity factor corresponding to the initiation of the crack, also referred to as fracture toughness.

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### **4. SUMMARY OF TEST METHOD**

- 4.1. A semicircular asphalt mixture specimen is positioned with the flat side on two rollers that are covered with a friction reducing material. A load is applied along the vertical diameter of the specimen and the load and load line displacement are measured during the entire duration of the test. The load is applied such that a constant CMOD of 0.0005 mm/s is obtained and maintained for the duration of the test to ensure stable crack growth conditions.
- 4.2. Fracture energy ( $G_f$ ), stiffness ( $S$ ), and fracture toughness ( $K_{IC}$ ) are calculated from the load and load line displacement results.

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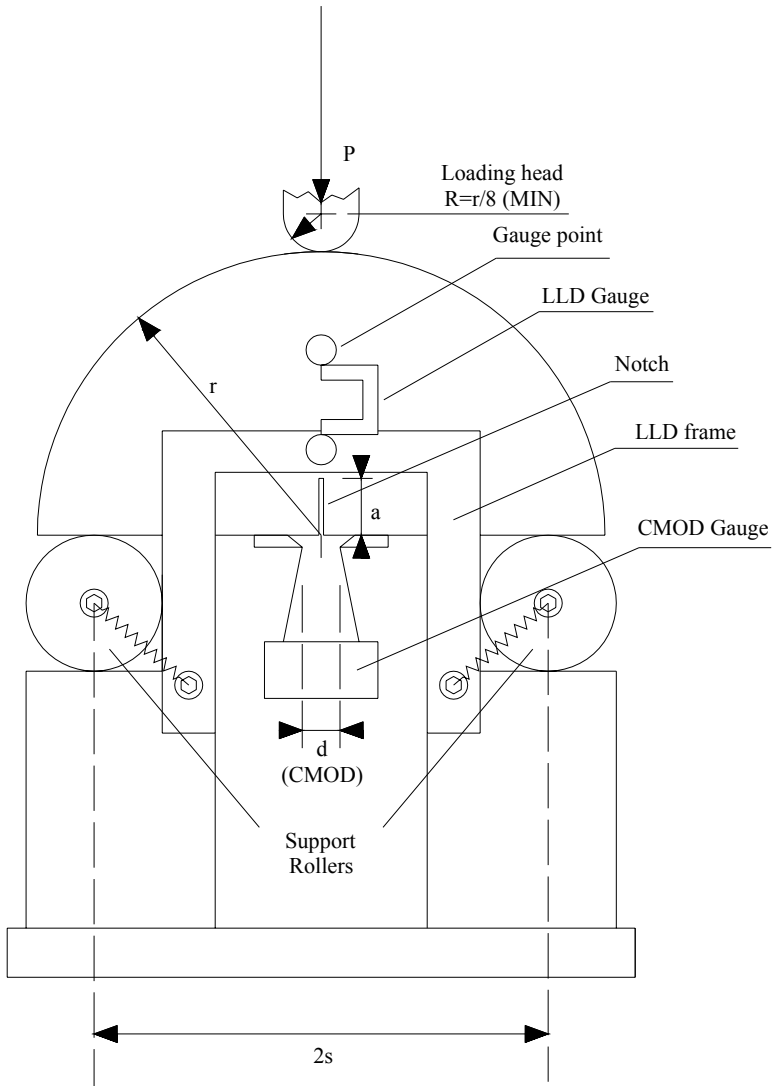
### **5. SIGNIFICANCE AND USE**

- 5.1. The SCB test is used to determine the low temperature fracture energy and fracture toughness of asphalt mixtures. These parameters describe the fracture resistance of asphalt mixtures.
- 5.2. Fracture energy can be used as an index parameter to identify mixtures with increased fracture resistance. It also represents the main parameter used in more complex analyses based on fictitious crack (cohesive zone) model.
- 5.3. Fracture toughness obtained with this test method can be used as an index parameter to identify mixtures with increased fracture resistance.
- 5.4. Stiffness obtained with this test method can be related to the elastic modulus of asphalt mixtures at low temperatures.
- 5.5. The specimens can be easily cut from Superpave™ gyratory compacted cylinders and from field cores with a diameter of 150 mm.

