
Standard Method of Test for

Determining Thermal Cracking Properties of Asphalt Mixtures through Measurement of Thermally Induced Stress and Strain

AASHTO Designation: TP XX- (2013)

1. SCOPE

1.1. This method of test is used to determine the thermal viscoelastic and thermal volumetric properties of field cored or laboratory compacted asphalt mixture specimens by measuring the thermally induced stress and strain while being cooled at a constant rate from an initial equilibrium temperature. The Thermal stress and strain can be measured using one of the two methods.

Method A: Uniaxial Thermal Stress and Strain Tester (UTSST)

Method B: Asphalt Thermal Cracking Analyzer (ATCA)

1.2. This standard method covers procedures for preparing and testing asphalt mixtures to measure thermal stress and strain and directly calculate: (1) the coefficient of axial thermal contraction; and (2) the relaxation modulus of asphalt mixture over a range of temperature.

1.3. The procedures described in this standard provide required information for estimation of thermal cracking susceptibility of asphalt mixtures. The procedures apply to test specimens having maximum aggregate size of 19 mm or less.

1.4. This standard can be used for conventional and non-conventional asphalt mixture: hot mixture, mixture with recycled materials, cold mixture, warm mixture, and modified mixture (e.g., polymer-modified).

1.5. This standard can be used to determine the following:

1.5.1.1. Thermal stress buildup of asphalt mixture during a single cooling event.

1.5.1.2. Thermal strain of asphalt mixtures as a function of temperature.

1.5.1.3. Coefficient of axial thermal contraction.

1.5.1.4. Relaxation modulus of asphalt mixture as a function of temperature

1.5.1.5. Thermal viscoelastic properties of asphalt mixture: viscous softening, viscous-glassy transition, glassy hardening, crack initiation, fracture temperature, and fracture stress.

1.6. The values stated in SI units are to be regarded as the standard.

1.7. *This method does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this method to establish appropriate safety and health practices and determine the application of regulatory limitations prior to use.*

2. REFERENCE DOCUMENTS

2.1. AASHTO Standards

- 2.1.1.** T166- Standard Method of Test for Bulk Specific Gravity (G_{mb}) of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens.
- 2.1.2.** T168- Standard Method of Test for Sampling Bituminous Paving Mixtures.
- 2.1.3.** T209- Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm}) and Density of Hot Mix Asphalt (HMA).
- 2.1.4.** T269- Standard Method of Test for Percent Air Voids in Compacted Dense and Open Asphalt Mixtures.
- 2.1.5.** T312- Standard Method of Test for Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor.
- 2.1.6.** T328- Standard Practice for Reducing Samples of Hot Mix Asphalt (HMA) to Testing Size.
- 2.1.7.** R30- Standard Practice for Mixture Conditioning of Hot-Mix Asphalt (HMA).
- 2.1.8.** PP060-09-UL Standard Practice for Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC)

2.2. ASTM Standards

- 2.2.1.** D 8, Standard Terminology Relating to Materials for Roads and Pavements
- 2.2.2.** D3549- Standard Test Method for Thickness or Height of Compacted Bituminous Paving Mixture Specimens.
- 2.2.3.** D3665-Standard Practice for Random Sampling of Construction Materials.
- 2.2.4.** F1684- Standard Specification for Iron-Nickel and Iron-Nickel-Cobalt Alloys for Low Thermal Expansion Applications.

2.3. Other Documents

- 2.3.1.** Chapra, Steven C. and Raymond P. Canale. *Numerical Methods for Engineers*. Fifth Edition, The McGraw-Hill Companies, Inc., New York, NY, 2006.
 - 2.3.2.** Sperling, L.H., *Introduction to physical Polymer Science*, Fourth Edition, Wiley Interscience, John Wiley and Sons Inc., New Jersey, 2006
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3. TERMINOLOGY

- 3.1. *Initial starting temperature, $T_{initial}$* - the temperature from which the test starts by cooling the specimens at a constant rate. The asphalt mixture specimens have to be at thermal equilibrium at the initial starting temperature prior to the starting of the test.
- 3.2. *Cooling rate*- the constant rate at which the temperature of asphalt mixture specimen decreases with time ($^{\circ}\text{C/hr}$) during the test.
- 3.3. *Uniaxial Thermal Stress, $\sigma(T)$* - accumulated tensile stress induced in the specimen by decreasing the temperature from $T_{initial}$ at a constant rate while maintaining the overall specimen height/length constant.
- 3.4. *Uniaxial Thermal strain, $\varepsilon(T)$* - accumulated contraction strain induced in the specimen by decreasing the temperature from $T_{initial}$ when the sample is free to contract axially.
- 3.5. *Coefficient of axial thermal contraction, $\alpha(T)$* - the fractional change in size in the axial direction associated with a temperature change.
- 3.6. *Thermal modulus, $E_{Th}(t, T)$* - the time and temperature dependent modulus of the asphalt mixture. The thermal modulus can be determined using the synchronized thermal stress and strain resulting from a change in temperature.
- 3.7. *Micro-cracking*- microscopic damage initiated at a certain temperature in the restrained specimen while cooling which leads to macro-cracking and eventually the fracture of the specimen.
- 3.8. *Thermal viscoelastic properties*- viscoelastic properties of the asphalt mixture determined from the thermal loading history including the viscous softening, viscous-glassy transition, glassy hardening, and crack initiation properties.
- 3.9. *Viscous softening stage*- from this stage the relaxation modulus of the asphalt mixture increases rapidly, mostly in a linear fashion, with decreases in temperature.
- 3.10. *Viscous-glassy transition stage*- at this stage the glassy properties of the asphalt mixture overcome its viscous properties.
- 3.11. *Glassy hardening stage*- at this stage the behavior of the asphalt mixture is considered glassy.
- 3.12. *Crack initiation stage*- in this stage micro-cracks occur in the specimen due to the induced thermal stresses when the asphalt mixture is characterized as glassy.

- 3.13. *Fracture stage*- at this stage the asphalt mixture specimen breaks due to the propagation of micro-cracks by the induced thermal stress.
- 3.14. Fracture stress- thermal tensile stress at failure.
- 3.15. Fracture temperature- temperature at failure.

