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16. Abstract

Hot mix asphalt (HMA) overlay is one of the most commonly used methods for rehabilitating deteriorated pavements. One major type of distress influencing the life of an overlay is reflective cracking. Many departments of transportation have implemented design-level tests to measure the rutting potential of HMA; these are typically wheel-tracking tests. However, currently, there is no national design-level test for measuring resistance to cracking. Currently, the Texas Department of Transportation uses the Overlay Tester (OT) to evaluate the cracking susceptibility of HMA mixes in the laboratory. While, the OT effectively simulates the reflective cracking mechanism of opening and closing of joints and/or cracks, repeatability and variability in the test results have been major areas of concern. In particular, variability in the OT test results poses a problem with most of the conventional dense-graded HMA mixes, such as Type C and D, which is approximately 75 percent of all the HMA used on Texas highways.

This laboratory study presents a comprehensive sensitivity evaluation of the critical steps of the OT test procedure in an attempt to optimize the OT repeatability and minimize variability in the test results. In general, the study indicated that the sample drying method, glue quantity, number of sample replicates, air voids, sample age at the time of testing, and temperature variations are some of the key aspects that have a significant impact on the OT test repeatability and variability. Overall, findings from this study indicate that variability in the OT test results can be minimized if these aspects are improved and/or more clearly specified in the OT test procedure (Tex-248-F).

17. Key Words
HMA, Cracking, Overlay Tester (OT), Peak Load, OT Cycles, Repeatability, Variability, Coefficient of Variation, Monotonic, Tensile Strength, Tensile Strain, Tensile Modulus, Fracture Energy (FE), FE Index, Pseudo Strain Energy, Air Voids, X-Ray CT

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LIST OF NOTATIONS AND SYMBOLS

AR	Asphalt-rubber
ASTM	American Society for Testing and Materials
AV	Air voids
Avg	Average
CAM	Crack attenuating mixtures
COV	Coefficient of variation
DOT	Department of Transportation
DT	Direct Tension Test
DSCTT	Disc-Shaped Compact Tension Test
DSR	Dynamic Shear Rheometer
HMA	Hot mix asphalt
IDT	Indirect Tension Test
LVDT	Linear variable displacement transducer
MTS	Material testing system
OGFC	Open graded friction course
OT	Overlay Tester
OT_R	Reaped load OT test or OT testing conducted in repeated loading mode
OT_M	Monotonic OT test or OT testing conducted in monotonic loading mode
PG	Performance grade
RAP	Reclaimed asphalt pavement
PM	Plant-mix
RAS	Recycled asphalt shingles
RCRI	Reflective crack relief interlayer
SCB	Semi-circular bending
SGC	Superpave gyratory compactor
SMA	Stone mastic asphalt
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation
WMA	Warm mix asphalt
G_f	Specific fracture energy

σ_t	HMA tensile strength
ε_t	Tensile strain at peak failure load (ductility potential)
E_t	HMA tensile modulus (stiffness)
ΔK	Stress Intensity Factor (SIF)

CHAPTER 1.
INTRODUCTION

Over the past decade, the Texas Department of Transportation (TxDOT), in an effort to mitigate rutting in the early life of hot mix asphalt (HMA) pavements, has used stiffer HMA that were potentially more prone to reflective cracking. One of the contributing factors to this issue is the complexity of the current mix designs due to the fact that HMA are now predominately produced with recycled materials such as reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS). The adaptation of the Hamburg rutting test (Tex-242-F, 2009) and stiffer asphalt binders, while almost eliminating rutting distresses, has not helped to reduce resistance to cracking. Consequently, there still remains an urgent need for a simple and practical performance-related cracking test that can be performed routinely during the laboratory mixture design process and production to ensure that HMA is not susceptible to premature cracking.

Reflective cracking is one of the predominant types of cracking in flexible pavements of new HMA overlays placed on HMA pavements that have experienced cracking caused by fatigue, aging, and/or thermal stresses. The opening and closing of joints and/or cracks induced by daily temperature variations and vehicle loading contributes to the rapid propagation of the subsurface defects through the overlay to the surface. This mechanism is simulated in the laboratory using a specially modified Overlay Tester (OT) device, which is currently used by TxDOT to evaluate the cracking susceptibility of HMA (Tex-248-F, 2009).

Since its adaption through the use of Tex-248-F, application of the OT as a reliable cracking susceptibility test in the laboratory has been a challenge due to repeatability and variability issues, particularly with the coarse and dense-graded mixes. While the test is fairly satisfactory with stone mastic asphalt (SMA) and crack attenuating mixtures (CAM), variability has been an issue with conventional TxDOT dense-graded HMA such as Type C and D mixes. By comparison, Type C and D mixes constitute approximately 75 percent of all HMA produced for TxDOT.

A laboratory mix test to characterize the cracking susceptibility of HMA mixes is thus greatly needed for all the Texas HMA mix types. As a minimum, such a test protocol must have the following characteristic features:

- Applicability for routine HMA screening and not necessarily performance prediction such as fatigue life.

- Practical and easy implementation by TxDOT.
- Easy sample preparation with potential to test both lab-prepared and field cores.
- Reasonable test duration of no more than 1 day.
- Acceptable level of variation and test reliability.
- Potential to simulate and/or correlate with the field conditions.

RESEARCH OBJECTIVES AND SCOPE OF WORK

To address the issue of developing a defensible cracking performance test, this research project evaluated various HMA crack tests that are presently in practice in view of finding a practical and reliable test for routine crack evaluation of HMA mixes with an acceptable level of variability. The technical objectives of this project were therefore as follows:

- Evaluate the current OT procedure and make it more repeatable and robust. Perform a comprehensive sensitivity analysis of all key steps in the OT protocol (Tex-248-F, 2009) and data analysis procedure.
- Recommend updates to Tex-248-F.
- Evaluate the repeatability between laboratories for the Overlay Test in a production environment by running duplicate tests in both the Texas Transportation Institute (TTI) and TxDOT labs on plant mixes from TxDOT projects.
- Evaluate the potential for having alternative tests to identify crack-susceptible mixes. Identify and evaluate other cracking tests that must (a) be performance related; (b) be sensitive to critical mix-design parameters such as asphalt content, mix type, etc.; and (c) provide improved repeatability.
- Develop new test procedures and specifications.
- Develop technical implementation recommendations.

RESEARCH METHODOLOGY AND WORK PLANS

This study attempted to improve the repeatability and robustness of TxDOT's current Overlay Tester equipment and Test Method 248-F, so it can be used with confidence on standard dense-graded surface mixes. These products will be readily implementable with suggested modifications to existing test procedures. The majority of the testing in this study was on actual mixes being placed on Texas highways. The field performances of these mixes were compared with the laboratory results to provide TxDOT designers with defensible data to justify and validate the need for implementation of these new test procedures.

To successfully achieve these goals, the research team conducted the tasks that are listed in the following work plan:

- Task 1: Search of literature.
- Task 2: Comprehensive evaluation of the sensitivity and improvement to the Overlay test procedure.
- Task 3: Parallel testing of split samples from TxDOT projects.
- Task 4: Development of test procedures for alternative cracking tests.
- Task 5: Comprehensive laboratory evaluations of potential repeated load fracture tests.
- Task 6: Correlation of lab test results with field test sections.
- Task 7: Recommendation of test procedures and specifications.
- Task 8: Case study: demonstration of how to improve asphalt mixture design.

However, the scope of this interim report is limited to Tasks 1 through 3, which focused predominantly on improving the OT repeatability and minimization of variability in the test results. In particular, Task 2 was the main focus during year 1 of this project and covered the bulk load of the work contained in this interim report. The work plan for this task incorporated extensive laboratory testing while iteratively evaluating the Tex-248-F test procedure. This interim report evaluates and discusses all the critical steps of Tex-248-F.

REPORT CONTENTS AND ORGANIZATIONAL LAYOUT

This report consists of nine chapters including this chapter (Chapter 1), which provides the background, research objectives, methodology, and scope of work. Chapter 2 includes the findings of a literature review performed to document the details of available laboratory cracking susceptibility tests for HMA mixes. The findings of the OT survey conducted within the various TxDOT labs and other states are presented in Chapter 3. Chapter 4 then discusses the experimental design plan.

Chapter 5 presents the details of the OT sensitivity evaluation study, which was the primary focus of this interim report, followed by a study of OT sample mold sizes in Chapter 6. Chapter 7 explores the alternative OT data analysis methods. Chapter 8 proposes some modifications to the OT Test Specification Tex-248-F based on the findings of Chapters 2 through 7. Finally, a summary of the report with a list of the major findings and recommendations is presented in Chapter 9. Some appendices of important data are also included at the end of the report.