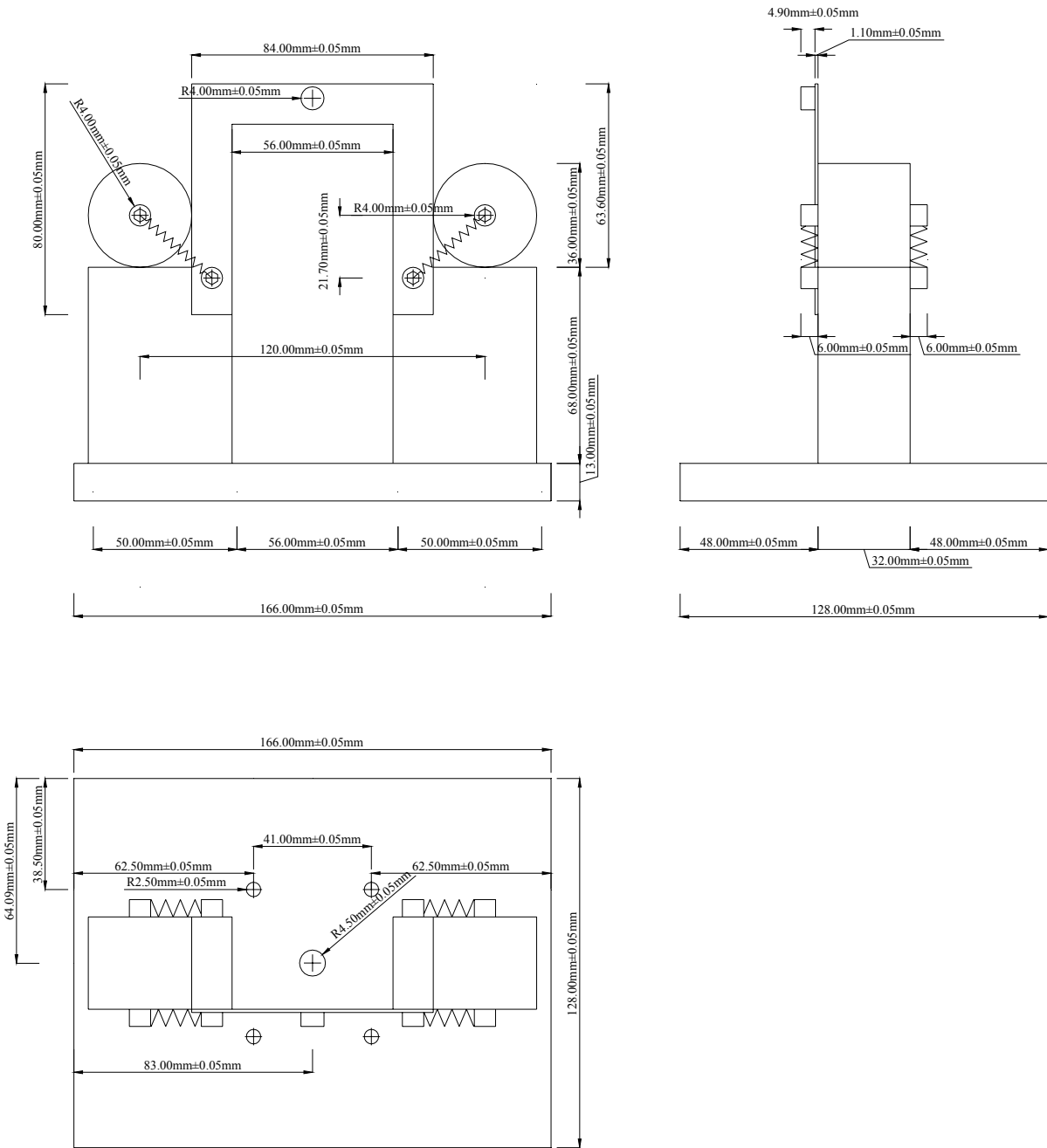
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## 6. APPARATUS