4. SUMMARY OF TEST METHOD AND PRACTICE

- 4.1. This standard describes the procedure for determining the thermal stress and thermal strain measurements from the restrained and unrestrained asphalt mixture specimens, respectively. The thermal stress and strain can be determined in accordance with *Method A* - Uniaxial Thermal Stress and Strain Tester (UTSST) or *Method B*- Asphalt Thermal Cracking Analyzer (ATCA).
- 4.2. The induced thermal stress and strain measured data are used to determine: (1) the coefficient of axial thermal contraction; and (2) the relaxation modulus of asphalt mixture and characterizing the thermal viscoelastic properties of the asphalt mixture at different stages of the material behavior.
- 4.3. The thermal strain is determined by measuring the uniaxial deformation from an asphalt mixture specimen during cooling from an initial equilibrium temperature while it is free to deform without any friction.
- 4.4. The relaxation modulus is determined from the concurrent measured data of thermal stress and strain data from restrained and unrestrained asphalt mixture specimen, respectively.
- 4.5. The thermal viscoelastic properties of the asphalt mixture including viscous softening, viscous-glassy transition, glassy hardening, and crack initiation are determined from the relaxation modulus curve in the temperature domain. The fracture stress and fracture temperature are determined from the induced thermal stress curve in the temperature domain.
- 4.6. A cylindrical (Method A) or prismatic (Method B) asphalt mixture specimen cored or cut either from Superpave gyratory compacted specimen or field cores of specific dimensions, is fixed at the ends to the platens of a test system and it is enclosed within an environmental chamber. A small initial tensile load is applied to the specimen and the specimen is cooled at a given temperature rate. In Method A, thermal contraction along the long axis of the specimen is monitored electronically using Linear Variable Differential Transformers (LVDTs) and the initial length of the specimen is maintained by automatic adjustment of the platens by the Test System. In Method B, specimen contraction is restricted by a steel loading frame with minimal compliance. The cooling process continues until tensile fracture of the restrained specimen occurs. Concurrently, an unrestrained

specimen is set on a frictionless roller stand and contraction along the long axis of the specimen is recorded while cooling using LVDTs. In Method A, unrestrained beam is made by gluing two cylindrical specimens cored from Superpave gyratory compacted specimen or field core specimen. In Method B, unrestrained beam is made by gluing three prismatic beams cut from Superpave gyratory compacted specimen or cylindrical core.

5. SIGNIFICANCE AND USE

- 5.1. The thermal strain measurements allow for the calculation of the coefficient of axial thermal contraction which can be directly used in the mechanistic-empirical pavement design.
- 5.2. The thermal stress and strain measurements allow calculations of the relaxation modulus of asphalt mixture in the temperature domain.
- 5.3. From relaxation modulus versus temperature and thermal stress versus temperature relationships the thermal viscoelastic and fracture properties may be determined for asphalt mixtures.
- 5.4. The derived relaxation modulus, thermal viscoelastic, and fracture properties may be used in evaluating the low temperature cracking resistance of asphalt mixtures.

6. APPARATUS

- 6.1. *Method A - Uniaxial Thermal Stress and Strain Tester (UTSST)*– A closed-loop servo-controlled test system, as described in Figure 1, capable of cooling unrestrained and restrained asphalt mixture specimens at a constant rate from an initial starting temperature through failure in the restrained specimen. The system shall be capable of measuring the tensile load in restrained specimen, contraction deformation in unrestrained specimen and the temperature from a control specimen.
 - 6.1.1. *A closed-loop servo-controlled test system*- A system capable of applying or maintaining an applied load based upon the response of the two or more LVDT's attached to the restrained specimen. The test is conducted by allowing no net change in the LVDTs, i.e., the platens must be held at a constant distance from each other. The minimum recommended loading system capacity is 20 kN.
 - 6.1.2. *Restrained specimen mild steel platens*- Two platens per specimen 150±25 mm in diameter or square platens of similar area. The platens should be of sufficient thickness to prevent significant deflection during sample testing. Typically, platens of 25 mm thick have been used successfully.
 - 6.1.2.1. Each platen should have holes containing set screws of the appropriate diameter to hold the LVDTs and the extension rods on the restrained specimen. These holes

should be at a constant radial distance and should align along the same axis (Figure 2).

6.1.2.2. Each platen should also have a pedestal approximately 5 mm height and the same diameter as the specimen oriented along the central axis of the platen.

Note 1: the pedestal shall be machined along with the platen and not be a separate component.

- 6.1.3.** *Environmental chamber*- the environmental chamber shall be equipped with temperature conditioners and controls capable of generating test temperature between 30°C and at least -50°C inside the chamber with a predefined constant rate for cooling.
- 6.1.4.** *Cooling/Heating System* – A cooling/heating system capable of applying temperatures as high as 30°C and as low as -50°C at a constant rate up to 20°C/hr is required. Air flow cooling systems may be utilized for this purpose.
- 6.1.5.** *Thermally stable rods*-rods made of invar (conforming to ASTM F1684, UNS 93050, or UNS 93600) or other material (e.g. certain ceramics) with similarly low coefficient of thermal expansion and contraction of sufficient geometry to permit the necessary measurement and subsequent restraint of the asphalt mixture specimen. For the restrained specimen, each LVDT requires one rod, and for the unrestrained specimen, one rod for each of the two LVDTs is required.
- 6.1.6.** *Deformation Measurement Device*-The unrestrained asphalt mixture specimen is placed on a frictionless roller stand during the test. The rollers should be smooth enough and have free movement to minimize the friction. The asphalt mixture must be free to contract during cooling in order to obtain accurate strain measurements. Two invar rods are glued to the ends of the unrestrained specimen and must be long enough to extend to the outside of the environmental chamber to make contact with the LVDT.
- 6.1.7.** *Data Acquisition System*- The data acquisition system shall be used to record the developed load in the restrained specimen, contraction deformation of unrestrained specimen, and the temperature of control specimen for the duration of the test.
- 6.1.8.** *Specimen Alignment Stand*- A device capable of providing concentric and perpendicular alignment of the platens and restrain the specimen within axial alignment of the platen while the epoxy cures.
- 6.1.8.1.** The alignment stand for the restrained specimen should rigidly affix the platens parallel and concentric with each other and permit the distance between the plates to be readily adjusted. The stand should also provide adjustable support to retain specimen once it is concentrically aligned with the platens. It should also be

capable of applying a small load or weight to the top platen to assure complete contact and aid in bonding of the epoxy. Although not the required design, the device provided in Figure 3 has been found adequate for gluing the restrained specimen.

6.1.8.2. The alignment stand for the unrestrained specimen shall be capable of restraining the specimens and the invar rods in axial alignment with each other. While being restrained, the specimens and the invar rods shall be compressed under a small load or weight to permit the adequate bonding of all epoxied surfaces. Although not the required design, the device provided in Figure 4 has been found sufficient for gluing the unrestrained specimens.

6.1.9. Miscellaneous Apparatus- Spatula (for proportioning and mixing epoxy components), metals pans, masking tape, and gloves.

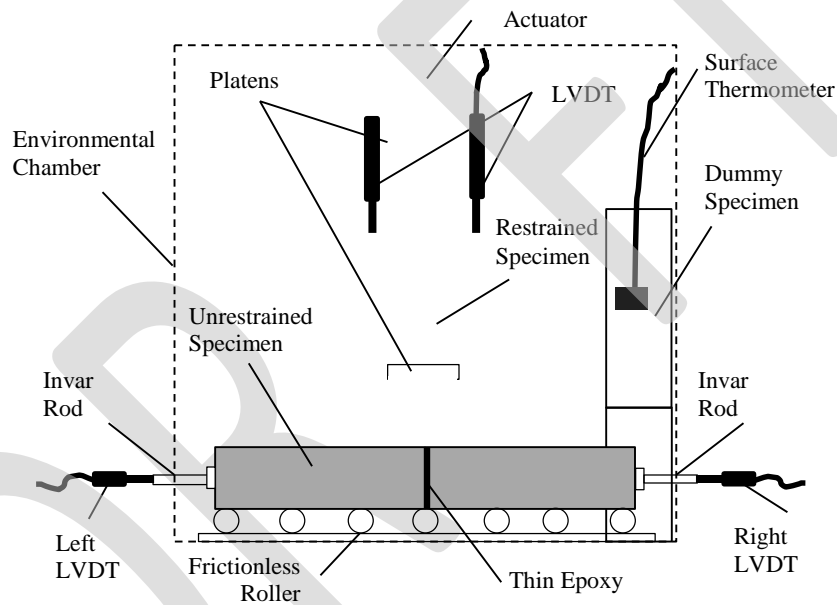


Figure 1: Uniaxial thermal stress and strain tester (UTSST)



Figure 2: Sketch of restrained specimen platens.