SUMMARY

In this introductory chapter, the background and the research objectives of this project were discussed. The research methodology and scope of work were then described, followed by a summary of the project work plan. The chapter ended with a description of the report contents and the organizational layout.

CHAPTER 2.
LITERATURE REVIEW

Researchers conducted a literature review consisting of an extensive information search of electronic databases and their resulting publications to gather data on the Overlay Tester and other currently available tests used to potentially measure the susceptibility of HMA to cracking worldwide. This chapter discusses the findings of the literature review.

The long-term performance of the HMA overlays depends on their ability to resist reflective cracking. While the severity of the effects of reflective cracking on overlay performance is widely accepted, when it comes to assessing the cracking susceptibility of HMA mixes in the lab, no single laboratory test has been established as the widely accepted standard cracking test. Several different test procedures of both monotonic and cyclic nature have been in practice by different agencies and state departments of transportation (DOTs; Loria-Salazar, 2008). A comparative evaluation of some HMA crack test procedures is presented in this chapter, starting with the Overlay Test. Appendix A contains the detailed findings of the literature review.

THE OVERLAY TEST

In 2003, Zhou and Scullion (2003) from TTI upgraded the TTI OT device, which had been widely used to evaluate the effectiveness of different geosynthetic materials since it was designed by Lytton et al. in the late 1970s (Zhou et al., 2004), and proposed its use in evaluating cracking resistance of HMA overlays. Since then, different researchers including Bennert (2009), Bennert et al. (2009), Bennert and Dongré (2010), Hajj et al. (2010), and Bennert et al. (2011) have used the OT and have rated it as a reliable and practical test for screening and evaluating the crack resistance of HMA in the laboratory. Loria-Salazar (2008) did a comprehensive literature review study that lists different potential laboratory tests that have been in practice to evaluate the resistance of HMA to reflective cracking. He concluded that the OT is the only laboratory test method to undergo field validation that exhibited consistency between the laboratory test results and their corresponding field performance.

The OT Protocol

The OT is a simple performance test traditionally used for characterizing the reflective cracking potential of HMA mixes in the laboratory. It is an electro-hydraulic system that applies repeated direct tension loads to specimens. Details of the OT test procedure have been outlined in the TxDOT test procedure designation Tex-248-F (2009) and are summarized in the subsequent text. Figure 2-1 illustrates the OT schematic layout and sample setup.

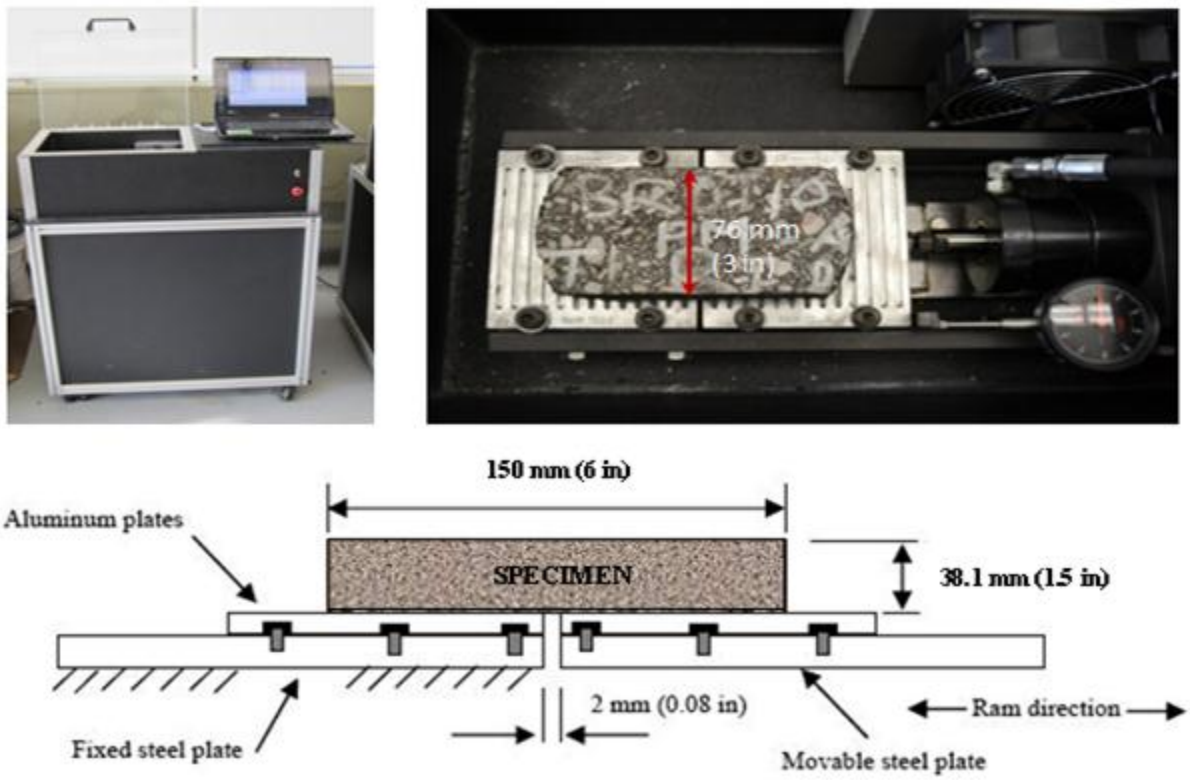


Figure 2-1. OT Schematic Layout and Sample Setup.

The key components of the OT device, as shown schematically in Figure 2-1, consist of two steel plates, one fixed and the other able to move horizontally to simulate the opening and closing of joints or cracks in the old pavements beneath an overlay. A plate sample is spanned across the crack and epoxied to the horizontal surface platens with half of the length of the specimen resting on each platen. The OT test specimens are 6 in. long, 3 in. wide, and 1.5 in. thick. They can be conveniently sawn by trimming a 6 in. diameter by 4.5 in. high SGC compacted sample, field-extracted cores, or a field-sawn slab. The lab-molded specimens are typically compacted to a target air-void level of 7 ± 0.5 percent (Tex-241-F, 2009).

The test is conducted in a controlled displacement mode at a repeated loading rate of one cycle per 10 sec. (5 sec. of loading and 5 sec. of unloading) with a maximum horizontal displacement of 0.025 at the testing temperature of 77°F. The repeated loading cycles are applied until failure, as defined by a 93 percent drop in the maximum peak load measured on the first cycle or a preset value of cycles (e.g., 1000), whichever occurs first.

OT Output Data and Result Interpretation

During OT testing, the measurable parameters include the applied load, opening displacement, time, number of load cycles, and test temperature. All these data are automatically recorded in the computer attached to the OT machine as an Excel spreadsheet. The primary output of the OT test is the crack-resistance potential of an HMA mix, which is essentially quantified in terms of the number of cycles for the sample to fail (i.e., 93 percent drop of the first cycle peak load). Figure 2-2 provides a summary illustration of the OT output data. The sample tested in this case failed after nine cycles.

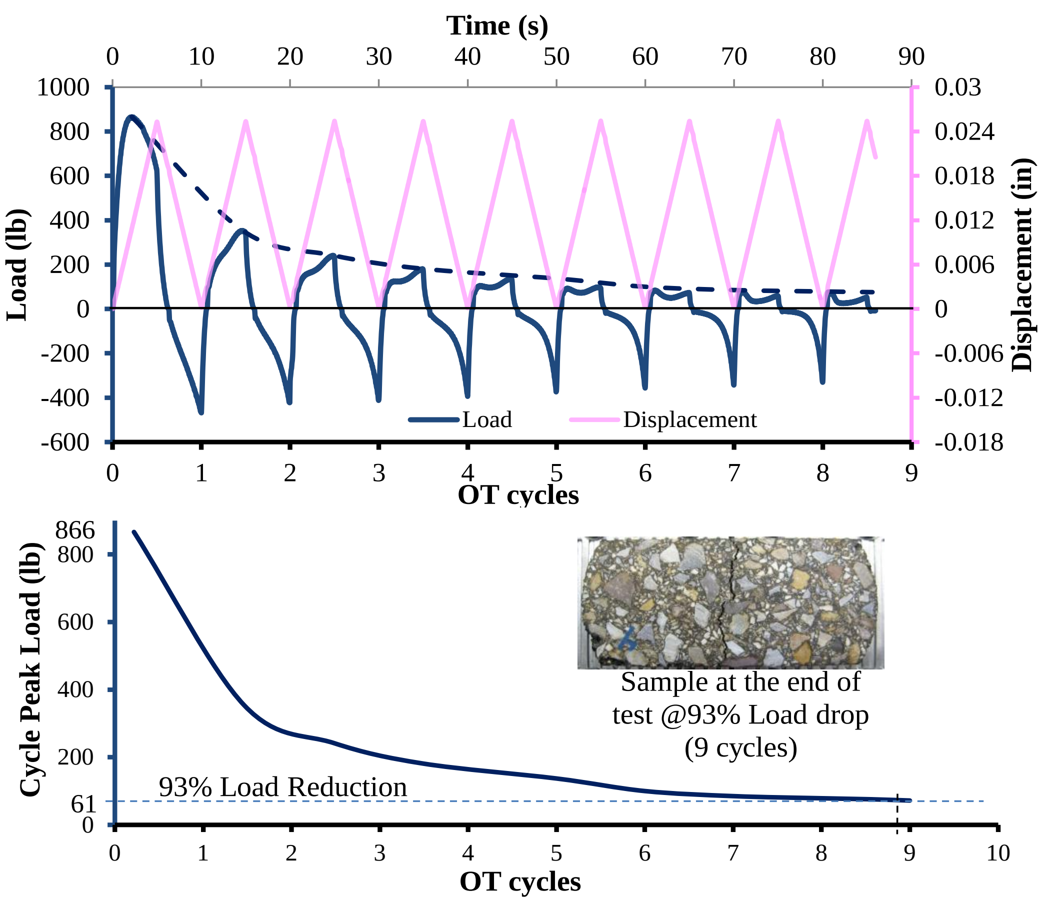


Figure 2-2. OT Output Data and Interpretation of the Results.

