Appendix B

Proposed revision to AASHTO TP105-13 (2015) Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB)

Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB)

AASHTO Designation: TP 105-13 (2015)[1]

Technical Section: 2d, Proportioning of Asphalt–Aggregate Mixtures

1. SCOPE

1.1. This test method covers the determination of the fracture energy (G_f) of asphalt mixtures by means of the semicircular 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 (its length expressed in meters) that makes an angle α 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 (α is equal to zero).

1.2. The procedures in this standard provide parameters that describe the fracture resistance of asphalt mixtures at low temperatures. These parameters are used in the new low-temperature module of the *Mechanistic Empirical Pavement Design Guide*.

1.3. These procedures apply to test specimens having a maximum aggregate size of 19 mm or less. Specimens shall be 150 ± 9 mm in diameter and 24.7 mm ± 2 mm thick. These procedures are valid at temperatures below the performance grade (PG) lower limit of the asphalt binder used to prepare the asphalt mixture plus 22°C.

1.4. *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.*

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:

- M 320, Performance-Graded Asphalt Binder
- T 166, Bulk Specific Gravity (G_{mb}) of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens
- T 269, Percent Air Voids in Compacted Dense and Open Asphalt Mixtures
- T 312, Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor
- T 322, Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device

2.2. *ASTM Standards*:

- D3549/D3549M, Standard Test Method for Thickness or Height of Compacted Bituminous Paving Mixture Specimens
- D5045, Standard Test Methods for Plane-Strain Fracture Toughness and Strain Energy Release Rate of Plastic Materials
- D5361/D5361M, Standard Practice for Sampling Compacted Bituminous Mixtures for Laboratory Testing
- E399, Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness KIC of Metallic Materials

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. *linear variable differential transformer (LVDT)*—sensor device for measuring linear displacement.

3.1.5. *semicircular bend (SCB) geometry*—a geometry that utilizes a semicircular specimen.

3.1.6. *fracture energy, G_f*—the energy required to create a unit surface area of a crack.

3.1.7. *stiffness, S*—the slope of the linear part of the ascending load-load line displacement curve.

3.1.8. *linear elastic fracture mechanics (LEFM)*—a method of fracture analysis for determining the stress required to induce fracture instability in a structure containing a crack-like flaw of known size and shape.

3.1.9. *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.

3.1.10. *mode I critical stress intensity factor, K_{IC}*—stress intensity factor corresponding to the initiation of the crack, also referred to as fracture toughness.

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 0.03±0.0015 mm/min 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.

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 a 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.

6. APPARATUS

6.1. *Semicircular Bend (SCB) Test System*—A semicircular 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 10 kN in compression with a resolution of 20 N or better. The load apparatus shall be capable of maintaining a constant crack mouth opening displacement within 1 percent of the target value throughout the test. The loading head shall be similar to the one described for the bend test fixture in ASTM E399 (see Figure 1).