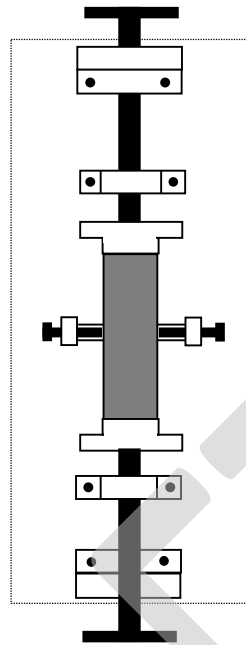


Figure 3: Specimen alignment stand for the restrained specimen

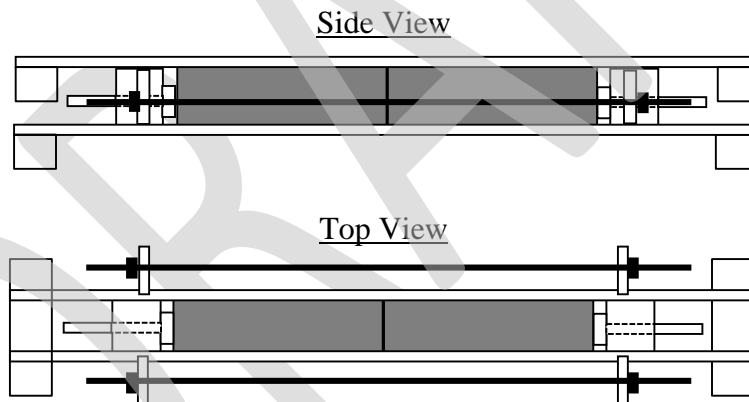


Figure 4: specimen alignment stand for the unrestrained specimen

- 6.2.** *Method B – Asphalt Thermal Cracking Analyzer (ATCA)*– The general setup of the apparatus used in Method B is shown in Figure 5. A steel loading frame capable of withstanding loads of up to 25 kN without compliance is required to restrain one of the samples. A suitable support system using rollers should be used to maintain the weight of the sample beams and prevent sagging, without inducing any movement resistance to the beam samples. Figure 6 shows the recommended frame and support system setup and design. Asphalt mixture temperature is measured using a dummy sample placed at the bottom of the environmental chamber.

- 6.2.1. Restrained specimen steel platens-** Two square platens 150 ± 25 mm by 150 ± 25 mm are used to attach restrained beam to loading frame. The platens should be of sufficient thickness to prevent significant deflection during sample testing. Typically, platens of 25 mm thick have been used successfully.
- 6.2.2. Environmental Chamber** –the environmental chamber shall be equipped with temperature conditioners and controls capable of generating test temperature between 30°C and at least -50°C inside the chamber with a predefined constant rate for cooling. Openings should be placed to allow for insertion of LVDTs on sample ends as well as fixing restrained beam to the frame. Figure 6 shows the typical setup for the environmental chamber.
- 6.2.3. Cooling/Heating System** – A cooling/heating system capable of applying temperatures as high as 30°C and as low as -50°C at a fixed rate of up to $1^{\circ}\text{C}/\text{min}$ is required. Liquid nitrogen, cryogenic gas, and mechanical cooling systems may be utilized for this purpose.
- 6.2.4. Thermally stable rods**-rods made of invar as indicated in 6.1.4. Two rods are needed for the unrestrained specimen to properly measure contraction of the sample.
- 6.2.5. Frictionless Roller Stand-** To allow for free contraction, the unrestrained beam is placed on a frictionless roller stand. The recommended support stand is shown in Figure 6c.
- 6.2.6. Data Acquisition System-** The data acquisition system shall be used to record the thermal load in the restrained specimen, thermal contraction of unrestrained specimen, and the temperature of the dummy specimen.
- 6.2.7. Specimen Alignment Stand-** An alignment system capable of providing concentric and perpendicular alignment of the platens and restrain the specimen while the epoxy cures. The recommended gluing setup for Method B is shown in Figure 7.

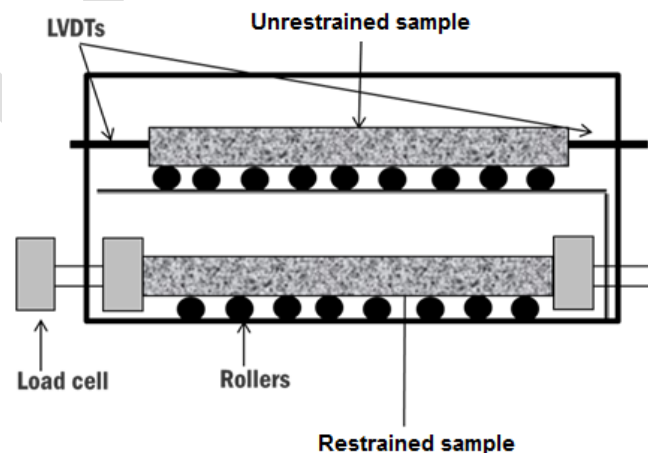


Figure 5: Schematic of the Asphalt Thermal Cracking Analyzer (ATCA) system.

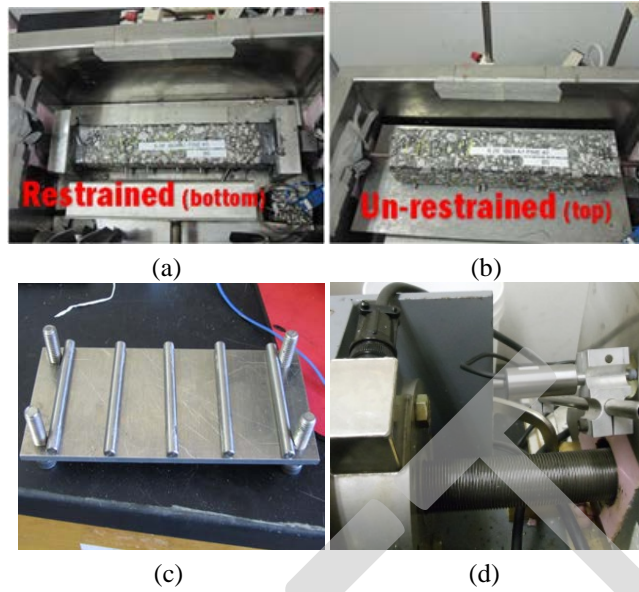


Figure 6: ATCA - (a) Restrained beam setup, (b) unrestrained beam setup, (c) adjustable height beam support platform with rollers, and (d) load cell and LVDT's.