From the curve, it is evident that the peak load kept on decreasing in each cycle as the crack steadily propagated to the top surface. When the cycle peak load reached 7 percent of that of the first cycle, the sample was determined to have failed, at which time complete cracking would have occurred throughout the specimen thickness (Figure 2-2).

OT Variability in the Literature

Extensive use of the OT test is limited to TTI and TxDOT laboratories along with laboratories in a few other states like New Jersey, Alabama, Oklahoma, Massachusetts, and Nevada. Therefore, the OT variability issue has not been reported as widely in the literature as it has been in Texas. Recently, however, Walubita et al. (2010) noted that one of the key problems contributing to the reported high variability in the OT test results was primarily related to non-adherence to the Tex-248-F specification and OT test procedures. In some instances, however, the provisional Tex-248-F specification itself was found to be obscure and not very elaborate, e.g., the specification does not clearly specify the glue amount per sample or the gluing procedure. All these aspects have perpetually contributed to the poor repeatability in the OT test results with a coefficient of variation (COV) higher than 30 percent, particularly for most dense- and coarse-graded mixes.

Nonetheless, most (if not all) of the cracking tests, by nature of their repeated (tensile) loading configuration and failure mode, are typically associated with high variability in the test results. From the literature review, and as shown in Table 2-1, most of the cracking tests, such as the flexural and diametral fatigue, were found to exhibit higher COV values on the order of 65 to 172 percent, way higher than 30 percent (SHRP, 1994).

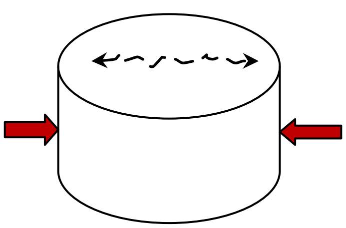
Compared to compressive loading tests such as the Hamburg, COV values of over 30 percent (see Table 2-1) should therefore not be unusual for cracking tests, and the OT is no exception. The onus is trying as much as possible to minimize this variability. Compared to compression tests like the Hamburg, the failure zone or point of failure in tensile crack tests such as the Overlay or the bending beam is highly localized and predetermined, i.e., at the center of the specimen. This is one potential cause of variability in most cracking tests because the weakest point in any given test specimen may not necessarily be the middle zone. For some specimens, the middle zone may actually turn out to be the strongest point, and thus, they would perform completely different from specimens whose weakest area is the middle point.

Table 2-1. Variability Comparison of Fatigue (Crack) Test Methods (SHRP, 1994).

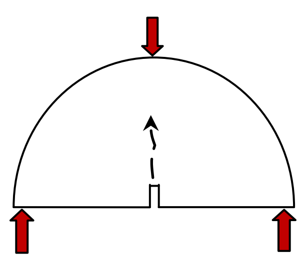
	Flexural Beam Fatigue	Flexural Trapezoidal Fatigue	Diametral Fatigue
Stiffness			
Coefficient of Variation (%)	12.3	11.4	19.7
Sample Variance (ln psi)	0.010	0.014	0.015
Cycles to Failure			
Coefficient of Variation (%)	98.7	171.8	65.5
Sample Variance (ln cycles to failure)	0.282	1.696	0.213

THE INDIRECT TENSION TEST (IDT)

Researchers have used indirect tension testing to characterize the properties of HMA mixes for over 30 years and has exhibited potential for accurately predicting the fatigue resistance properties of HMA mixes (Walubita et al., 2004). The typical IDT setup requires a servo-hydraulic closed-loop testing machine capable of axial compression (Huang et al., 2005). Several publications recommend using a loading rate of 2 inch/min, most notably the standard procedures in Tex-226-F (TxDOT, 2004) and American Society for Testing and Materials (ASTM) D6931 (ASTM, 2005). As Figure 2-3 illustrates, the specimen is typically loaded diametrically in compression, and this indirectly induces horizontal tensile stresses in the middle zone of the specimen, which ultimately causes cracking. For the evaluation of the tensile properties of the HMA mixes, the permanent deformation under the loading strip is undesirable (Huang et al., 2005). Therefore, the compressive load is distributed using loading strips, which are curved at the interface to fit the radius of curvature of the specimen.



(a) IDT



(b) SCB

Figure 2-3. Schematic Diagrams: IDT and SCB Tests.

The fracture energy of the IDT specimen is calculated using the strain at the center of the specimen, which is determined from the displacements with a 2-in. gauge length using linear viscoelastic solutions (Kim and Wen, 2002). However, one issue that may be problematic with the IDT setup is the gauge length of the linear variable displacement transducers (LVDTs). The existence of large aggregates, particularly for coarse-graded mixes, in the middle of the specimen can affect the displacement measurements between the gauge points if the length is too short. Thus, caution must be exercised to watch out for such potential problems and account for them in the subsequent data analyses and interpretation of the results.

Typical test temperatures range from −20°C (Buttlar et al., 1996) to 25°C (Huang et al., 2005). The data captured during IDT testing include time, applied load, and horizontal and vertical specimen deformation.

THE SEMI-CIRCULAR BENDING TEST (SCB)

The development of SCB as a predictor of cracking resistance in HMA mixes has appeared relatively recent in the field of pavement engineering. The SCB specimen is a half disk, typically 4 to 6 in. in diameter and 1.5 to 2 in. thick (Huang et al., 2009), that is loaded in compression using a three-point flexural apparatus; see Figure 2-3. The same equipment that is used with the IDT can be used for the SCB. However, an additional apparatus must be utilized to achieve the three-point bending mode. The rate at which the specimen is loaded is not very well specified, but Walubita et al. (2010) had success when using 0.05 in/min loading rate. Specimen fabrication and preparation for the SCB test is very simple and quick. Many researchers cut a notch in the base of the specimen to ensure that the crack initiates in the center of the specimen. Notch depths vary depending on many factors, such as specimen thickness, diameter, loading rate, test temperature, mix type, etc.

At first glance, the calculation of stiffness in the middle point of the lower specimen surface may seem difficult because affixing the strain gauges onto the specimen is time and resource consuming. In the case of the current study, however, HMA stiffness determination may be an important parameter to explore. The SCB test accommodates this requirement in that the stiffness can be obtained by replacing the horizontal strain with vertical deflections, as in the flexural bending beam fatigue analysis (Huang et al., 2009).

For analysis purposes, the spacing between the supports is typically 0.8 times the specimen diameter. From the literature search, the typical test temperatures for the SCB test are between 10°C (Huang et al., 2009) and 25°C (Molenaar et al., 2002). Data recorded during IDT testing include the following: time, applied load, and horizontal displacement at the crack (Molenaar et al., 2002) or vertical deflection in the specimen.

THE DIRECT TENSION TEST (DT)

The DT test has recently become popular for fatigue cracking analysis. It is the most straightforward test and has the simplest analysis equation of all the test methods because the specimen is tested in direct-tension loading mode; see Figure 2-4. The specimen is typically a cylinder of 6 in. in height and 4 in. in diameter (Walubita, 2006). This geometry is in part based on the ease of specimen fabrication using the Superpave gyratory compactor. The loading rate is typically 0.05 in/min (Walubita et al., 2010). However, the specimen setup process requires gluing end plates to the specimen ends that are in turn attached to the hydraulic system. This step is a very critical process for this test, and it requires meticulous work to ensure reliable results. Gluing time can also be a hindrance to testing efficiency, as the process usually requires 24 hours for curing.