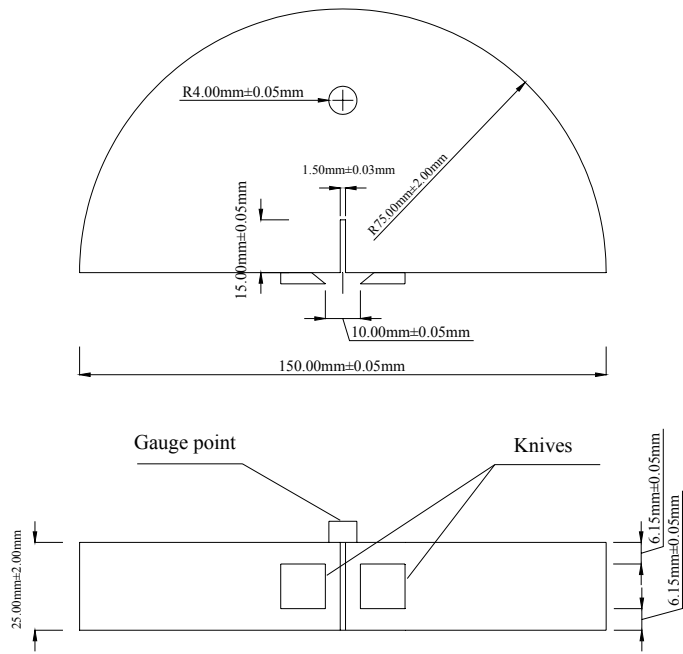
- 6.1. *Semi-Circular Bend (SCB) Test System* — A semi-circular bend (SCB) test system consisting of a closed-loop axial loading device, a load measuring device, a bend test fixture, specimen deformation measurement devices, an environmental chamber, and a control and data acquisition system (see Figure 1).
- 6.1.1. *Axial Loading Device* — The loading device shall be capable of delivering a minimum load of 20 kN in compression with a resolution of 5 N or better. The load apparatus shall be capable of maintaining a constant crack mouth opening displacement within 1% of the target value throughout the test. The loading head shall be similar to the one described for the bend test fixture in ASTM E 399 (see Figure 1).
- 6.1.2. *Load Measuring Device* — The load measuring device shall consist of an electronic load cell, designed for placement between the loading platen and piston, with a minimum capacity of 20 kN and a sensitivity of 5 N or better.
- 6.1.3. *Bend Test Fixture* — The test fixture is composed of a steel base plate, two L-shaped roller support steel blocks, two steel rollers, and a U-shaped frame (see Figure 2). The loading fixture is designed to minimize frictional effects through the use of rollers (as suggested by ASTM E399). The surface of the rollers is covered with Polytetrafluoroethylene (PTFE) strips to further reduce friction. The initial roller position is maintained by soft springs and backstops which establish the test span dimension. The support rollers are allowed to rotate out away from the backstops during the test but will remain in contact with the sample. The roller support blocks are secured to a 12.7 mm thick base plate with a 9.5 mm diameter dowel hole for alignment with the actuator center. To obtain an accurate measure of the load-line displacement (LLD), a U-shaped reference frame is secured to the L-shaped roller support blocks. A brass gauge point (see 6.1.5) is permanently attached to the center of the upper arm of the reference frame.
- 6.1.4. *Specimen Deformation Measuring Devices* — The specimen deformation measurement devices shall consist of a CMOD gauge and an LLD gauge, with a range of at least 1 mm and a resolution of 0.0005 mm or better. The CMOD gauge is attached to the two gauge points glued to the bottom of the SCB specimen via knife edges (see Figure 3 and Figure 4). The LLD gauge is attached to the gauge point glued to the specimen front face and to the gauge point on the U-shaped reference frame.
- 6.1.5. *Gauge Points* — Three brass gauge points having a diameter of 8 mm and a height of 3.2 mm are required per specimen.
- 6.1.6. *Mounting Template* — A mounting template for placing and mounting the three brass gauge points on the SCB specimen is shown in Figure 5.
- 6.1.7. *Environmental Chamber* — The environmental chamber should be equipped with temperature conditioner and controls capable of generating test temperature between -40°C and 0°C inside the chamber and maintaining the desired test temperature to within  $\pm 0.2^\circ\text{C}$ . The internal dimensions of the environmental chamber should be capable to hold a minimum of 3 test specimen for a period of  $2 \pm 0.5$  hours prior to testing.
- 6.1.8. *Control and Data Acquisition system* — Specimen behavior during semi-circular bend test is evaluated from time records of applied load, CMOD, and LLD. The applied load is controlled via the closed-loop by the CMOD rate kept constant during the test.