Figure 7: Sample gluing setup for Method B.

7. MATERIALS

- 7.1. *Epoxy* –Devcon Plastic Steel® Putty (A) 10110 has been found sufficient.
- 7.2. *Miscellaneous Materials* – 240-grit sandpaper, acetone or other degreaser.

8. HAZARDS

- 8.1. Follow the safety requirements listed in the manufacturer's safety information sheet when using epoxy, acetone.

9. TEST SPECIMENS

- 9.1. *Obtain Test Specimens* – Obtain the test specimens for Method A (cylindrical specimens) or Method B (prismatic Specimens).
- 9.2. *Method A – Uniaxial Thermal Stress and Strain Tester (UTSST):*
- 9.2.1. *Laboratory Mixed Laboratory Compacted Asphalt Mixture Specimens* – Mix, age, and compact the asphalt mixture specimens according to T312 using the 150 mm diameter molds. Follow the short-term and long-term aging recommendations of R30 for Mixture Mechanical Testing. Specimens should be compacted to obtain a target air void level $\pm 0.5\%$ after trimming to the final dimensions as determined by T269.
- 9.2.2. *Field Mixed Laboratory Compacted Asphalt Mixture Specimens* – Obtain the asphalt mixture samples in accordance with T168. Reduce the sample to the appropriate specimen sizes adding to T328. Follow the applications section of T312 to compact the specimens using the 150 mm diameter molds. Follow the short-term and long-term aging recommendations of R30 for Mixture Mechanical Testing. Specimens should be compacted to obtain a target air void level $\pm 0.5\%$ after trimming to the final dimensions as determined by T269.
- 9.2.3. *Field Mixed Field Compacted Asphalt Mixture Specimens* – Obtain mixture cores in accordance with T168, to obtain core samples nominally 150 mm in diameter. Take care to prevent deformation or other disturbance of the samples during storage and transport to the testing location. When the samples are taken from existing pavement obtain them in accordance with ASTM D3665, unless specific locations are under investigation.
- 9.2.4. *Coring of Test Specimens* – Obtain the test specimens by laying the sample, either SGC sample or field core, on its side and core the test specimen 90° from the axis of compaction with a wet diamond core bit. Depending upon the nominal maximum aggregate size (NMAS) of the mixture, the cored specimens, after side-coring, shall be 57 ± 5 mm or 45 ± 5 mm in diameter for 19 mm and 12.5 mm NMAS mixtures, respectively. However, the 57 mm samples may also be used for 12.5 mm NMAS mixtures as well.
- Trim the length of the side-cut cores using a wet diamond blade so that the ends of the sample are a perpendicular as possible to the sides. The length of the specimens shall be as long as possible, but sufficient to remove the radius ends of from the original sample geometry. The final length of the test specimens should be no shorter than 140 mm.
- 9.2.5. *Bulk Specific Gravity*– Determine the bulk specific gravity according to T166 and the corresponding air voids in accordance with T269.

9.2.6. Drying of the Specimens – Assure the specimens are dry from appreciable moisture after the specific gravity determinations either by air drying in front of high-output fans for several days, or other sufficient means.

9.2.7. Measurement of Core Specimens – Determine the dimensions, diameter and height, of the specimens in accordance with ASTM D3549. Use the average diameter to determine the cross-sectional area of the restrained specimen. Use the average height to determine the length of unrestrained specimen. Record the average cross-sectional area to the nearest 1 mm² and the height to the 0.1mm.

9.3. Method B – Asphalt Thermal Cracking Analyzer (ATCA):

9.3.1. Laboratory or Field Compacted - To produce restrained and unrestrained beams for Method B, four prismatic beams of 50 by 50 mm in cross section and 150 mm long are cut from 170 mm height samples. Two of these beams are sawed in half to produce four 75 mm blocks. By gluing a 75 mm block to each end of the two 150 mm blocks, two 300 mm beams are produced. Follow the short-term and long-term aging recommendations of R30 for Mixture Mechanical Testing. Figure 9 shows how to procure unrestrained and restrained beams for Method B.

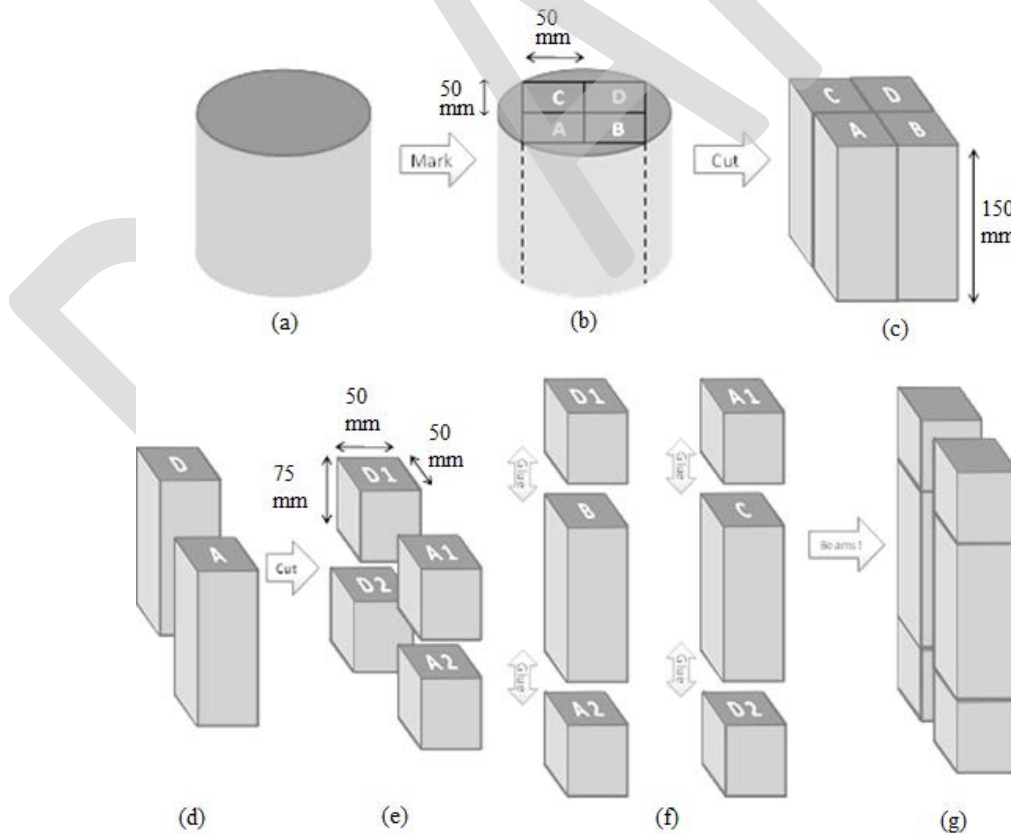


Figure 9: Step by step procedure for producing prismatic asphalt mixture sample (Method B) from cylindrical samples.