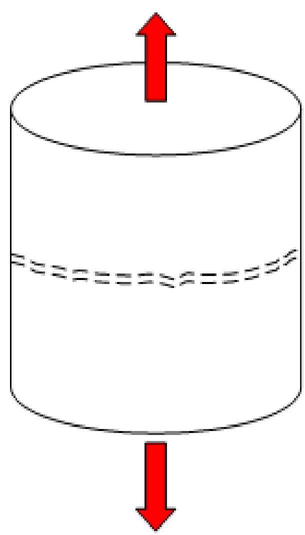


Figure 2-4. Schematic Diagram: DT Test.

In addition, the failure of the specimen must be closely monitored, as cracking near the ends can be an indicator that end effects may be introduced into the data and resulting analysis. In fact, proper gluing techniques must be ensured, otherwise the specimen may fail in the glued area. This also means that the HMA may not have failed before the test actually terminated, and therefore the calculated stresses and strains will be erroneous. As the LVDTs are generally attached to the specimen, HMA stiffness determination is thus possible with this test.

The DT test can be run at either 68°F or room temperature. The data that are captured during DT testing include the load, vertical displacement, and time. However, sample preparation (coring) and setup (gluing) are the main challenges associated with this test.

THE DISC-SHAPED COMPACT TENSION TEST (DSCTT)

The DSCTT test method was developed for determining the fracture resistance of asphalt-aggregate mixtures. The specimen geometry is readily adapted to 150 mm diameter specimens, such as those fabricated from Superpave gyratory compactors. The specimen geometry can also be adapted for forensic investigations using field core specimens (ASTM D7313, 2008).

The disc-shaped specimens are 2 in. thick and have a 1.4 in. deep notch along the diameter. As Figure 2-5 shows, the samples are loaded through two pins that fit into two equal-sized circular holes cored through the thickness of the specimen and are allowed to roll freely on the flat surfaces of the loading clevis.

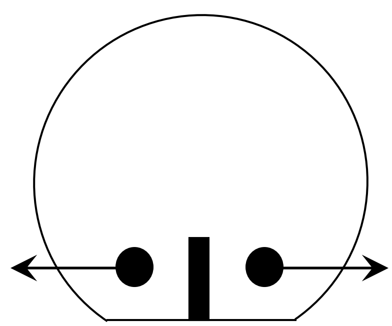


Figure 2-5. Schematic Diagram: DSCTT Test.

Tensile loading is applied with a constant crack mouth opening displacement rate. The crack mouth opening displacement is recorded along with the applied load and time. Fracture energy is calculated from a load-displacement plot using fracture mechanics principles.

Based on the findings of this literature review, TTI researchers have also been able to set up and run the DSCTT test in the TTI-McNew lab. Appendix B summarizes the test setup and other review results. Detailed results of the DSCTT tests at TTI will be included in future reports.

REVIEW OF OTHER AVAILABLE CRACK TESTS

Researchers also completed an extensive worldwide literature review of other available crack tests, and Appendix A summarizes the results. Compared to the OT, one of the key challenges with these other crack tests is that they have not been validated in the field. The researchers did not find field data related to most of these tests during their literature search.

SUMMARY

This chapter presented a review of the literature of the currently available cracking tests including the Overlay Test. Among the other notable HMA crack tests reviewed were the Indirect Tension Test, the Semi-Circular Bending Test, the Direct Tension Test, and the Disc-Shaped Compact Tension Test. Currently, TTI has the capacity and equipment to successfully run all these crack tests.

CHAPTER 3.
OT SURVEY QUESTIONNAIRES

In order to have an in-depth consensus understanding of the key issues/problems related to the OT and formulate appropriate remedial strategies/work plans, researchers sent a survey questionnaire to various OT users both locally and nationally. The survey questions focused on major problems faced with the OT and the districts' suggestions for improvements and/or modifications. This chapter summarizes the key findings of the survey.

STATE LEVEL: TEXAS LABORATORIES

Several laboratories in the state of Texas use the OT test for cracking susceptibility evaluation. The state laboratories that were selected to participate in this questionnaire study were Atlanta, Childress, and Houston. Appendix C presents an example of the responses of the labs to the model questionnaire. The respondents indicated that they use the Standard Tex-248-F Test Method, predominantly to evaluate dense-graded mixes in terms of:

- Verifying the mix design.
- Screening the mix design.
- Testing plant mixes for the contractors.
- Monitoring production mixes.

In general, all the labs indicated "consistency and variability in the test results" as one of the key challenges associated with the OT test, particularly for the dense- to coarse-graded, RAP, and warm mix asphalt (WMA) mixes. Their suggestions/recommendations to improve the robustness and repeatability of the OT test included the following:

- Harmonization and upgrading of the OT software (software versions are currently different).
- Formalized and periodic calibration of the OT machines, e.g., semi-annually or yearly.
- Use of the same technician for all the sample preparation stages, i.e., molding, cutting, bulking, gluing, etc.
- Use of trained operators/technicians to run the OT machine.
- Adherence to the Tex-248-F spec and tightening up of all the spec tolerances.

NATIONAL LEVEL

Several laboratories outside the state of Texas also participated in the questionnaire survey. The states and institutes that were surveyed were:

- Alabama (AL).
- New Jersey (NJ)—University of Rutgers.
- Nevada (NV)—University of Nevada at Reno.
- Massachusetts (MA)—University of Massachusetts at Dartmouth.
- Oklahoma (AK) —Road Science
- Wisconsin (WI)—Mathy Construction.

Appendix D lists an example of the responses of the labs. The general findings from this national survey are listed below:

OT Spec and Modifications

In general, the respondents indicated that they use the Standard Tex-248-F Test Method with additional spec recommendations and modifications as follows:

- New Jersey—59°F for surface and reflective crack relief interlayer (RCRI) mixes (at 0.025 in. displacement) plus the Standard Tex-248-F for all other mixes; up to 1200 OT cycles at 93 percent reduction in the peak load (Bennert et al., 2009).
- Nevada—0.018 in. displacement at 50°F (4000 OT cycles) plus the standard OT specification of 0.025 in. at 77°F (1200 OT cycles) at 93 percent reduction in the peak load. These researchers also use a torque force of 21 lbf for fastening the sample-plate assembly into the OT machine (versus the Tex-248-F spec of 15 lbf torque force) (Hajj et al., 2010).

Materials and Mixes

The review results indicated that the respondents use the OT test to evaluate various mixes including:

- Superpave mixes.
- Coarse- and dense-graded mixes.
- OGFC (AR) and SMA mixes.
- Asphalt rubber gap-graded mixes.

- Mixes with high RAP and RAS content.
- WMA mixes.
- CAM and stress relief mixes.
- Interlayer mixes.

OT Applications

Most of the respondents and the review results indicated that they use the OT predominantly for research applications including but not limited to the following:

- Testing lab-prepared samples, plant mixes, and field cores.
- Investigating and characterizing the reflective cracking-resistance potential of mixes as a function of mix-design variables such as material type, mixing/compaction temperature, test temperature, asphalt-binder content, aggregate gradation, aging, etc.
- Evaluating and characterizing the cracking-resistance potential of RAP and WMA mixes.
- Designing/evaluating interlayer and overlay thickness against reflective cracking.
- Screening mixes, verifying mix designs, and correlating to field performance.

Reported Results

In general, most of the out-of-state laboratories' mixes indicated superior performance in the OT including OGFC (AR) and WMA mixes, particularly at low mixing temperatures (hypothesized to reduce oxidative aging, polymer degradation, and asphalt-binder absorption). However, their Superpave, dense-graded, RAP, and some coarse-graded mixes exhibited performance similar to the Texas experience. From the survey responses, their reported results (at different temperatures and loading rates) indicated the following (detailed examples of some of these results are listed in Appendices E and F):

- OT cycles—Superpave mixes: 20–300
- OT cycles—dense-graded and rich mixes: > 1200
- OT cycles—coarse-graded mixes: 10 to over 1200
- OT cycles—OGFC (AR) mixes: 900–3600
- OT cycles—RAP mixes: 20–150
- OT cycles—WMA mixes: up to 4000
- OT cycles—CAM mixes: > 1200

- OT cycles—RCRI (interlayer crack-resistant) mixes: > 3000
- Range of standard deviation (Stdev) for OT cycles: 0.2–135
- Range of COV for OT cycles: 4–60 percent
- Range of peak load at 77°F: 400–900 lbf
- Range of peak load at 50°F: 800–1200 lbf

Reported Advantages of the OT Test

The review results and respondents indicated the following as some of the advantages of the OT test:

- Is rapid and reliable for evaluating the crack resistance of HMA mixes.
- Can test both lab-prepared samples and field cores.
- Results correlate to field performance of flexible and composite pavements.
- Is sensitive and able to capture the effects of RAP content and WMA additive/technology.
- Test setup is mobile and portable.
- Can be used to evaluate the effects of the interlayer (RCRI) thickness on the reflective crack life of an overlay.