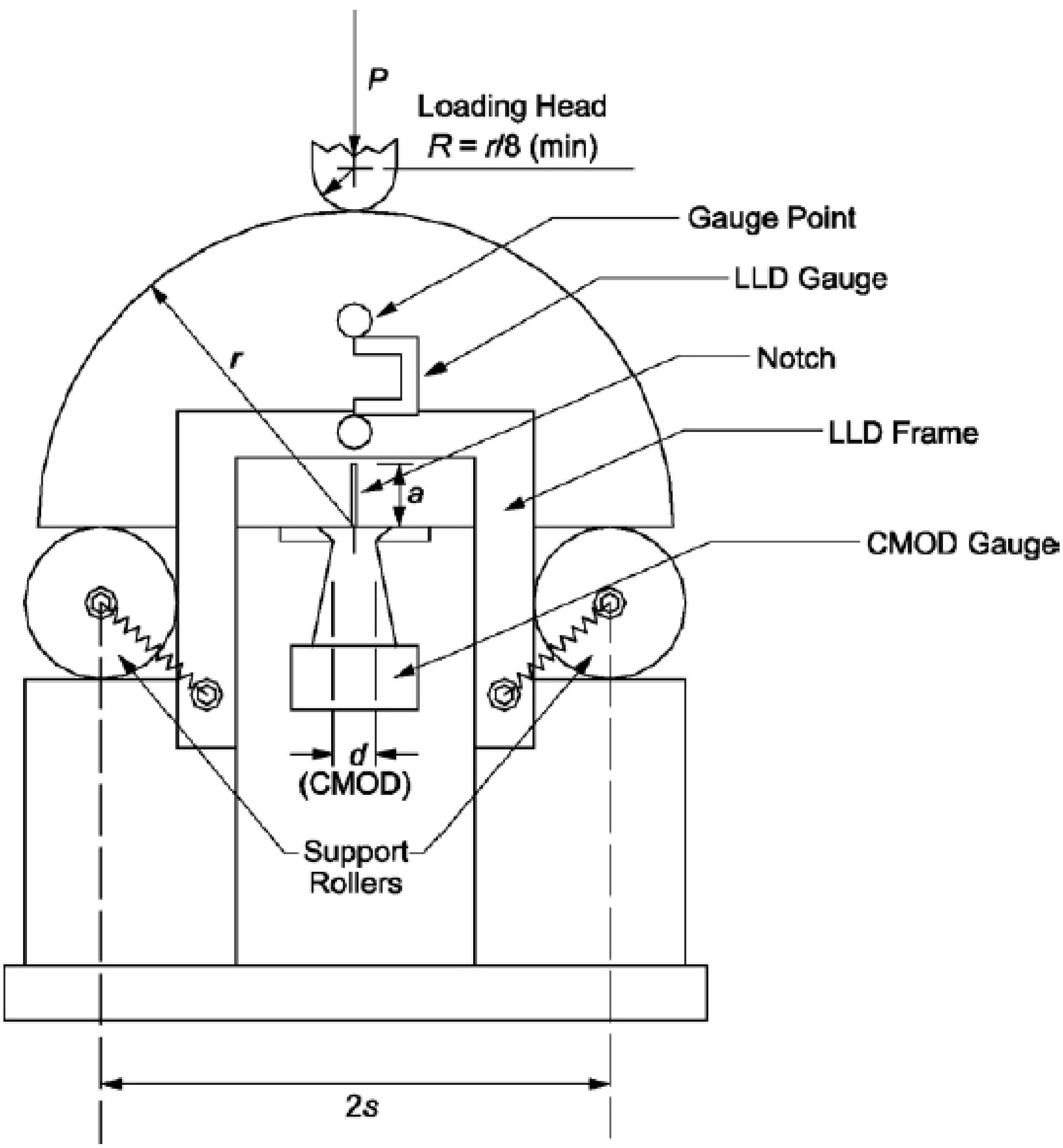

Figure 1 – SCB Loading Setup for Front and Back Sides of Test Specimen

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 10 kN and a sensitivity of 10 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 two U-shaped frames (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 that 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), two U-shaped reference frames are secured to the L-shaped roller support blocks, one on each side of the blocks. A steel gauge point (see Section 6.1.5) is