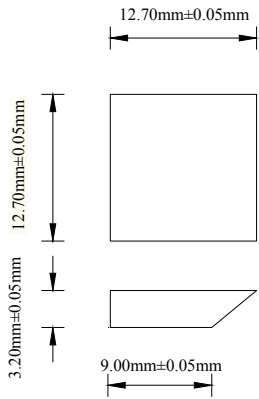
**Figure 1**—SCB loading setup



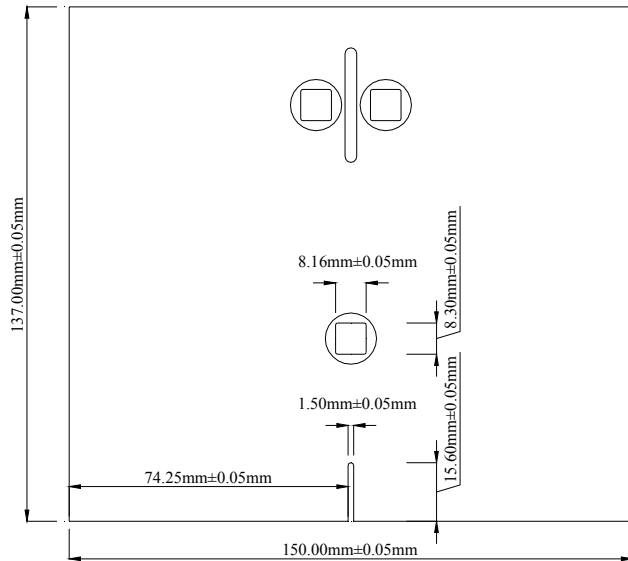
**Figure 2**—SCB test fixture



**Figure 3** — Gauge points locations



**Figure 4**—CMOD gauge knife edges



**Figure 5**— Gauge points template

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## 7. HAZARDS

- 7.1. Observe standard laboratory safety precautions when preparing and testing HMA specimens.

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## 8. STANDARDIZATION

- 8.1. The testing system should be calibrated prior to initial use and at least once a year thereafter.
- 8.1.1. Verify the capability of the environmental chamber and component to maintain the required temperature within the specified accuracy.
- 8.1.2. Verify the calibration of all measurement components (such as load cells and LDVTs) of the testing system.
- 8.1.3. If any of the verifications yield data that does not comply with the accuracy specified, correct the problem prior to proceeding with testing. Appropriate action may include maintenance of system components, calibration of system components, (using an independent calibration agency, or service by the manufacturer, or in-house resources), or replacement of the system components.

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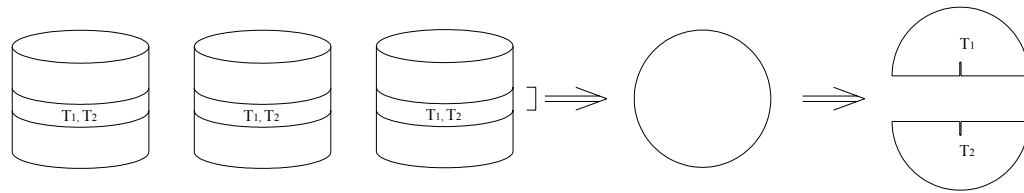
## 9. SAMPLING

- 9.1. *Laboratory Molded Specimen*— Prepare three replicate laboratory molded specimens, as a minimum for each test temperature, in accordance with T 312.
- 9.2. *Roadway Specimen*— Obtain roadway specimens from the pavement in accordance with ASTM D 5361. Prepare cores with smooth and parallel surfaces that conform to the height and diameter requirements specified in section 10.2. Prepare three replicate cores for each test temperature.