10. SPECIMEN PREPARATION

10.1. *Restrained Specimen Preparation (Method A and B)*

10.1.1. *Platen Preparation*– Scrape the epoxy and remain mixtures from the platens with spatulas after heating the plates or as suggested by the epoxy manufacturer to remove residual epoxy. Sand the platen surface with a piece of sandpaper to completely remove any epoxy or specimen-end residue remaining from prior tests and to provide a rough surface for epoxy adhesion. Clean the surface of the platen using acetone or other degreaser to remove all the debris remained on the surface after sanding.

10.1.2. *Restrained Specimen Preparation* – Verify that the specimen has been sufficiently dried and is free from saw slurry, dust, grease, or other debris on the exterior of the specimen that maybe inhibit the bonding of epoxy to the surface. Prior to applying any epoxy, wrap a single layer of masking tape around the circumference of the sample leaving the middle portion and approximately 5 to 10 mm of each end exposed and uncovered. This will be to assure a straight line of epoxy on the sample after gluing. It is recommended to leave a small tab of the tape wrapped back upon itself to aid in removal of the tape with minimal disturbance of the sample prior the epoxy setting.

10.2. *Epoxy Preparation* – Follow the mixing, proportioning, applying, and curing instructions supplied by the manufacturer for the epoxy being used. If Devcon Plastic Steel® Putty (A) 10110 is used; obtain 25 grams or more of mixed epoxy blended by the recommended mix ratio (typically 9:1 by weight of resin and hardener, respectively). Thoroughly mix the two epoxy components until a uniform color and consistency results.

10.3. *Attaching the Restrained Specimen to Platens (Method A and B)*

10.3.1. Apply 2 to 3 mm thick film of epoxy over a nearly the entire diameter of one end the specimen. Holding the specimen in alignment with the center pedestal on the platen on the non-epoxied end of the specimen, apply the collar to that to assure complete alignment between the sample and the platen. While holding the epoxied end in alignment with the pedestal with ones fingers, apply the axial load to assure complete adhesion of the epoxy on the platens. While maintaining the specimen alignment, apply the sample restraints to restrain the specimen in that position.

10.3.2. Assure that epoxy has been squeezed out between the specimen and the platen pedestal and that not gaps exist around its perimeter. Assure that the alignment of the specimen still coincides with the pedestals. Using the remainder of the epoxy, apply a small band of epoxy around the perimeter of both the specimen and the pedestal on the platen. The epoxy should

- cover the sample up to the masking tape and the remainder of the pedestal, but need not be a thick mass of epoxy, such as a fillet weld would appear.
- 10.3.3.** With the specimen in alignment and restrained by the alignment stand and while the epoxy is still fresh and pliable, carefully remove the masking tape on the epoxied end of the specimen revealing a clean line of epoxy in the specimen.
- 10.3.4.** Though not required, it is recommended to allow the first epoxied end of the specimen to mostly set, before attempting to affix the other end. It will likely reduce the chance of misalignment due to handling while the epoxy is still fresh.
- Note 2:** If Devcon 10110 epoxy is used, the permissible set time is approximately 45 minutes to two hours prior to gluing the other end of the specimen.
- Note 3:** Alignment is critical to obtaining meaningful test results. Therefore, the alignment device must sufficiently align the platens and specimen, and support the specimen in a level position while the epoxy cures.
- 10.3.5.** To apply epoxy to the second end of the restrained specimen, make sure the specimen restraints are firmly in place, remove the collar from the non-epoxied end of the specimen, and remove the load or weight to permit separation of the platen and non-epoxied end of the specimen. Assure the specimen does not move and remains in alignment with both platens. Apply a film of epoxy of approximately the same thickness as the first end to the now exposed specimen end, making sure to get complete and uniform coverage of the specimen.
- 10.3.6.** Make contact with the specimen and platen by applying the contact load or weight. Again, make sure the epoxy is squeezed from the between the two with no gaps or voids.
- 10.3.7.** Be sure to align the holes in both the top and bottom platens used to align the LVDTs and the invar rods before the epoxy is set on the second end of the specimen.
- 10.3.8.** Apply the same procedure as the first end, by applying the overlapping band-aid to the end of the specimen and the platen pedestal. Remove the masking tape to provide the clean straight line of epoxy on the sample.
- 10.4.** *Preparation of the Unrestrained Specimen – Method A:*

- Verify that the specimens are sufficiently dried and are free from saw slurry, dust, grease, or other debris on the exterior of the specimen that maybe inhibit the bonding of epoxy to the surfaces.
- 10.4.1.** Align the two specimens, the invar extension rods, and their restraints on the bottom rack of the gluing jig such that any gaps between the two specimen will be minimized if they were not cut exactly perpendicular to the sides.
 - 10.4.2.** Follow the mixing, proportioning, applying, and curing instructions supplied by the manufacturer for the epoxy being used. If Devcon Plastic Steel® Putty (A) 10110 is used; obtain 25 grams or more of mixed epoxy blended by the recommended mix ratio (typically 9:1 by weight of resin and hardener, respectively). Thoroughly mix the two epoxy components until a uniform color and consistency results.
 - 10.4.3.** Apply the minimum required amount of epoxy between the two samples and verify the fit by making sure the epoxy is squeezed out along the entire perimeter of the joint. Adjust as needed before the epoxy sets. Using a card or other means remove as much of the excess epoxy as possible. Attempt not to create the band-air seal as was done in the restrained specimen, but remove all the excess as much as possible.
 - 10.4.4.** Follow the mixing, proportioning, applying, and curing instructions supplied by the manufacturer for the epoxy being used. If Devcon Plastic Steel® Putty (A) 10110 is used; obtain 25 grams or more of mixed epoxy blended by the recommended mix ratio (typically 9:1 by weight of resin and hardener, respectively). Thoroughly mix the two epoxy components until a uniform color and consistency results.
 - 10.4.5.** Apply enough epoxy to the end of the invar extensions to adequately adhere them to the sample.
 - 10.4.6.** Lightly squeeze the component together assure a proper fit and adequate epoxy. Apply the top of the alignment jig to maintain axial alignment of the epoxied components. Adding a small load or weight to the top of the jig for confinement may be necessary to assure proper axial alignment.
 - 10.4.7.** Apply the lateral pressure to the retainers on the invar rods to firmly squeeze the components together. Check and verify the fit and alignment of the components. Remove any additional epoxy that may have been extruded between the samples.
- 10.5.** *Preparation of the Unrestrained Specimen – Method B:*
- 10.5.1.** *Attaching Invar Rods to Sample* – Mark the cross section centroid on each end of the beam by using an ink marker to draw diametric lines across the

surface. Apply a 2 ± 0.5 gram of fast curing epoxy resin to the back surface of each invar rod end-piece and place firmly on the cross point of the diametric lines at each end of the beam. The end-piece may be kept in place using masking tape until epoxy cures. Invar rods are screwed into each end-piece of the beam. It may be necessary to place beam in chamber and screw in invar rods through the openings designed to have LVDTs outside the environmental chamber.

Note 4: The use of invar rods extending out of chamber in Method B is to minimize temperature effects and creep of LVDT during the test procedure.

- 10.6.** *Curing* - Permit both the restrained and unrestrained specimens to remain undisturbed until the epoxy has fully cured. At least 16 hours is recommended for the Devcon 10110 epoxy.