permanently attached to the center of the upper arm of each of the reference frames.

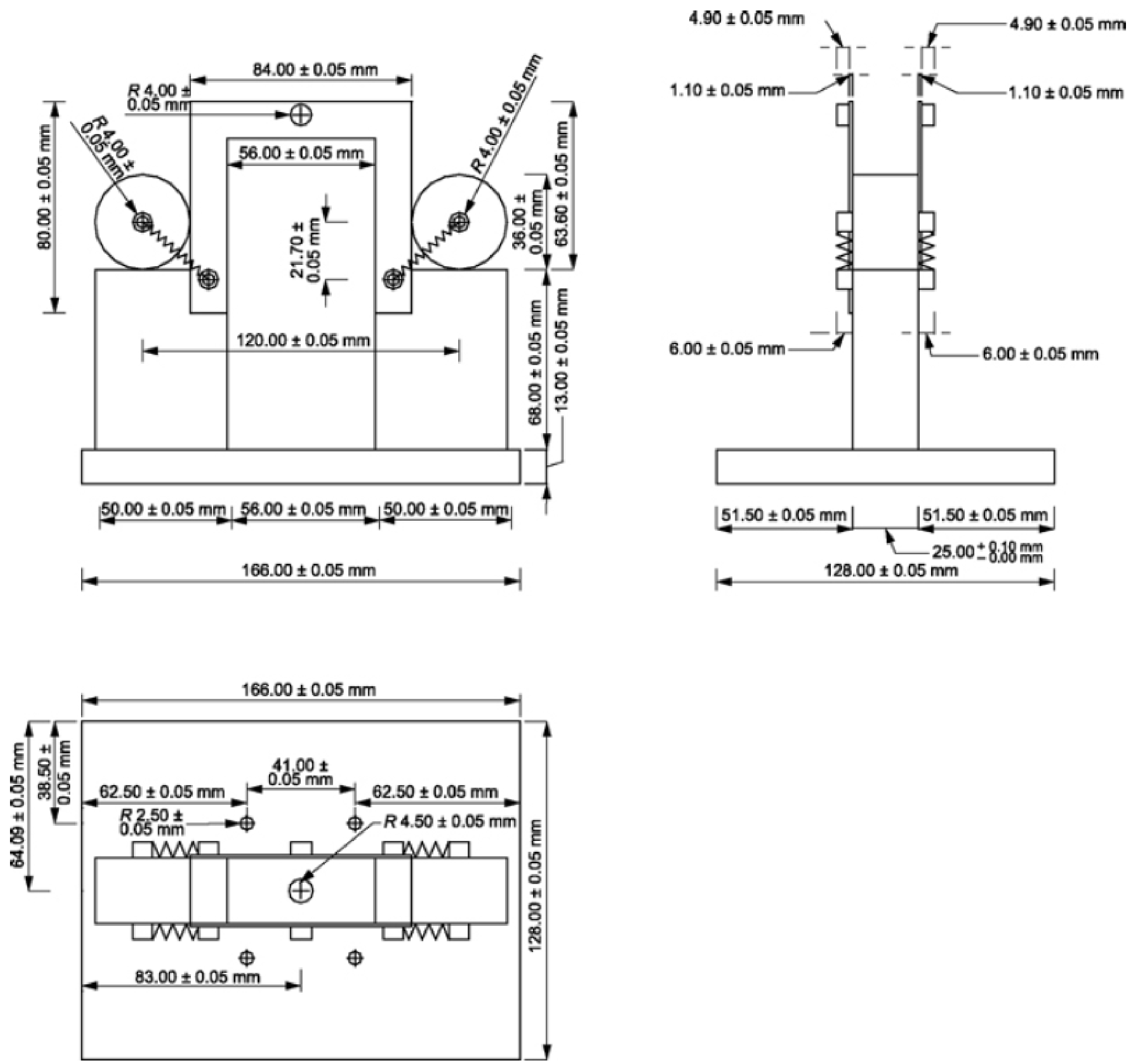

Figure 2 – SCB Test Fixture

6.1.4. *Specimen Deformation Measuring Devices*—The specimen deformation measurement devices shall consist of a CMOD gauge and two LLD gauges, 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 Figures 3 and 4). The two LLD gauges are attached to the gauge points glued to the specimen's front and back sides and the corresponding gauge points on the two U-shaped reference frames.