Reported Challenges of the OT

The reported disadvantages and challenges associated with the OT were:

- Sample preparation requires cutting and gluing; this could be a potential source of errors and variability in the test results particularly because the glue amount (per sample) is not clearly quantified.
- Poor consistency exists in the test results for some mixes, with more variability at lower test temperatures.
- Testing at 77°F and only for 1200 OT cycles is not sufficient to capture the differences in the resistance to cracking of some mixes, particularly in mixes with superior quality aggregates.
- Occasional shear failure of the glue occurs when affixing specimens to test plates during the testing of very stiff mixtures (specifically those containing RAP and RAS or high-density mixtures).

Suggestions and Recommendations for OT Improvements

The suggestions and recommendations to improve the robustness and repeatability of the OT test based on feedback from OT users outside of Texas include the following:

- Modifying the OT test parameters (i.e., loading rate, test temperature, acceptable OT cycles) as needed for different materials/mixes, applications, and environmental conditions so as to better capture the different mixes' cracking-resistance potential, i.e., surface versus dense-graded or WMA mixes or coarse-graded or RCRI mixes, or cold versus warm regions.
- Using more than three replicate samples to get acceptable results.
- Modifying the molded sample dimensions to reduce the wastage of materials.
- Standardizing and clearly quantifying the necessary glue amount per sample.
- Introducing a more thorough and standardized specimen-mounting procedure.
- Considering other variables and test parameters such as the air voids, aging, and temperature when analyzing the OT test data.
- Calibrating the OT machine regularly, e.g., at least semi annually.
- Preferably testing the OT samples within five days of molding.

OT USERS' GROUP MEETING

In addition to distributing the survey questionnaire, researchers held a meeting in Washington, DC, on January 25, 2011, with the following two primary objectives:

- To discuss, exchange, and share ideas on the OT and how to further improve it.
- To discuss the ASTM OT Round Robin and the ASTM Work Group WK26816.

Appendix G includes the minutes of this meeting. As discussed subsequently, the meeting focused on, among other key issues, the following items: OT results and variability, OT test parameters and failure criteria, comparison with other crack tests, glue type being used, and suggestions for OT improvements to maximize repeatability and minimize variability in the test results.

OT Results and Variability

On the issue of OT results and their variability, the participants of the meeting brought about the following points:

- While variability in the OT test results was accepted as an issue, most of the participants emphasized that the major concern of focus should be whether the mix passes or fails the specification, i.e., if the number of OT cycles is less than or greater than 300. If it fails the specification, the mix should simply be rejected or redesigned; there is no need to worry about variability. Likewise, if a mix passes the specification, it should simply be accepted; there is no need to start worrying about variability.
- Variability in the OT results is not an unexpected phenomenon bearing in mind that most repeated crack tests, as evident from Monismith's data (SHRP, 1994), are by their nature very variable. Although an acceptable level of the variability could not be agreed upon, some of the participants proposed a COV value of 20 percent or less as acceptable. However, others argued out that this value was practically unattainable.
- To address the issue of high variability resulting in one outlier value among the three tested specimens as per the current Tex-248-F specification, the participants suggested testing more than three replicates, i.e., four or five.
- The general consensus among the participants is that the OT is a rapid test that easily captures the effects of asphalt-binder content and closely relates to crack propagation in the field. Also, the OT is a better discriminator of HMA mixes and can be conducted in a reasonably short time period.
- Thus far, other states have not seen any double cracking in the OT other than what has been reported in the state of Texas, mainly by TTI and TxDOT.

Comparison with Other Crack Tests

All the participants aired the following as some of the OT's major advantages, compared to other crack tests:

- Fast, simple, and reasonable test time.
- Practical and reasonable correlation with field performance.
- Sensitivity to asphalt-binder changes, which means it can easily discriminate and screen mixes.

Glue Type

The participants discussed the variety of glue types that their respective laboratories use for attaching the samples to the testing plates. Table 3-1 lists these different glue types.

Table 3-1. Glue Types Used by Different Laboratories.

#	Institute	State	Glue Type
1	TTI	TX	Devcon Two-Part, 2 Ton Epoxy Resin (16 g/sample)
2	Western Regional Superpave Center, Reno, NV	NV	Devcon Two-Part, 2 Ton Clear Epoxy, Epoxy Resin
3	Mathy Construction, Onalaska, WI	WI	Devcon Plastic Steel 5 Minute (SF)
4	Center for Advanced Infrastructure and Transportation (CAIT), Rutgers University, NJ	NJ	Devcon Plastic Steel 5 Minute (SF)
5	NCAT, Auburn University, AL	AL	Devcon Two-Part 2 Ton Epoxy Resin
6	Highway Sustainability Research Center, UMASS, Fall River, MA	MA	Devcon High-Strength 5 Minute Epoxy S-208 (1500 psi strength)
7	Road Science/ASTM	OK	Devcon Plastic Steel 5 Minute Epoxy Putty

In general, Table 3-1 shows that the seven laboratories represented are using no fewer than five different glue varieties, and this is believed to be one of the possible factors contributing to the differences and variability of the OT results. Besides TTI, none of the laboratories was able to quantify the glue amount its uses per sample. Thus, there is a need to unify the glue type including specifying the quantity and the application procedure.

Suggestions and Ideas for OT Improvement

Based on the meeting deliberations (Appendix G), the suggestions made by the participants on improving the OT repeatability and minimizing variability in the test results are as follows:

- Providing a more thorough and standardized specimen-mounting procedure.
- Providing a standard gluing procedure including glue type and amount to be used on each plate. Evaluating different glue types (quick set versus long set or different strength epoxy) may also prove beneficial and worth investigating.
- Using more than three replicate samples to get acceptable results.
- Modifying the molded sample dimensions to reduce material wastage as well as optimizing efficiency.

SUMMARY

This chapter provided a compilation of the input from several laboratories, both within and outside the state of Texas, in response to the OT survey questionnaire. The laboratories responded with various issues regarding the OT test, such as its applications, advantages, challenges, etc. Evaluation of all this information played a vital role in planning the tasks so as to improve the OT test protocol (i.e., maximize repeatability and minimize variability) as well as in exploring other surrogate crack tests.

CHAPTER 4.
EXPERIMENTAL DESIGN PLAN AND HMA MIXES

Four HMA mix types (Type B, C, CAM, and D) with up to 10 different mix designs were evaluated and are discussed in this chapter. The experimental design including the test plan, HMA specimen fabrication, and air void (AV) measurements are also discussed in this chapter. To wrap up the chapter, researchers provide a summary of key points at the end.

MATERIALS AND MIX DESIGNS

As a minimum, the intent of the experimental design plan for this project was as follows:

- Evaluate at least two commonly used Texas dense-graded mixes, with known poor and good field cracking performance, respectively, preferably a Type C (typically poor crack-resistant) and CAM (good crack-resistant) mix.
- Evaluate at least two asphalt-binder contents: optimum and optimum ±0.5 percent.
- Evaluate at least two asphalt-binder types, with a PG 76-22 included in the matrix.
- Evaluate at least two commonly used Texas aggregate types, typically limestone (relatively poor quality) and crushed gravel or quartzite (good quality).

HMA Mix Types

On the basis of the above experimental design proposal, four commonly used Texas mixes (Type B, C, CAM, and D) with up to 10 different mix designs were utilized and are discussed in this interim report. Table 4-1 lists these mixes and includes the material type, material sources, and asphalt-binder content (AC). Where applicable, names of highways where the mix had recently been used are also indicated in the table. In terms of usage, the selected mixes cover a reasonable geographical and climatic span of Texas, which includes the central, northern, and southwestern regions.

Table 4-1. Materials and Mix-Design Characteristics.

#	Mix Type	Source	Binder	Aggregate	Sample Type	OAC
1	CAM	Bryan	PG 76-22	Limestone + 1% Lime	Both Plant Mix & Raw Materials	6.7%
2	Type D	Chico	PG 70-22	Limestone		5.0%
3	Type D	Atlanta	PG 64-22	Quartzite + 20% RAP		5.1%
4	Type D	Atlanta	PG 64-22	Quartzite + 20% RAP		5.2%
5	Type D	Atlanta	PG 64-22	Quartzite + 20% RAP		5.5%
6	Type B	TxDOT	-	Limestone	Field Core	-
7	Type C	Laredo	PG 64-22	Crushed Gravel + 20% RAP	Both Plant Mix & Raw Material	5.0%
8	Type D	Childress	PG 58-28	Granite + 20% RAP	Plant Mix	4.9%
9	Type C	Fort Worth	PG 70-22	Granite + 15% RAP	Both Plant Mix & Raw Materials	4.6%
10	Type C	Odessa	PG 70-22	Limestone		5.8%

Aggregate Sieve Analysis

In order to accurately reflect the specified aggregate gradation for each mix type and account for the dust particles, adjustments were made to the original aggregate gradation based on the results of a wet sieve analysis. Wet sieve analysis is necessary when adjusting the aggregate gradation because quite often, dust particles and the aggregate fractions passing the number 200 sieve size tend to cling to the surfaces of the particles that are larger than the number 200 sieve size. This phenomenon is often not well accounted for in a given gradation specification.