11. CONDITIONING

- 11.1.** *Specimens Pre-Conditioning* – After the epoxy has cured, remove the restrained specimen/platen assembly and invar rods/unrestrained specimen assembly from their respective alignment stands. Condition both assemblies at $20\pm 2^\circ\text{C}$ environment for minimum of 2 hours prior to testing.

12. PREPARATION OF APPARATUS

- 12.1.** *Preparation of the Environmental Chamber* –
Method A: Both the environmental and loading systems can be initialized and warmed up simultaneously.
Method B: The environmental chamber is initialized and warmed up.
- 12.1.1.** Set the environmental chamber to 20°C and permit the chamber and all interior components to come to equilibrium for a minimum of 30 minutes.
- 12.1.2.** *Method A:* Turn on the servo-controlled loading system. If the loading system is servo-hydraulic, initialize the system and run it through a warm-up scheme for a period of approximately 30 minutes or until the hydraulic fluid has been brought to the operating temperature before proceeding.
- 12.2.** *Restrained Specimen-*
- 12.2.1.** *Method A:*

Insert the invar connecting rods into the appropriate holes in the bottom plate and secure with the set screws.

Connect the restrained specimen/platen assembly to the bottom universal joint by screwing the bottom platen to the bottom threaded connecting rod. By controlling the location of the ram attached to the top universal joint, insert the top universal joint connection rod assembly into the top universal joint and secure with the pin as shown in Figure 10a without applying any load to the specimen.

Note 5: Clevis, ball-joint, or other moment reduction devices have been successfully used rather than the universal joints (Figure 10b).

Insert the LVDTs into the appropriate holes in the top platen and lightly secure with set screws.

Note 6: It is quite easy to over tighten the LVDT set screws and destroy the LVDT. As such, care should be taken to avoid damage. It is suggested to obtain set screws that contain a plastic buffer on the bearing surface of the set screw to help minimize damage to the LVDTs.

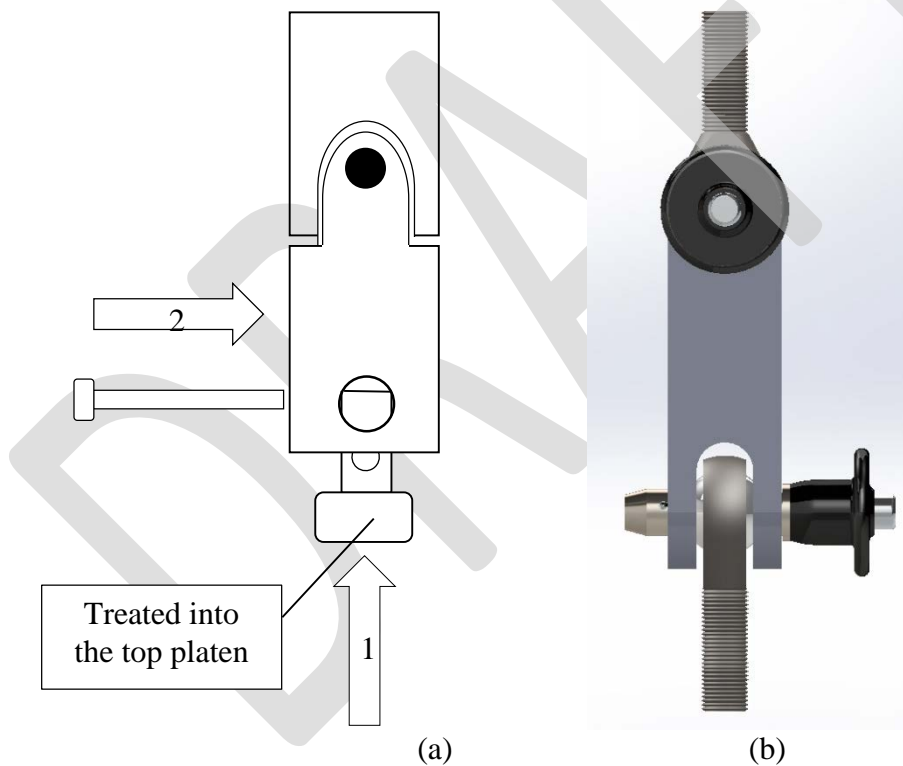


Figure 10: (a) Top universal joint and pin connector, (b) Alternate pin-ball joint connection.

12.2.2. Method B:

Restrained sample glued to two steel platens is placed in the environmental chamber and screwed into the steel framed as shown in Figure 6a. Care should be

paid in not applying torsion when screwing beam into the steel frame. This can be minimized by using steel stripes as support during placement of the beam.

12.3. *Preparation of the Unrestrained Specimen*

12.3.1. *Method A*

Place the unrestrained specimen on the frictionless roller stand, taking care not to damage the end extension rods while installing them through the environmental chamber walls.

Since the unrestrained specimen for Method A is round it is possible for the specimen to roll laterally during the test if the stand is not perfectly level. To restrict this movement, it is permissible to apply a restrictive band very near the center of the specimen. Care should be taken in the installation, so that the lateral movement is in no way restricted by the band.

Adjust the unrestrained LVDTs such that they come into contact with the extension rods on the specimen. It is preferred to set the LVDTs such that they are depressed to near the full length of their stroke, such that and contraction of the specimen will not exceed the stroke of the LVDTs.

Note 5: It is important that the LVDTs remain outside of the environmental chamber as many of the current manufactured LVDTs will not operate through the temperature range expected during this test, i.e. they may begin to exhibit non-linear behavior due to thermal contraction of the LVDT itself.

12.3.2. *Method B*

Place six roller rods at equally spaced intervals across the placement location of the unrestrained specimen in chamber. Place beam sample on roller rods and align ends with openings of the chamber. Center beam on rollers such that the beam is equally spaced from the side walls of the chamber and invar rod is extended equally from both sides of chamber.

Place each LVDT on invar rod extruding out of chamber opening in such a manner that the LVDTs be initially compressed to a length of 1 ± 0.2 mm on each side. Insure that assembly holding LVDTs sufficiently tight and secure to eliminate any sliding or shifting of the LVDTs during test.

12.4. Set the control specimen in close proximity to the other specimens within the chamber and close the chamber door.

- 12.5. Assure the chamber returns to thermal equilibrium without applying any load to the restrained specimen. Verify that the LVDTs on the unrestrained specimen at an acceptable value, so they will remain within their readable range throughout the duration of the test.

13. PROCEDURE

- 13.1. Start conditioning of the environmental chamber to the initial temperature of 20°C. When the average surface temperature is 20±1°C, apply the initial tensile load to the specimen.
- 13.2. Apply an initial tensile load of 50±10 N to the specimen immediately before starting the test.
- 13.3. Start cooling the cabinet at predefined constant cooling rate (X °C per hour).

Note 6: Although the actual maximum cooling rate of an asphalt pavement has been shown to be around 2.7°C per hour or lower, the lowest practical rate has been assumed to be 2.5°C per hour. For evaluations focused on ranking the thermal viscoelastic and fracture performance of different mixes a rate of 10°C per hour has been commonly used. Faster rates may be possible depending upon the cooling equipment available. However, the material response discussed in this standard has not been verified for cooling rates faster than 17.5°C per hour.