6.1.5. *Gauge Points*—Two steel gauge points having a diameter of 8 mm and a height of 6 mm and two knives are required per specimen (see Figures 3 and 4).

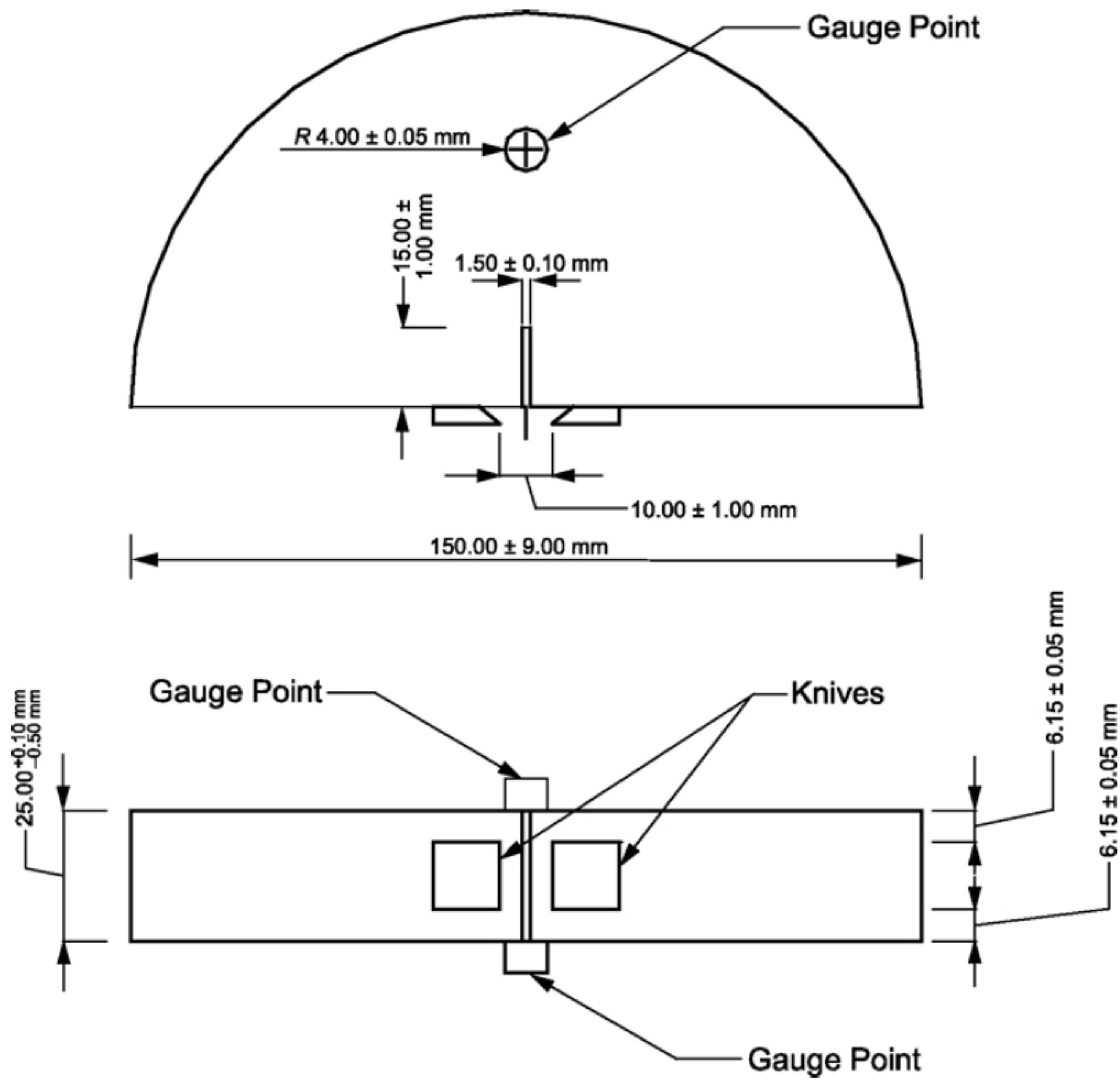

Figure 3 – Gauge Points Locations

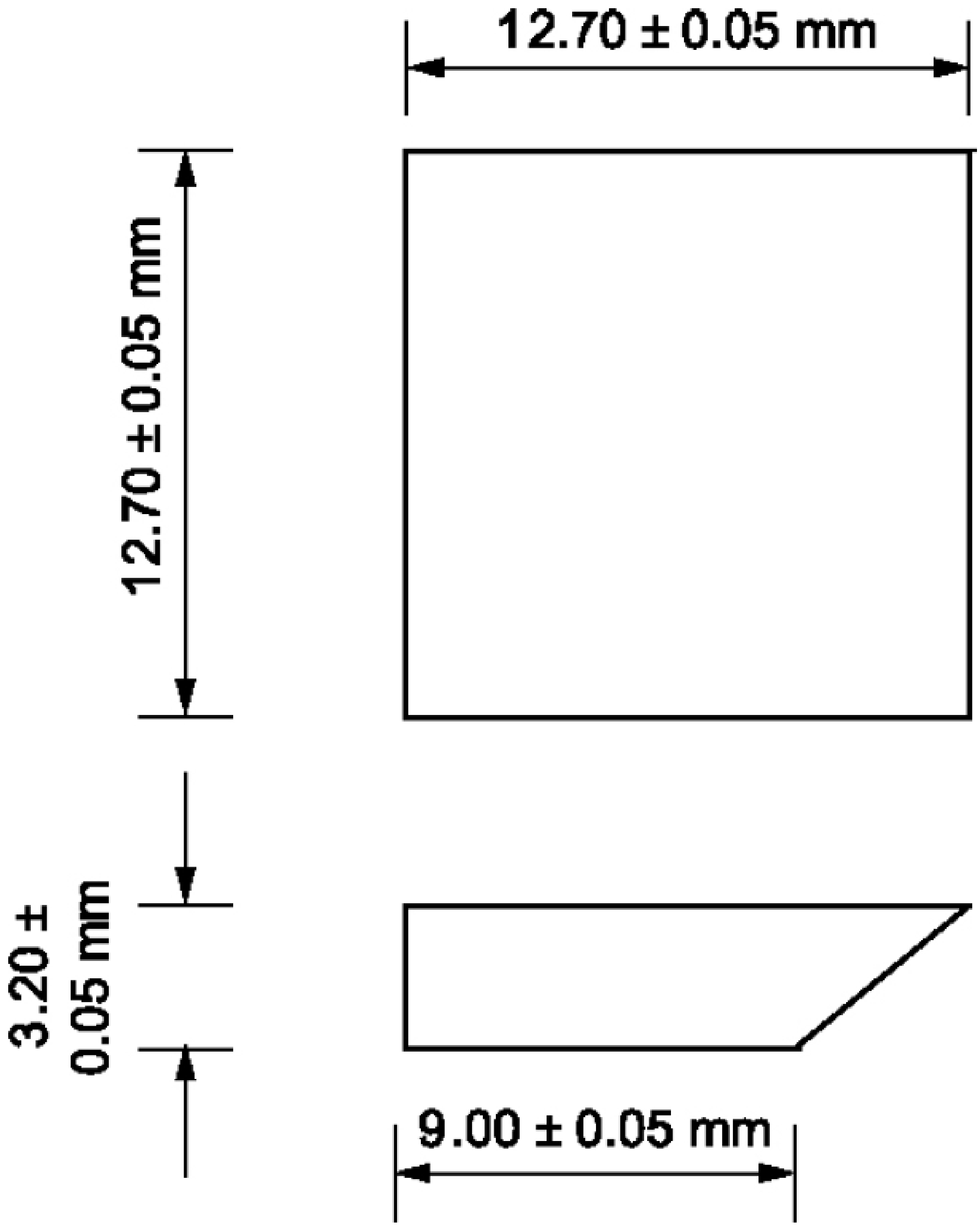

Figure 4 – CMOD Gauge Knife Edges

6.1.6. *Mounting Template*—A mounting template for placing and mounting the two steel gauge points on the SCB specimen is shown in Figure 5.