Wet sieve analysis is basically an iterative process of aggregate sieving, wetting/washing, and drying, followed by subsequent gradation adjustments based on the aggregate mass loss or gain on the individual sieve sizes. For this study, researchers accomplished the analysis based on the TxDOT standard specification Tex-200-F (TxDOT, 2004). On average, three to four iterations were required prior to achieving the final adjustment. After gradation adjustment, new maximum theoretical specific gravities were accordingly determined using the ASTM standard D2041. A wet sieve adjustment does not change the fundamental properties of the gradation but instead gives a more accurate representation of the specified gradation.

HMA SPECIMEN FABRICATION

For the lab-molded samples, the HMA specimen preparation procedure was consistent with the TxDOT standard specifications Tex-205-F and Tex-241-F (TxDOT, 2009). The basic procedure involved the following steps: aggregate batching, wet sieve analysis, asphalt-aggregate mixing, short-term oven aging, compaction, cutting, and, finally, volumetric analysis to determine the AV. Table 4-2 summarizes the HMA mixing and compaction temperatures.

Table 4-2. HMA Mixing and Compaction Temperatures.

#	Asphalt Binder Performance Grade (PG)	Mixing Temperature	Compaction Temperature
1	PG 76-22	325°F (163°C)	300°F (149°C)
2	PG 70-22	300°F (149°C)	275°F (135°C)
3	PG 64-22	290°F (143°C)	250°F (121°C)

Aggregate Batching

For fabricating the lab-molded samples, the aggregates (including recycled materials, when applicable) were batched according to the mix-design sheets (Tex-204-F) based on the Tex-205-F test procedure (TxDOT, 2011). The procedure was carefully followed so that it was consistent with the TxDOT standard specification Tex-205-F. Calculated amounts of dry aggregates for each sieve size were added to the pan along with mineral filler and hydrated lime and were mixed thoroughly. The mixed aggregates were left in the oven at an appropriate mixing temperature.

Mixing and Sample Molding

Once the aggregates reached the required mixing temperature, they were removed and placed in the mixing bowl along with the heated recycled material (RAP). Required amounts of asphalt binder were added and were thoroughly mixed using a mechanical mixer. The mixture was placed into the oven at an appropriate compaction temperature for short-term aging.

HMA short-term oven aging for both lab-molded samples and plant mixes lasted for 2 hours at the compaction temperature consistent with the American Association of State Highway and Transportation Officials AASHTO PP2 aging procedure for Superpave mix performance testing. Short-term oven aging simulates the time between HMA mixing, transportation, and placement up to the time of in situ compaction in the field.

All the HMA specimens were gyratory compacted and molded using the standard SGC according to Tex-241-F (TxDOT, 2009). All the HMA specimens were compacted to a target AV content of 7 ± 1 percent. The specimens were compacted to a height of 4.5 in. in a 6 in. diameter mold, except for those used in molded dimension studies, which had a molded height of either 2.5 in. or 5.0 in.

Cutting of Specimens and AV Measurements

Based on the test specimen geometries and the required OT specimen dimensions, typically only one OT specimen was obtainable from a 4.5-in. long molded sample using a double-blade saw following the standard OT Test Specification Tex-248-F. However, for the molded specimen dimension study, OT samples were also obtained from 2.5 in. tall molded specimens, 5.0 in. tall molded specimens (two OT samples obtained from each), and 4.5 in. tall molded specimens (two OT samples obtained from each).

After the specimens were cut and cored, volumetric analysis based on fundamental water displacement principles as specified in ASTM D2726 were completed to determine the exact AV content of each test specimen. HMA specimens that failed to meet AV specification (i.e., 7 ± 1 percent) were discarded. The good specimens were stored at ambient temperature on flat shelves in a temperature-controlled facility prior to gluing and testing.

SUMMARY

This chapter provided a presentation of the materials and mix designs used in this study. In total, four common Texas mix types (Type B, C, D, and CAM) with up to 10 different mix designs were evaluated. The experimental design including the HMA specimen fabrication, short-term oven aging, and specimen cutting were also discussed.

CHAPTER 5.
OT SENSITIVITY EVALUATION

This chapter discusses the main focus of this project, which was to search for ways to improve repeatability and minimize the variability in the OT test results. To achieve this objective, a step-by-step evaluation of the current Tex-248-F OT test procedure was conducted so as to have an in-depth understanding of the key issues related to the OT testing procedure (Tex-248-F, 2009). Researchers identified and studied up to nine different variables to determine how they could be improved so as to improve the OT repeatability and minimize variability in the test results. The variables evaluated are listed below:

- Number of sample replicates.
- Sample drying method.
- Sample sitting time prior to testing.
- Air-void variation.
- Glue type, quantity, and gluing criteria.
- Temperature variation.
- Test loading parameters.
- Plate gap width.
- Sample dimension (discussed in the next chapter).

Plant mix and raw materials (asphalt binders and aggregates) were collected from various field projects, and extensive laboratory OT tests were conducted by varying the variables for each of these critical steps to analyze the sensitivity of the OT results and variability. For all the sample fabrication process and testing, similar operators and the same OT equipment were used in the TTI lab. This was necessary to exclude the operator and/or equipment effect in the analysis. The following subsections discuss the results obtained from the studies in detail.

NUMBER OF SAMPLE REPLICATES

Testing the appropriate number of replicate specimens is critical to ensure the correct statistical characterization of the HMA cracking-resistance potential from the OT test. The current OT protocol is to test three replicates, as recommended by Zhou and Scullion (2005). For the mixes evaluated, these researchers used statistical analyses to show that testing three samples will yield an error of less than 10 percent. However, unusual failing patterns have been widely reported for one of the three samples, resulting in a number of failure cycles that is significantly different from the other two replicates. Experience has shown that there has always been one outlier out of the three replicates that tends to mess up the results. In this study, options for testing more than three replicate samples were explored.

From a practical point of view based on laboratory experience, when samples are molded in the lab, from either plant mix or raw materials, it is often very difficult to maintain 100 percent mix uniformity, even within the same batch. When mixes are heated in the oven prior to molding, homogeneity of the mixes gets impaired due to segregation of heavier and bigger aggregates within the mixing pan. This leads to one or two samples showing cracking characteristics that are significantly different from the other samples batched from the same pan. One option considered in this study to address this issue was testing five replicate samples and then discarding one or two samples that were outliers. Table 5-1 lists the OT test results (number of cycles) for three different mix types, namely Type C, Type D, and CAM, from five different projects.

Five air-dried and five oven-dried samples were tested in each case (effect of drying procedure on OT results will be discussed subsequently). For each set of samples, COV for all five, best four, best three, and best two samples were reported ("best" subsets were chosen based on the lowest COV consideration). As expected, when all five samples were considered, the results showed a very high degree of variability (in this study, a COV of 30 percent was used as a threshold), with the CAM samples being the only exception. Results became somewhat more repeatable if one dissimilar sample result was discarded (best four). Repeatability kept on improving as fewer replicate samples were considered, and the results were most repeatable when only the best two samples were picked from the five available replicates. Figure 5-1 gives a graphical representation of selecting the appropriate number of replicate samples to minimize variability.

However, by picking only two out of five replicates, one runs the risk of reporting a crack life value that is statistically unrepresentative of the "true" reflective cracking life of the mix. Also, discarding three samples is understandably wasteful and, hence, deemed impractical. As Table 5-1 and Figure 5-1 illustrates, most of the mixes are within the acceptable limit of variability (COV $\leq$ 30 percent) when the best three samples are considered. This observation is also consistent with a practical perspective since while discarding two results, one is supposedly discarding the unrepresentative samples having aggregate structure and distribution different from those of the three remaining samples. Additionally, and as Table 5-1 shows, the average numbers of OT cycles in each case (all five, best four, and best three) do not differ significantly. Therefore, from the findings of this study, it is recommended that five or four replicate samples be tested and then, the three replicate samples that yield the lowest COV should be reported. In the rest of this report, all the reported OT cycles are obtained considering the best three results out of five tested replicates, if not indicated otherwise. A macro was developed to automatically pick the best three results out of four or five tested samples based on the lowest COV; refer to the included CD.

Table 5-1. Effects of the Number of Replicate Samples.