- 13.4. Automatically record the elapsed time, dummy specimen temperature, restrained specimen thermally induced tensile load, and unrestrained specimen thermal deformation as the test progresses at every predefined time step.
- 13.5. Continue the test until the restrained specimen fails or to a temperature below fracture temperature if additional strain measurements data is required.

14. CALCULATIONS

- 14.1. This section provides a standard procedure for calculating thermal modulus and indexes of thermo-viscoelastic and fracture behavior of asphalt mixtures. The thermal modulus is determined from the thermal stress and strain induced in restrained and unrestrained asphalt mixtures specimens, respectively, obtained using either *Method A (UTSST)* or *Method B (ATCA)*.
- 14.2. *Calculation of thermal stress*
- 14.2.1. Obtain the average cross section area of the restrained specimen according to Section 8.5.

14.2.2. Determine the maximum induced thermal load, F_{nMax} by finding the maximum of the recorded thermal tensile load data.

14.2.3. Calculate the thermal stress at each measured temperature by dividing measured induced thermal tensile load at any recorded temperature to the average cross section area of the specimen.

$$\sigma_n(T) = \frac{F_n(T)}{A_{ave}} \quad (1)$$

where:

$\sigma_n(T)$ = thermal stress at temperature T;

$F_n(T)$ = induced thermal tensile load;

A_{ave} = cross section area of the restrained specimen.

14.2.4. Normalized the thermal stress values by subtracting all the calculated stress values (at each temperature) from the initial stress at the start of the test (i.e. time zero).

14.2.5. Smooth the thermal stress versus temperature curve by fitting a polynomial of degree 5 or 6 to the measured values of thermal stress and check for acceptable fit of the polynomial.

14.3. *Calculation of thermal strain*

14.3.1. Obtain the average length of the unrestrained specimen after both specimens are epoxied together in accordance with the procedure found in ASTM D3549.

14.3.2. Normalize the thermal deformation measurements from both left and right ends of the unrestrained specimen, at each recorded temperature, to the initial value at the start of the test (i.e. time zero) by subtracting each value from the initial deformation at time zero.

14.3.3. Calculate the total normalized deformation by summation of normalized thermal deformation from left and right ends of the unrestrained specimen.

$$\Delta_{n_{ave}}(T) = \Delta_n^L(T) + \Delta_n^R(T) \quad (2)$$

where:

$\Delta_{n_{ave}}(T)$ = normalized thermal deformation of the specimen;

$\Delta_n^L(T), \Delta_n^R(T)$ = normalized thermal deformation from the left and right end of unrestrained specimen, respectively.

14.3.4. Compute the normalized thermal strain by dividing the normalized total thermal deformation, at each recorded temperature, to the average length of the specimen.

$$\varepsilon_n(T) = \frac{\Delta_{n_{ave}}(T)}{L_{ave}} \quad (3)$$

Where:

$\varepsilon_n(T)$ = Normalized thermal strain at temperature of T;

$\Delta_{n_{ave}}(T)$ = normalized thermal deformation of the specimen;

L_{ave} = Average length of the unrestrained specimen.

14.3.5. Smooth the thermal strain versus temperature curve by fitting a polynomial of degree 3 or 4 to the measured values of thermal stress and check for acceptable fit of the polynomial.

14.4. *Calculation of coefficient of axial thermal contraction (CTC)*

14.4.1. Calculate the coefficient of axial thermal contraction (CTC) at each temperature by finding the slope of the thermal strain versus temperature curve.

Note 7: The temperature dependency of the coefficient of axial thermal contraction (CTC) can be defined using a binary function. The binary function results in two values for the CTC before and after the glassy temperature of the asphalt mixture.

14.5. *Calculation of thermal modulus in temperature domain*

14.5.1. The thermal modulus is determined by back-calculation of Boltzmann's convolution integral which represents the uniaxial constitutive relation for linear viscoelastic materials.

$$\sigma(t) = \int_0^t E_{Th}(t-t') \frac{\partial \varepsilon(t')}{\partial t'} dt' \quad (4)$$

where:

$E_{Th}(t)$, thermal modulus;

$\sigma(t)$, thermal stress;

$\varepsilon(t)$, the thermal strain.

Note 7: Back-calculation is done by representing the Boltzmann equation in discrete form.

14.5.2. Rewriting the Boltzmann equation in discrete form by:

$$\sigma(t_n) = \sum_{i=1}^n E(t_n - t_i) \times (\varepsilon(t_i) - \varepsilon(t_{i-1})) \quad (5)$$

Where:

n is a time index start from zero

$\sigma(t_0)$ and $\varepsilon(t_0)$ are set to be zero corresponding to initial test condition.

14.5.3. Calculate thermal modulus at any temperature by:

$$E(T(t_n)) = \frac{(\sigma(t_{n+1}) - \sum_{i=2}^{n+1} E(t_{n+1} - t_i)(\varepsilon(t_i) - \varepsilon(t_{i-1})))}{\varepsilon(t_1)} \quad (6)$$

Note 8: if the data of thermal strain is not available, the thermal modulus of asphalt mixture can be estimated by assuming a constant value for thermal coefficient of contraction, α , by:

$$E_{Th-est.}(T(t_n)) = \frac{\sigma(T(t_n)) - \sigma(T(t_{n-1}))}{\alpha \times (T(t_n) - T(t_{n-1}))} \quad (7)$$

14.6. *Determination of thermal viscoelastic properties*

14.6.1. Compute the first derivative of thermal modulus with respect to temperature.

$$E_{Th}'(T(t_i)) = \frac{E_r(T(t_i)) - E_r(T(t_{i-1}))}{T(t_i) - T(t_{i-1})} \quad (8)$$

14.6.2. Calculate the second derivative of thermal modulus with respect to temperature.

$$E_{Th}''(T(t_i)) = \frac{E_r'(T(t_i)) - E_r'(T(t_{i-1}))}{T(t_i) - T(t_{i-1})} \quad (9)$$

14.6.3. *Determination of crack initiation properties.*

14.6.3.1. The crack initiation modulus is defined as the maximum value of the thermal modulus. This point is identified when the first derivative of the thermal modulus with respect to temperature is equal to zero.

14.6.3.2. The crack initiation temperature is the temperature that corresponds to the maximum thermal modulus.

14.6.3.3. The crack initiation stress is defined as the developed thermal stress at the crack initiation temperature.

14.6.4. *Determination of glassy hardening properties.*

14.6.4.1. Glassy hardening modulus is defined as the modulus at the point at which the second derivative of the thermal modulus with respect to temperature is zero on the colder side of the second derivative curve.

13.5.1.1. Glassy hardening temperature is defined as the temperature corresponding to the glassy hardening modulus.

13.5.1.2. Glassy slope determined as the absolute value of first derivative of the thermal modulus with respect to temperature at the point of glassy hardening.

14.6.5. Determination of viscous-glassy transition properties.

14.6.5.1. Viscous-glassy transition modulus- the modulus at the point at which the second derivative of thermal modulus in respect to temperature is maximum.

14.6.5.2. Viscous-glassy transition temperature- the corresponding temperature to the viscous-glassy transition modulus.

14.6.6. Determination of viscous softening properties.

14.6.7. Viscous softening modulus- the modulus at the point at which the second derivative of the thermal modulus is zero at the warmer side.