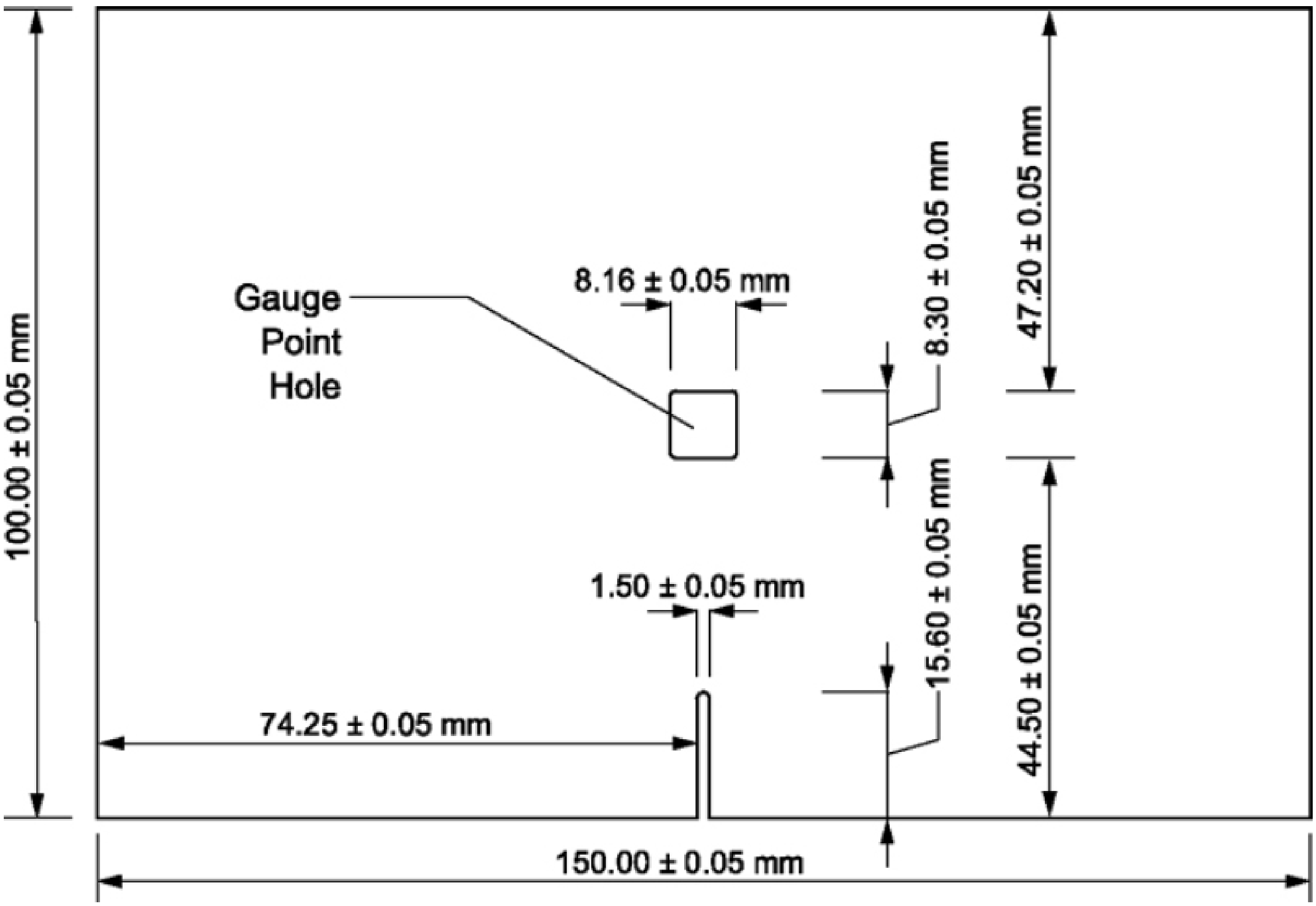

Figure 5 – Gauge Points Template

6.1.7. *Environmental Chamber*—The environmental chamber should be equipped with a temperature conditioner and controls capable of generating a test temperature between –40°C and 0°C inside the chamber and maintaining the desired test temperature to within ±0.5°C. The internal dimensions of the environmental chamber should be capable of holding a minimum of three test specimens for a period of 2 ± 0.5 h prior to testing.

6.1.8. *Control and Data Acquisition System*—Specimen behavior during the semicircular 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 being kept constant during the test.

7. HAZARDS

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

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 to maintain the required temperature within the specified accuracy.

8.1.2. Verify the calibration of all measurement components (such as load cells and LVDTs) 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, service by the manufacturer, or in-house resources), or replacement of the system components.

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 D5361/D5361M. 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. SPECIMEN 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 24.7 ± 2 mm and a diameter of 150 ± 9 mm (see Figure 3).

10.2. *SGC Specimens*—Prepare three SGC specimens according to T 312. From the center of each 115 ± 5 mm-tall specimen, obtain a cylindrical slice that is 24.7 ± 2 mm thick (see Figure 6). Cut the slice in two identical "halves", and the height of the semi-circular specimen shall be 73.5 ± 2 mm. Then cut a notch along the axis of symmetry of each half that is 15 ± 2.0 mm in length and no wider than 1.5 mm (see Figures 3 and 6), and the maximum allowable offset between the notch center and the axis of symmetry of the specimen shall be 2 mm. 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 temperatures are necessary, cut additional 24.7 ± 2 mm-thick slices from the SGC cylinder, located as close to the middle slice as possible.

Note 1— The ruggedness testing indicated that the asphalt mixtures had statistically equal fracture energy results when compacted to 7% ±1% air voids.

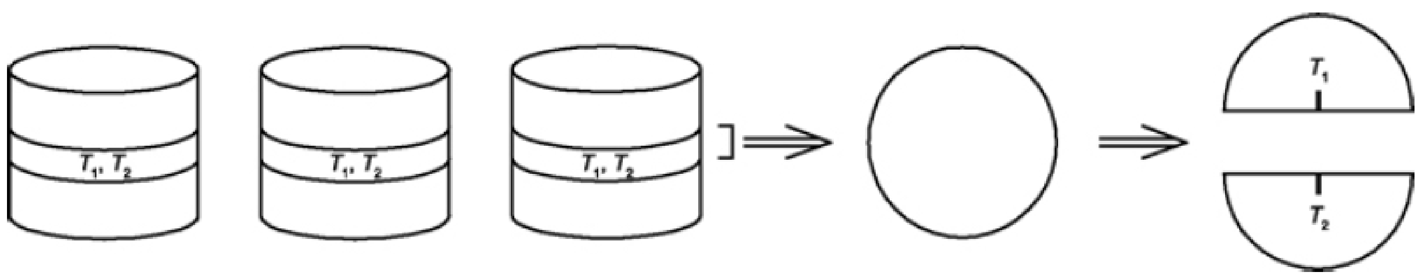

Figure 6 – Sample Preparation

10.3. *Field Cores*—Field cores can also be used to fabricate the specimens. The target thickness for specimens obtained from field cores should be 24.7 ± 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 2—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 an 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/D3549M, and determine individual measurements to the nearest 1 mm. Measure the notch length on both faces of the specimen and record the average value to the nearest 0.5 mm.