## 10. SPECIMENS PREPARATION AND PRELIMINARY DETERMINATIONS

- 10.1. *Specimen Size* — For mixtures with maximum aggregate size of 19 mm or less, prepare specimens with a thickness of  $25 \pm 2$  mm and a diameter of  $150 \pm 9$  mm in diameter (see Figure 3).
- 10.2. *SGC Specimens* — Prepare three SGC specimens according to T 312. From the center of each  $115 \pm 5$  mm tall specimen, obtain a cylindrical slice that is  $25 \pm 2$  mm thick (see Figure 6). Cut the slice in two identical “halves” and then cut a notch along the axis of symmetry of each half that is  $15 \pm 0.5$  mm in length and no wider than 1.5 mm (see Figures 3 and 6). Use one half from each cylinder for testing at one test temperature ( $T_1$ ) and the other half for testing at the second test temperature ( $T_2$ ). If more replicates or test temperature are necessary, cut additional  $25 \pm 2$  mm thick slices from the SGC cylinder, located as close to the middle slice as possible.



**Figure 6** — Sample Preparation

- 10.3. *Field Cores* — Field cores can also be used to fabricate the specimens. The target thickness for field cores should be  $25 \pm 2$  mm. The top and bottom of the core shall be cut to ensure that the test specimen has parallel faces. If multiple slices are cut from taller cores, the lift thickness shall be considered to obtain representative samples.
- Note 1** — A typical laboratory saw for mixture specimen preparation can be used to obtain cylindrical slices with smooth parallel surfaces. Diamond-impregnated cutting faces and water-cooling are recommended to minimize damage to the specimen. When cutting the SCB specimens, it is recommended not to push the two halves against each other because it may create uneven base surface of the test specimen that will significantly affect the results.
- 10.4. *Determining Specimen Dimensions* — Measure and record the diameter and thickness of each specimen in accordance with ASTM D3549, and determine individual measurements to the nearest 1mm. Measure the notch length on both faces of the specimen and record the average value to the nearest 0.5mm.
- 10.5. *Determining the Bulk Specific Gravity* — Determine the bulk specific gravity directly on the  $115 \pm 5$  mm tall GSC specimen in accordance with T 312.
- 10.6. *Specimen Drying* — If specimens were immersed directly into water, after determining the bulk specific gravity, allow each specimen to dry at room temperature to a constant mass.
- 10.7. *Mounting Deformation Measuring Devices* — Epoxy the three gauge points on the specimen as shown in Figure 3. A template, similar to the one in Figure 5, can be used for this purpose.

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## 12. TEST PROCEDURE

- 12.1. *Conditioning* —The specimens shall be placed in a temperature controlled chamber at the desired test temperature for  $2 \pm 0.2$  h. The temperature shall be within  $1^\circ\text{C}$  throughout the conditioning and testing times. Two test temperatures are recommended:  $10^\circ\text{C}$  above the PG lower limit of the asphalt binder used to prepare the asphalt mixture, and  $2^\circ\text{C}$  below the PG lower limit.
- 12.2. After temperature conditioning, the specimen shall be placed on the test fixture and the LLD and the CMOD gauges shall be attached to the specimen.
- 12.3. First, a small contact load of  $0.3 \pm 0.02$  kN is imposed in stroke control with a displacement rate of  $0.05\text{mm/s}$ . Then, a seating load up to  $0.6 \pm 0.02$  kN is applied in stroke control with a displacement rate of  $0.005\text{mm/s}$ . Three small amplitude loading cycles are applied to ensure contact between the loading head and the specimen.
- 12.4. The test is then executed and the load, the CMOD, and the LLD are measured and recorded. An initial load of  $1 \text{ kN} \pm 0.1 \text{ kN}$  is reached first, starting from the seating load in stroke control with a rate of  $0.001\text{mm/s}$ . When this initial load level is reached, the system switches to CMOD control and the load is applied such that the CMOD rate is kept constant at  $0.0005 \text{ mm/s}$  for the entire duration of the test.
- 12.5. The test stops when the load drops below  $0.5\text{kN}$  or when the CMOD gauge range limit is reached, whichever occurs first.