14.6.8. Viscous softening temperature- the corresponding temperature to the viscous softening modulus.

Note 9: viscous softening properties may not always be detected based on the testing program described in this standard.

Note 10: the calculations contained in this standard need to be performed by a computer. Software to perform the calculation can be written or purchased as a stand-alone program.

15. EXAMPLE OF CALCULATION

15.1. In this example an asphalt mixture has been evaluated to determine thermal viscoelastic properties using data generated with Method A - Uniaxial Thermal Stress and Strain Test (UTSST).

15.2. The test is conducted on a sample of hot mixture asphalt. The initial equilibrium temperature was 20°C and the cooling rate was 10°C per hour.

15.3. Calculate the average diameter of restrained specimen and average length of the unrestrained specimen.

Average diameter of restrained specimen = 57.4 mm

Average length of unrestrained specimen = 279.6 mm

15.4. Calculation of normalized smoothed thermal stress and strain (Figure 11).

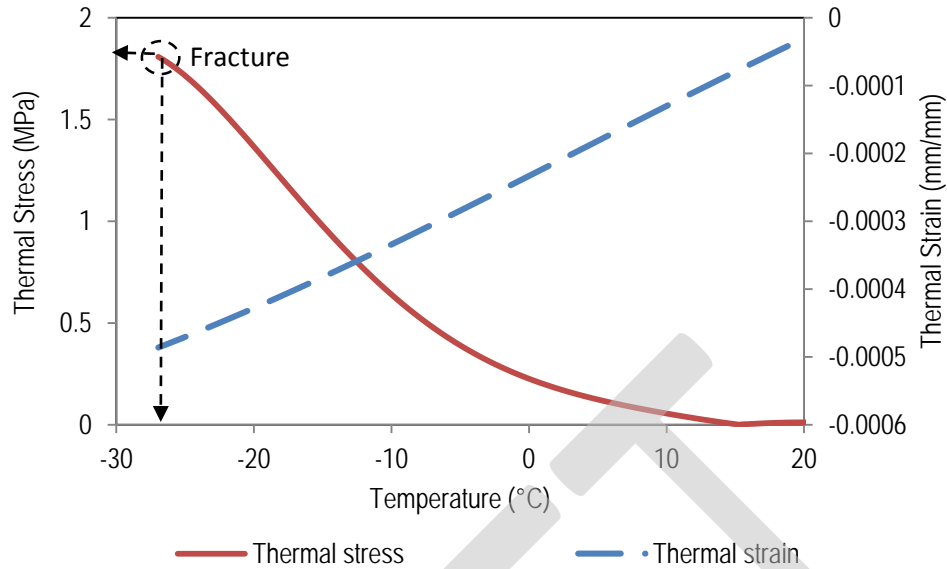


Figure 11: Thermal stress and thermal strain obtained from Method A (UTSST)

- 15.5. Determination of rate of thermal stress and rate of thermal strain.
- 15.6. Calculation of thermal modulus and first and second derivatives with respect to temperature.
- 15.7. Determination of thermal viscoelastic and strength properties (Figure 12).

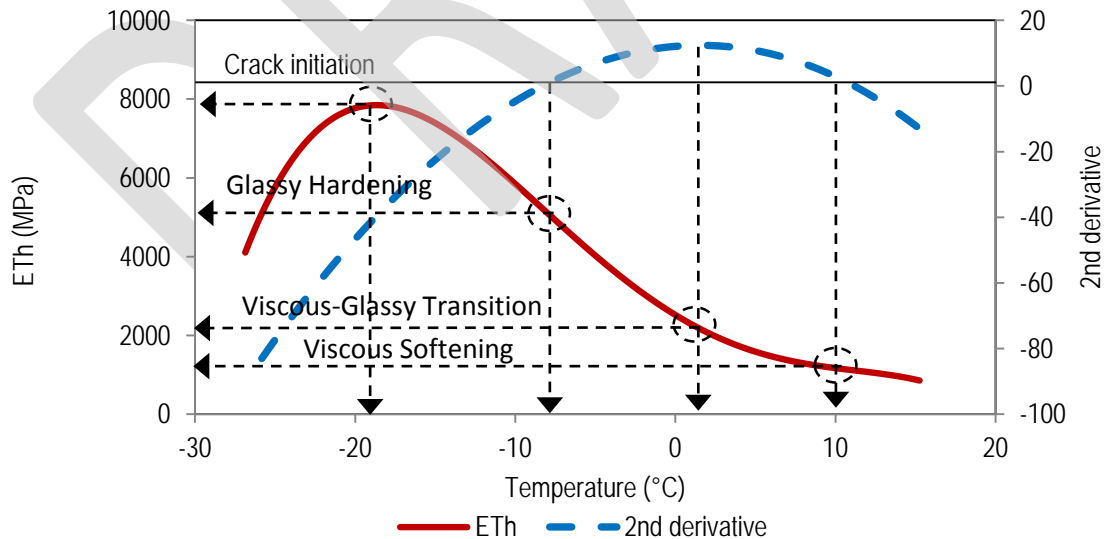


Figure 12: Determination of thermal viscoelastic properties of asphalt mixture

16. REPORT

- 16.1. *Test Specimen Description* – asphalt binder type, asphalt binder content, aggregate gradation, and air void percentage of test specimen.
- 16.2. *Test Specimen Aging History*- temperature, pressure and period of aging.
- 16.3. *Test Method Description*- method (UTSST or ATCA), cooling rate, initial equilibrium temperature, time step.
- 16.4. Average cross-sectional area of the specimen, nearest 1 mm².
- 16.5. Average length of the unrestrained specimen, nearest 0.1 mm.
- 16.6. Normalized thermal stress versus temperature curve.
- 16.7. Normalized thermal strain versus temperature curve.
- 16.8. Coefficient of axial thermal contraction.
- 16.9. Thermal modulus versus temperature curve.
- 16.10. Thermally induced tensile load, nearest 10 N.
- 16.11. Fracture temperature, nearest 0.1°C.
- 16.12. Fracture stress, nearest 50 kPa.
- 16.13. Crack initiation temperature, nearest 0.1°C.
- 16.14. Crack initiation modulus, nearest 1 MPa.
- 16.15. Crack initiation stress, nearest 50 kPa.
- 16.16. Glassy hardening temperature, nearest 0.1°C.
- 16.17. Glassy hardening modulus, nearest 1 MPa.
- 16.18. Glassy hardening slope.
- 16.19. Viscous-glassy temperature, nearest 0.1°C.
- 16.20. Viscous-glassy modulus, nearest 1 MPa.
- 16.21. Viscous softening temperature, nearest 0.1°C.

16.22. Viscous softening modulus, nearest 1 MPa.

16.23. Failure Description – location of break along specimen length, nature of break (angular, flat, broken aggregate, etc.).

17. PRECISION AND BIAS

17.1. *Precision* – The work necessary to determine the precision of this test has not yet been performed.

17.2. *Bias* – No justifiable statement can be made on the bias of this test method due to the lack of availability of a valid reference value available.

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