10.5. *Determining the Bulk Specific Gravity*—Determine the bulk specific gravity directly on the 115 ± 5 mm-tall SGC 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*—Superglue the four gauge points on the specimen as shown in Figure 6. A template, similar to the one in Figure 5, can be used for this purpose.

11. TEST PROCEDURE

11.1. *Conditioning*—The specimens shall be placed in a temperature controlled chamber at the desired test temperature for 2 ± 0.5 h. The temperature shall be maintained within 0.5°C of the desired test temperature throughout the conditioning and testing periods. Two test temperatures are recommended: 10°C above the PG lower limit of the asphalt binder used to prepare the asphalt mixture, and 2°C below the PG lower limit.

11.2. 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.

11.3. First, a small contact load of 0.3 ± 0.02 kN is imposed in stroke control with a displacement rate of 0.05 mm/s. Then, a seating load up to 0.6 ± 0.02 kN is applied in stroke control with a displacement rate of 0.005 mm/s. Three small amplitude loading cycles (see Figure 7) are applied to ensure contact between the loading head and the specimen.

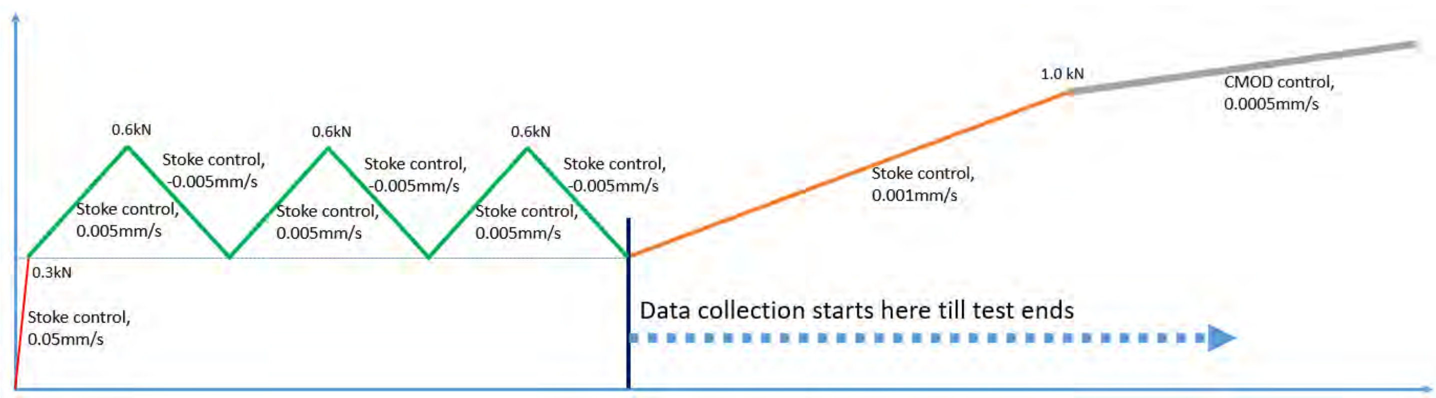

Figure 7. Illustration of the Three Amplitude Loading Cycles

11.4. The test is then executed and the load, the CMOD, and the LLD on both sides of the specimen are measured and recorded. An initial load of 1 ± 0.1 kN is reached first, starting from the seating load in stroke control with a rate of 0.001 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 0.03±0.0015 mm/min for the entire duration of the test.

11.5. The test stops when the load drops below 0.5 kN or when the CMOD gauge range limit is reached, whichever occurs first.

12. FRACTURE ENERGY G_F

12.1. *Fracture Energy (G_f)*—The fracture energy G_f is obtained according to the RILEM TC 50-FMC (1985) recommendation, and it is calculated by dividing the work of fracture (the area under the load versus average 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 (J/m^2);

W_f = work of fracture (J), where

W_f = $\int P du$

P = applied load (N);

u = average load line displacement (m);

A_{lig} = ligament area (m^2), where

A_{lig} = $(r - a) \times t$

r = specimen radius (m);

a = notch length (m); and

t = specimen thickness (m).

Note 3—In some instances, data recording can start at a load value different than zero (see Figure 8) and can introduce an error in the calculation of the area under the curve (triangle OO'A in Figure 8). This error can be neglected if the load level is less than 0.3 kN (point A in Figure 8).