Mix Type	Drying Method	COV (Avg. OT cycles), %			
		All 5	Best 4	Best 3	Best 2
Type D 5.2% AC	Air	68.9 (119)*	21.6 (83)	8.5 (92)	2.9 (96)
	Oven	34.5 (122)	25.1 (135)	6.3 (118)	4.3 (115)
Type D 5.5% AC	Air	61.2 (538)	40.6 (645)	26.1 (527)	12.7 (600)
	Oven	46.7 (396)	36.5 (450)	19.5 (520)	0.7 (579)
Type D 4.9% AC	Air	57.2 (187)	43.3 (217)	31.6 (176)	19.1 (204)
	Oven	61.2 (392)	34.7 (479)	7.5 (560)	0.1 (536)
CAM 6.7% AC	Air	17.2 (928)	0.0 (1000)	0.0 (1000)	0.0 (1000)
	Oven	18.4 (856)	14.9 (903)	6.0 (967)	0.0 (1000)
Type C 5.0% AC	Air	41.7 (20)	32.1 (22)	22.3 (25)	10.1 (28)
	Oven	50.4 (36)	31.2 (29)	15.6 (24)	2.7 (27)

*Values in parentheses indicate the average OT cycles.

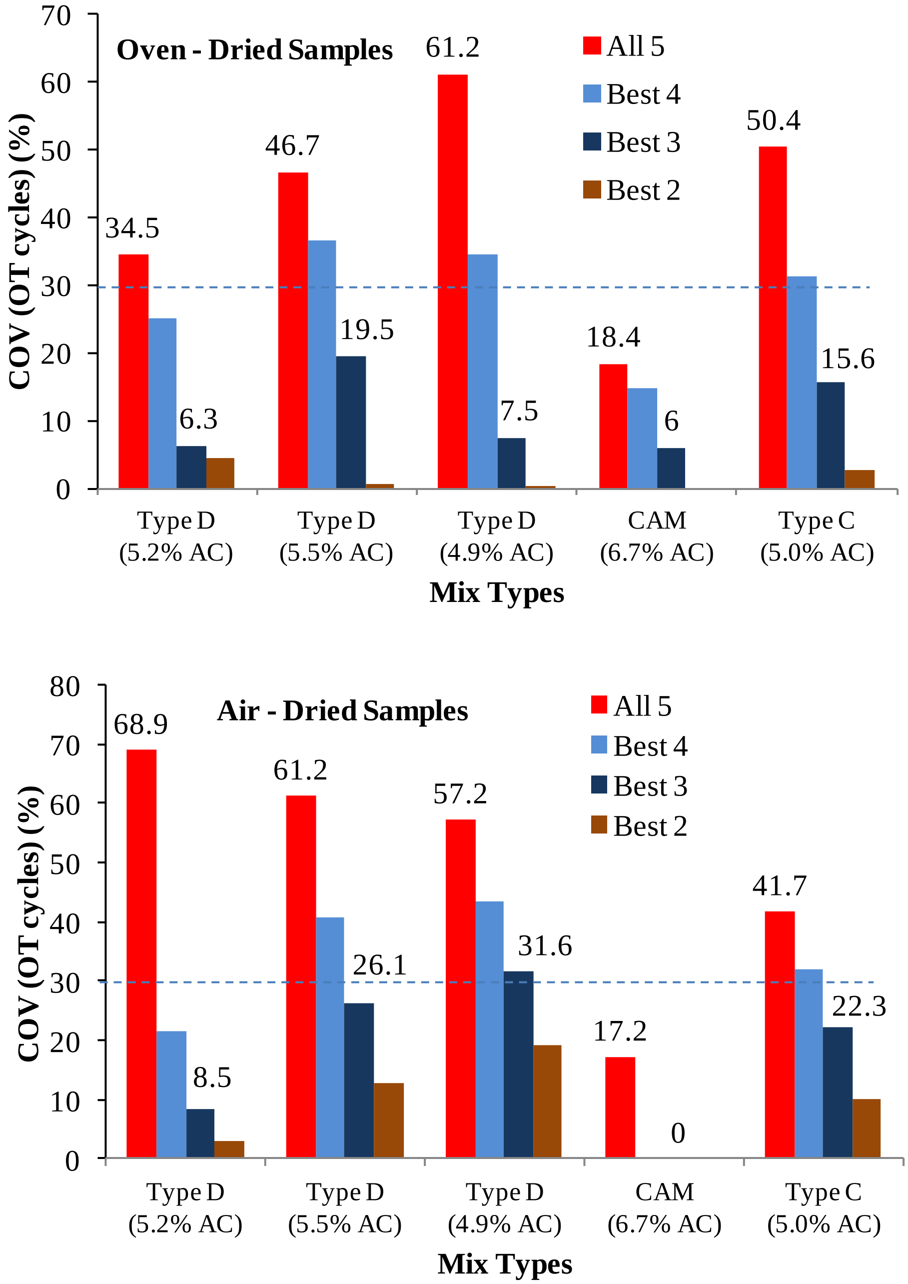


Figure 5-1. Effects of the Number of Replicate Samples on Variability.

SAMPLE DRYING METHOD

After the specimens are trimmed to the target dimensions prior to gluing, they are dried to ensure that all the moisture is removed. The current OT test procedure designation Tex-248-F requires the trimmed specimen to be dried at a maximum temperature of 60 ± 3°C (140 ± 5°F) to constant weight, which is considered to be a very high temperature, particularly for mixes with PG 64-22 asphalt binders. This temperature (60°C) is very close to the upper PG temperature grade of the PG 64-22 asphalt binder, and even higher than that of the PG 58-28 asphalt binder. As such, there is a possibility of overheating or chemically aging the asphalt binder.

Currently, the TTI lab uses overnight air drying in front of a fan at room temperature (25°C), whereas the TxDOT CST lab uses drying in a 40°C (104°F) convectional oven. For consistency and to minimize variability in the OT test results, there is a need to harmonize the sample drying method. In this study, both the air drying (in front of a fan) and oven drying (at 104°F) were evaluated. In each method, samples were dried for a minimum period of 12 hrs and, thereafter, weighed at 1 hr intervals until the sample reached a constant weight. Caution was taken to ensure that the samples were not aged by extended drying in the oven. The results for the mixes evaluated are shown in Figure 5-2.

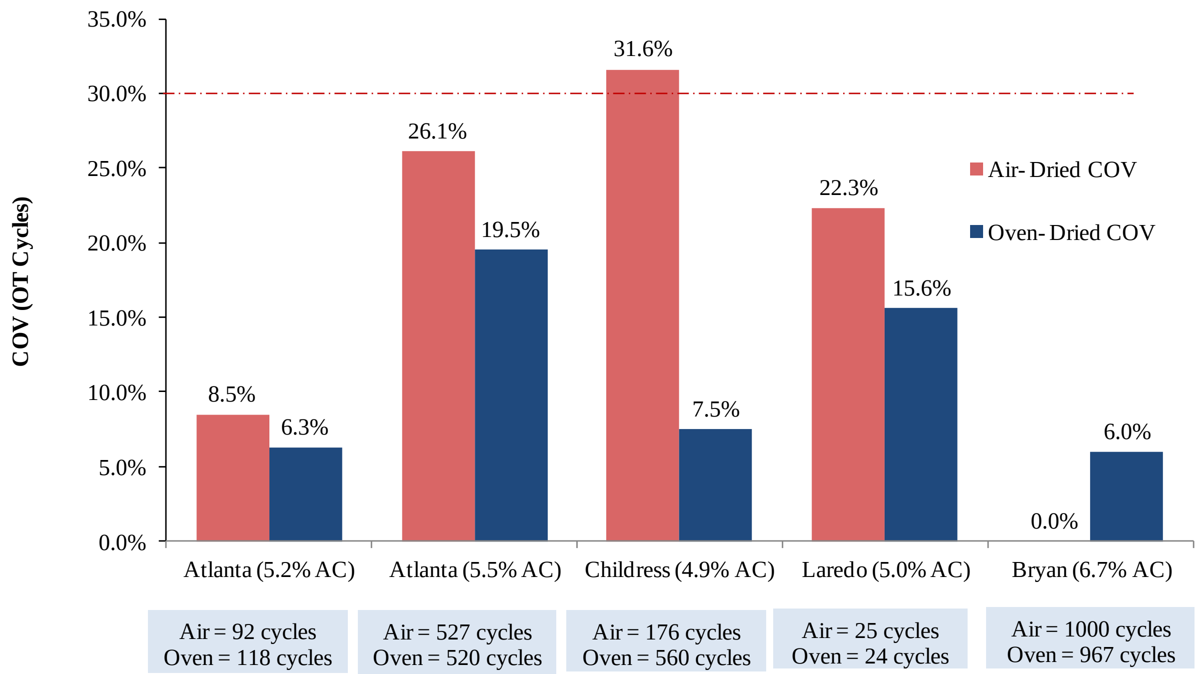


Figure 5-2. Effects of the Sample Drying Method on Variability in OT Test Results.