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## 13. FRACTURE ENERGY $G_f$

- 13.1. *Fracture energy ( $G_f$ )* — The fracture energy  $G_f$  is obtained according to RILEM TC 50-FMC recommendation and it is calculated by dividing the work of fracture (the area under the load vs. load line displacement curve, see Figure 7) by the ligament area (the product of the ligament length and the thickness of the specimen) of the SCB specimen prior to testing:

$$G_f = \frac{W_f}{A_{lig}} \quad (1)$$

where

$G_f$  = fracture energy ( $\text{J/m}^2$ );  
 $W_f$  = work of fracture (J), and

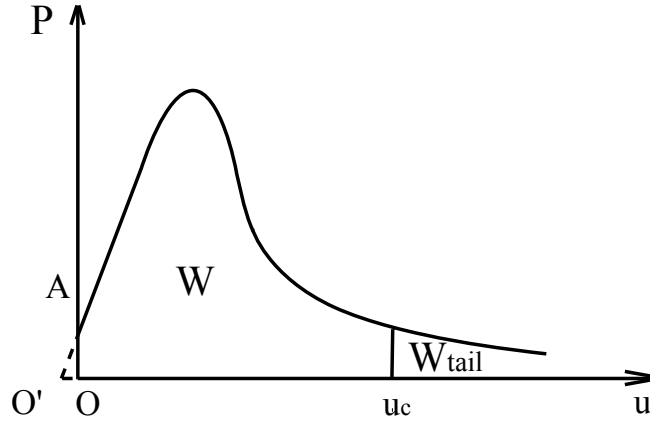
$$W_f = \int P du \quad (2)$$

$P$  = applied load (N);  
 $u$  = load line displacement (m);

$$A_{lig} = \text{ligament area (m}^2\text{), and} \quad (3)$$

$A_{lig} = (r - a) \times t$   
 $r$  = specimen radius (m);  
 $a$  = notch length (m);  
 $t$  = specimen thickness (m).

**Note 2** —In some instances, data recording can start at a load value different than zero (see Figure 7) and can introduce an error in the calculation of the area under the curve (triangle OO'A in Figure 7). This error can be neglected if the load level is less than  $0.3 \text{ kN}$  (point A in Figure 7).



**Figure 7** — Load vs. load line displacement ( $P-u$ ) curve

13.2. *Determining work of fracture ( $W_f$ )* — The work of fracture is calculated as the area under the load vs. load line displacement ( $P-u$ ) curve. The test is stopped when the load drops below 0.5kN or when the CMOD gauge range limit is reached (point  $u_c$  in Figure 7) and the remainder of the curve must be extrapolated. The total work of fracture  $W_f$  is calculated as the sum of the area under the experimentally obtained  $P-u$  curve ( $W$ ) and the area under the extrapolated tail of the curve ( $W_{tail}$ ).

13.2.1. *Calculating area under the experimental curve ( $W$ )* — the work of fracture  $W$  under the experimental curve can be computed using a technique called the quadrangle rule:

$$W = AREA = \sum_{i=1}^n (u_{i+1} - u_i) \cdot (P_i) + \frac{1}{2} \cdot (u_{i+1} - u_i) \cdot (P_{i+1} - P_i) \quad (4)$$

where

- $P_i$  = applied load (N) at the  $i$  load step application;
- $P_{i+1}$  = applied load (N) at the  $i+1$  load step application;
- $u_i$  = LLD load line displacement (m) at the  $i$  step;
- $u_{i+1}$  = LLD load line displacement (m) at the  $i+1$  step;