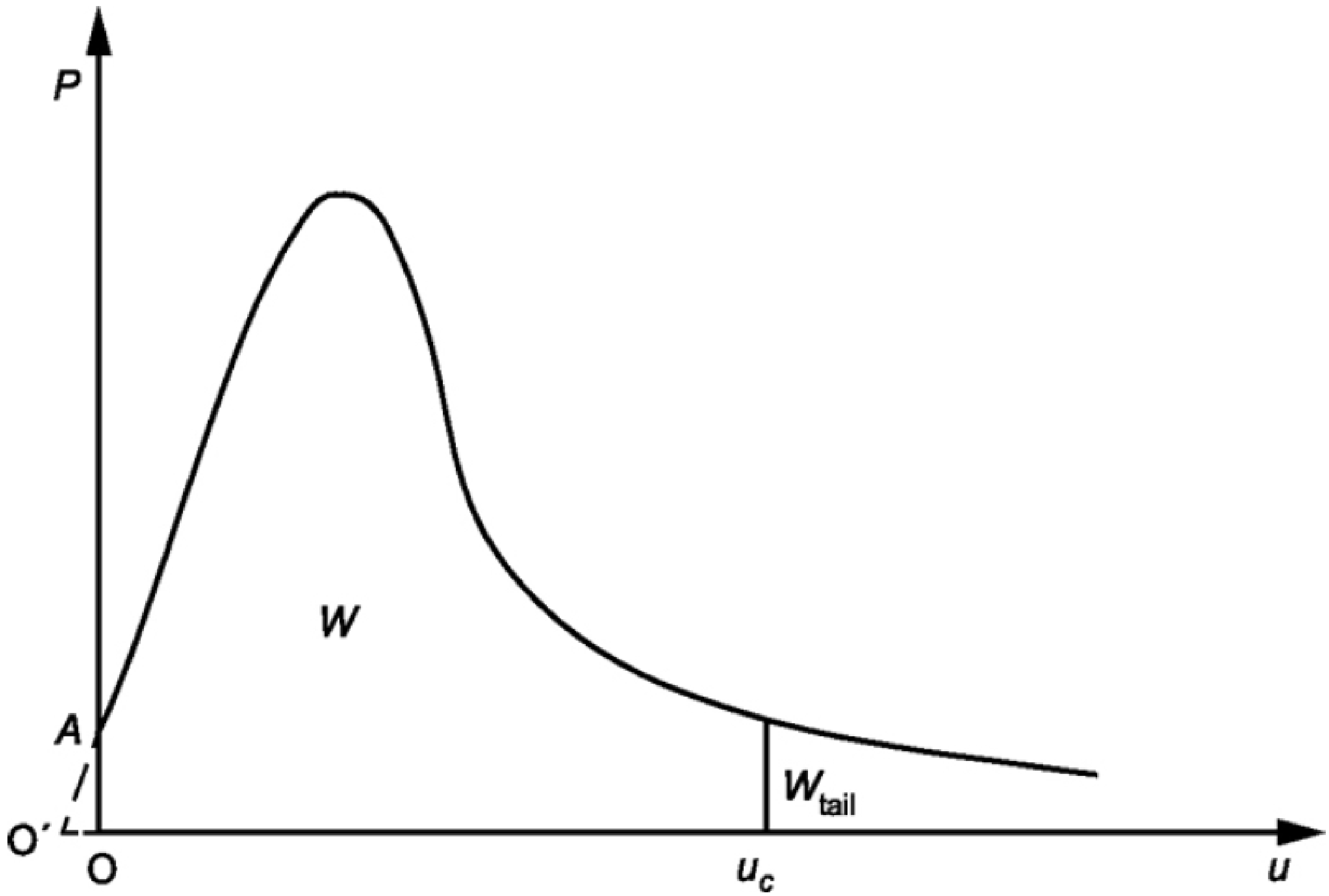

Figure 8 – Load versus Average Load Line Displacement (*P* – *u*) Curve

12.2. *Determining Work of Fracture (W_f)*—The work of fracture is calculated as the area under the load versus load line displacement (*P* – *u*) curve. The test is stopped when the load drops below 0.5 kN 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}).

12.2.1. *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:

$$W = \text{area} = \sum_{i=1}^{n} (u_{i+1} - u_i) \times P_i + \frac{1}{2} \times (u_{i+1} - u_i) \times (P_{i+1} - P_i) \qquad (2)$$

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 = average LLD load line displacement (m) at the *i* step; and

u_{i+1} = average LLD load line displacement (m) at the *i* + 1 step.

12.2.2. *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 percent of the peak load (Li and Marasteanu, 2004):

$$P = \frac{c}{u^2} \tag{3}$$

Next, coefficient c is obtained by fitting Equation 3 to the experimental $P – u$ curve below 60 percent of the peak load. Then, the $P – u$ curve is extrapolated to $P = 0$ and the tail area is calculated as:

$$W_{\text{tail}} = \int_{u_c}^{\infty} Pd(u) = \int_{u_c}^{\infty} \frac{c}{u^2} d(u) = \frac{c}{u_c} \tag{4}$$

where:

u = integration variable equal to average load line displacement (m);

u_c = average load line displacement value at which the test is stopped (m);

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

$$W_f = W + W_{\text{tail}} \tag{5}$$

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 D5045.

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.

13. FRACTURE TOUGHNESS, K_{IC}

13.1. *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.

13.2. *Stress Intensity Factor (K_I)*—The following equation is used to compute K_I (Lim et al., 1994; Li and Marasteanu, 2004):

$$\frac{K}{\sigma_0 \sqrt{\pi a}} = Y_{I(0.8)} \tag{6}$$

where:

σ_0 = $\frac{P}{2rt}$

P = applied load (MN);

r = specimen radius (m); and

t = specimen thickness (m);

a = notch length (m); and

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:

$$Y_{I(0.8)} = 4.782 + 1.219\left(\frac{a}{r}\right) + 0.063\exp\left(7.045\left(\frac{a}{r}\right)\right) \quad (7)$$

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 percent 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.