13.2.2. *Estimating area under the extrapolated tail of the curve ( $W_{tail}$ )* — The area under the extrapolated tail of the curve is calculated using the following method. First, a power law with coefficient equal to -2 is assumed for the portion of the post peak  $P-u$  curve with  $P$  values lower than 60% of the peak load [Li Xue, Marasteanu, M., 2004]:

$$P = \frac{c}{u^2} \quad (5)$$

Next, coefficient  $c$  is obtained by fitting equation (5) to the experimental  $P-u$  curve below 60% of the peak load. Then, the  $P-u$  curve is extrapolated to  $P = 0$  and the tail area is calculated as:

$$W_{tail} = \int_{u_c}^{\infty} P d(u) = \int_{u_c}^{\infty} \frac{c}{u^2} d(u) = \frac{c}{u_c} \quad (6)$$

where

- $u$  = integration variable equal to load line displacement (m);
- $u_c$  = load line displacement value at which the test is stopped (m);

13.2.3. The total work of fracture is then calculated as the sum of  $W$  and  $W_{tail}$ :

$$W_f = W + W_{tail} \quad (7)$$

**Note 3** — An alternate expression to obtain the tail of the  $P$ - $u$  curve is

$$P = a \cdot u^b \quad (8)$$

where

$a, b$  = fitting parameters;

Solving the integral results in the following alternative equation to calculate the area:

$$W_{tail} = -\frac{a \cdot (u_c)^b}{b-1} \quad (9)$$

**Note 4** — For temperatures above the values recommended in this test method, the energy must be corrected for loading head penetration and specimen compression. Additional tests performed on un-notched specimens are required, as described in ASTM D 5045.

**Note 5** — The use of  $G_f$  in crack propagation analyses involving the fictitious crack model assumes that  $G_f$  is size independent and the local fracture energy is constant along the crack path over the entire fracture area ( $A_{lig}$ ). None of these assumptions have been evaluated for the  $G_f$  obtained using the present test method.

## 14. FRACTURE TOUGHNESS $K_{IC}$

14.1. *Fracture toughness ( $K_{IC}$ )* — The fracture toughness  $K_{IC}$  is obtained as the stress intensity factor  $K_I$  at the critical load  $P_c$ . The critical load is assumed to be the maximum load recorded during testing.

14.2. *Stress intensity factor ( $K_I$ )* — The following equation is used to compute  $K_I$  [Lim et al., 1994, Li and Marasteanu, 2004]:

$$\frac{K_I}{\sigma_0 \sqrt{\pi a}} = Y_{I(0.8)} \quad (10)$$

where

$$\sigma_0 = \frac{P}{2rt} \quad (11)$$

$P$  = applied load (MN);

$r$  = specimen radius (m);

$t$  = specimen thickness (m).

$a$  = notch length (m);

$Y_I$  = the normalized stress intensity factor (dimensionless).

For the dimensions of the SCB specimen used in this test method,  $Y_I$  is calculated as follows:

$$Y_{I(0.8)} = 4.782 + 1.219 \left( \frac{a}{r} \right) + 0.063 \exp \left( 7.045 \left( \frac{a}{r} \right) \right) \quad (12)$$

**Note 6** — The equations used to calculate fracture toughness are derived using linear elastic fracture mechanics (LEFM). For the test temperatures recommended, the assumption of linear elastic conditions is reasonable: the modulus changes less than 5% for the time range of the test, and the fracture process zone is small [Li and Marasteanu, 2006].

**Note 7** — The assumption of size independence for the fracture toughness obtained with this method has not been evaluated.

14.3. *Unit* — The unit of measure for fracture toughness ( $K_{IC}$ ) is  $\text{MPa} \times \text{m}^{0.5}$ .

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## 15. STIFFNESS

15.1. *Stiffness(S)* — The stiffness ( $S$ ) is calculated as the slope of the linear part of the ascending load-load line displacement ( $P-u$ ) curve. An example is shown in Figure 7.

15.2. *Unit* — The unit of measure for stiffness ( $S$ ) is kN/mm

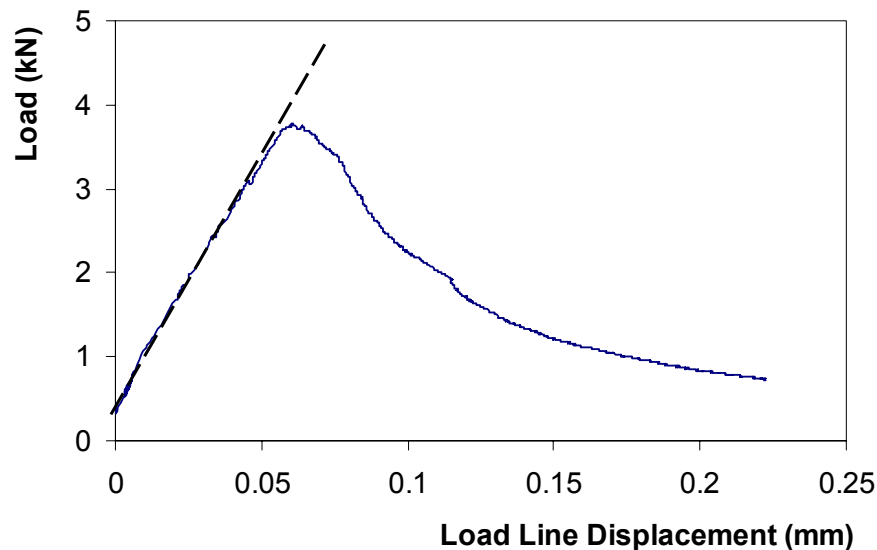


Figure 7 — Example of stiffness determination

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## 16. REPORT

16.1. *Report the following information:*

16.1.1. Bulk specific gravity of each specimen tested, to the nearest 0.001;

16.1.2. Maximum specific gravity of asphalt concrete mixture, to the nearest 0.001;

16.1.3. Air voids of each specimen, to the nearest 0.1;

16.1.4. Thickness  $t$  and radius  $r$  of each specimen tested, to the nearest 0.5 mm;

16.1.5. Test temperature, to the nearest 0.2°C;

16.1.6. Initial notch length  $a$ , to the nearest 0.5 mm;

16.1.7. Peak load, to the nearest 0.1 kN;

16.1.8. Time at peak load, to the nearest 0.1 s;

16.1.9. Value of  $u_c$  (LLD when test is stopped), to the nearest 0.001 mm;

16.1.10. Plot of the  $P-u$  curve and fitted line used to determine stiffness  $S$ ;

16.1.11. Stiffness  $S$ , to the nearest 0.1 kN/m;

- 16.1.12. Fracture toughness  $K_{IC}$ , to the nearest  $0.001\text{MPa}\times\text{m}^{0.5}$ ;
- 16.1.13. Fracture energy  $G_f$ , to the nearest  $\text{IJ/m}$ .

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**17. PRECISION AND BIAS**

- 17.1. *Precision* — The research required to develop precision estimates has not been conducted.
- 17.2. *Bias* — The research required to establish the bias of this method has not been conducted.

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**18. KEYWORDS**

- 18.1. Semi circular bend (SCB); stiffness; fracture toughness, fracture energy, work of fracture.

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**19. REFERENCES**

- 19.1. RILEM Technical Committee 50-FMC, “Determination of the Fracture Energy of Mortar and Concrete by Means of Three-point Bend Tests on Notched Beams,” *Materials and Structures*, No. 106, Jul-Aug, pp. 285-290, 1985.
- 19.2. Lim I. L., Johnston I. W., and Choi S. K., 1993, “Stress Intensity Factor for Semi Circular Specimen under Three-Point Bending”, *Engineering Fracture Mechanics*, Vol. 44, No.3, 363-382.
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- 19.4. Li, Xinjun, Marasteanu, M. O., “Investigation of Low Temperature Cracking in Asphalt Mixtures by Acoustic Emission,” *Road Materials and Pavement Design*, Vol. 7/4, 2006, pp. 491-512.