13.3. *Unit*—The unit of measure for fracture toughness (K_{IC}) is MPa × $m^{0.5}$.

14. STIFFNESS

14.1. *Stiffness (S)*—The stiffness (S) is calculated as the slope of the linear part of the ascending load-average load line displacement ($P – u$) curve. An example is shown in Figure 9.

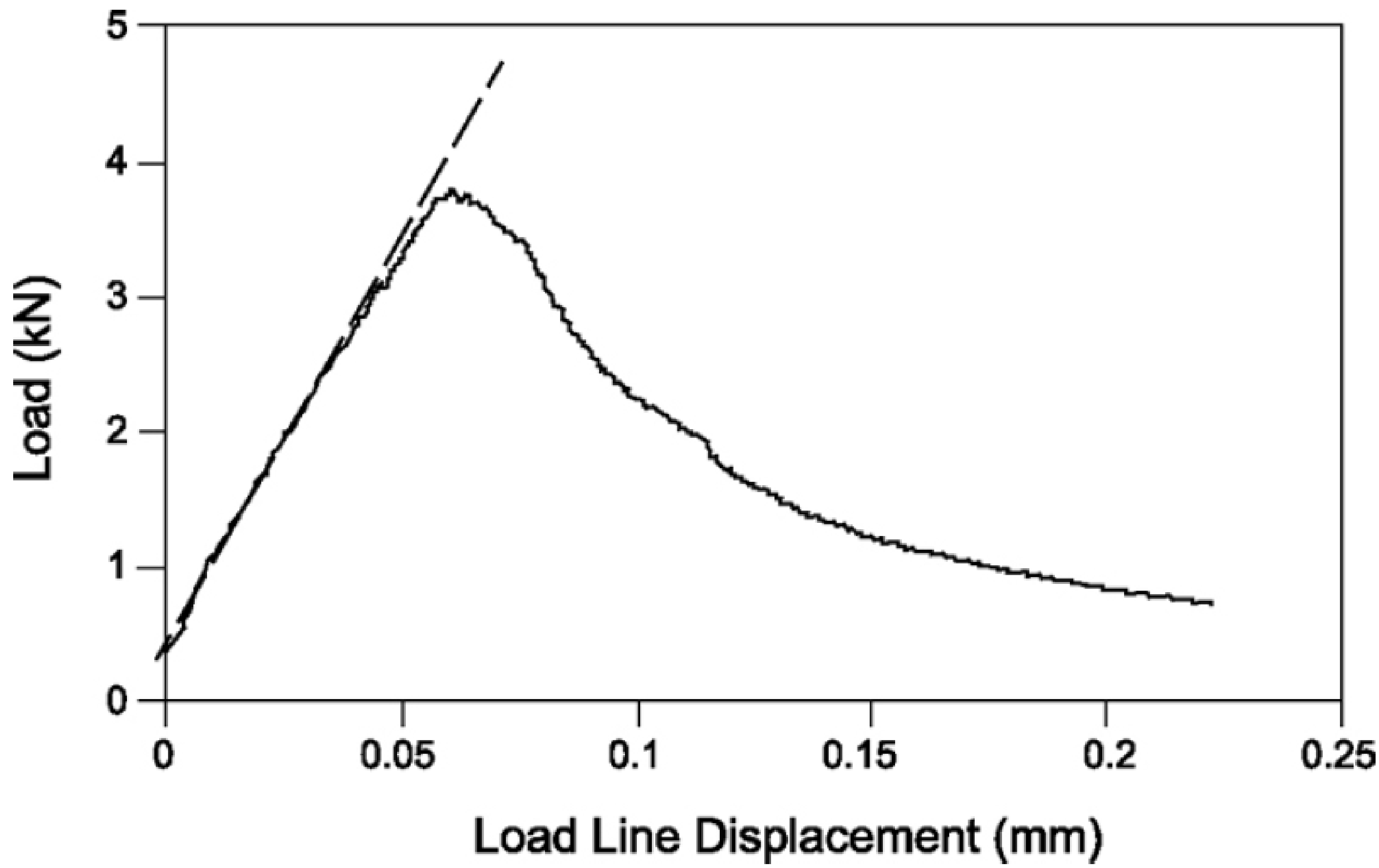

Figure 9 – Example of Stiffness Determination

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

15. REPORT

15.1. Report the following information:

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

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

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

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

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

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

15.1.7. Peak load, to the nearest 0.1 kN;

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

15.1.9. Average value of u_c (LLD when test is stopped), to the nearest 0.001 mm;

15.1.10. Plot of the *P* – *u* curve and fitted line used to determine stiffness *S*;

15.1.11. Stiffness *S*, to the nearest 0.1 kN/m;

15.1.12. Fracture toughness K_{IC}, to the nearest 0.001 MPa × $m^{0.5}$;

15.1.13. Fracture energy G_f, to the nearest 1 J/m.

16. PRECISION AND BIAS

16.1. *Precision*—The research required to develop precision estimates has not been conducted.

16.2. *Bias*—The research required to establish the bias of this method has not been conducted.

17. KEYWORDS

17.1. Fracture energy; fracture toughness; semicircular bend (SCB); stiffness; work of fracture.

18. REFERENCES

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[1] This provisional standard was first published in 2013.