It is clear from Figure 5-2 that although the OT cycles do not differ significantly, except for the Type D3 mix, oven drying of the samples produces much more repeatable results with lower COV. This trend is evident for all the five mixes that were tested. The zero percent COV obtained for the CAM1 mix is due to the fact that four out of the five samples that were tested did not fail before 1000 cycles (a threshold where the TTI OT machine is automatically set to stop running), and hence, an OT failure cycle of 1000 was assigned to each of these samples. Therefore, zero percent COV in this case does not represent zero variability in replicate behavior.

The improved repeatability of the OT results in the case of oven drying is, however, a fairly expected behavior because oven drying provides a uniform heating environment at a constant temperature; therefore, a more uniform drying of the samples and complete moisture removal may be achieved. In the case of air drying, on the other hand, samples are subjected to atmospheric room temperature variations; hence, a uniform drying environment is difficult to achieve. Expectedly, more uniformly dried specimens lead to more repeatable test results.

The significant difference in the OT cycles for the Type D3 mix in terms of air- versus oven-dried samples could be attributed to incomplete moisture removal from the air-dried samples that negatively impacted the OT performance of the samples. In general, the presence of moisture has a tendency to reduce the crack-resistance potential of HMA mixes. Although constant weight was attained, it is possible that there was incomplete moisture removal, particularly related to the fluctuating ambient temperature.

Based on these results, the best drying method is therefore to use oven drying at 104°F (40°C) for a minimum period of 12 hours to constant weight, but not to exceed 24 hours. The challenge, however, is whether the different laboratories will have the capacity to possess and consistently maintain a 104°F (40°C) oven every time OT sample drying is required. As an alternative, use of the core dryer was also explored, but unsuccessfully. Table 5-2 gives a comparative illustration of the OT cycle COVs obtained from core-dried samples alongside air- and oven-dried sample results for two mixes.

Table 5-2. OT Cycle COV for Core-Dried Specimens.

Mix Type	**COV (OT cycles), %**		
	Air-Dried	Oven-Dried	Core-Dried
CAM	0.0 (1000)	6.0 (967)	9.0 (510)
Type D1	8.5 (92)	6.3 (118)	21 (91)

* Values in the parentheses indicate the average OT cycles.

From Table 5-2 and for the two mixes evaluated, it is clear that the core-dried samples show higher variability in OT cycles than both air- and oven-dried samples, although in the case of both mixes, COV values were within an acceptable range (<30 percent); see more results in Appendix H. The distinct advantage of using a core dryer, however, is that samples can be dried significantly faster than with the other two methods. A set of five OT samples can be dried within an hour, whereas both the other two methods require overnight drying of the samples. As shown in Appendix H, however, oven drying at 104°F proved to be the best method.

SAMPLE SITTING TIME PRIOR TO TESTING

Age hardening and embrittlement of HMA during service is an issue of great concern among the pavement engineering community. Aging of HMA is primarily due to factors such as volatilization, oxidation, and steric hardening of the asphalt binder in the mix. However, all these factors take a much longer time to affect HMA performance (long-term aging) and, therefore, are not expected to greatly affect the OT results of samples aged for 3 to 5 days. Nonetheless, the researchers deemed that it is necessary to study the effects of sample sitting time on the variability of the OT results in this study.

In the current OT test setup, the minimum attainable sitting time for the OT samples from the day of molding before they are ready for testing is 3 days. This period is accounted for by the time taken in cutting, drying, measuring AV, and gluing the samples. This particular task evaluated the effects of the samples' sitting time on the OT result variability. The samples were stored at room temperature for a number of days ranging from 3 to 60 days from the day of molding. Figure 5-3 presents the effect of sample sitting time on the OT test results for Type C (Laredo) and CAM (Bryan) mixes.

Figure 5-3 shows the variation of the average OT cycles and the OT cycle COV with sample sitting time varied between 3 and 15 days. Both mixes show similar trends for the average OT cycle variation. Results show a slight initial decline in average OT cycles (3 days to 5 days) and a much more noticeable decline when samples are stored for 7 days. This large decrease in OT cracking performance can be attributed to the initiation of oxidative aging after 5 to 7 days. The cracking life seems to steady after 7 days. The COVs of the OT cycles, on the other hand, show no definitive trend with variation in the sitting period. In both cases, however, the COV exhibits a peak at 7 days.

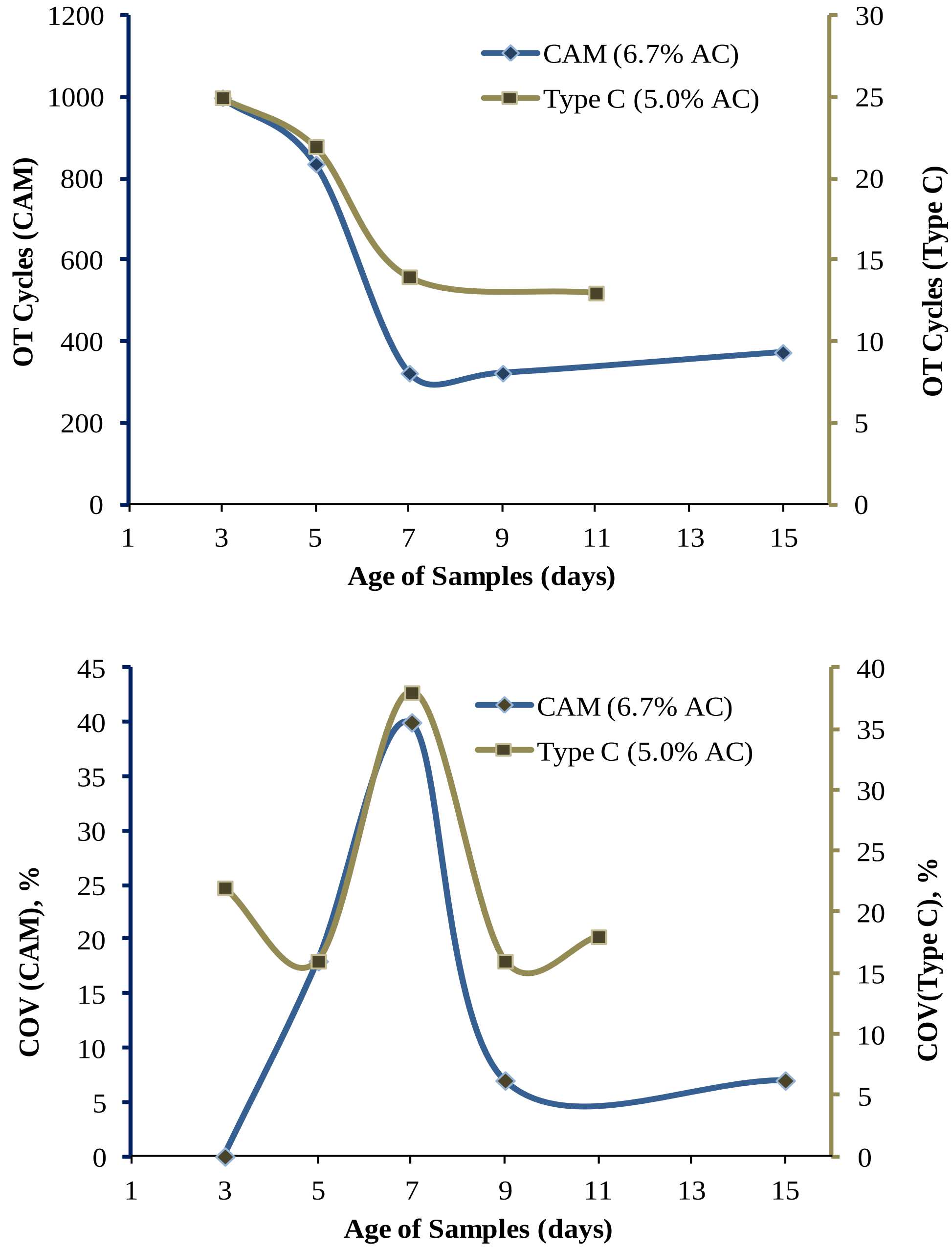


Figure 5-3. Effects of Sample Sitting Time from Day of Molding to Day of Testing.

To further study the effects of sample sitting time, another mix, namely Type D (5.0 percent AC) from the Chico District, was tested at different sample sitting periods, but only a total of three (not five) replicate samples were molded and tested for each sitting condition. Figure 5-4 presents the effects of sitting time on the OT results for Type D Mix.

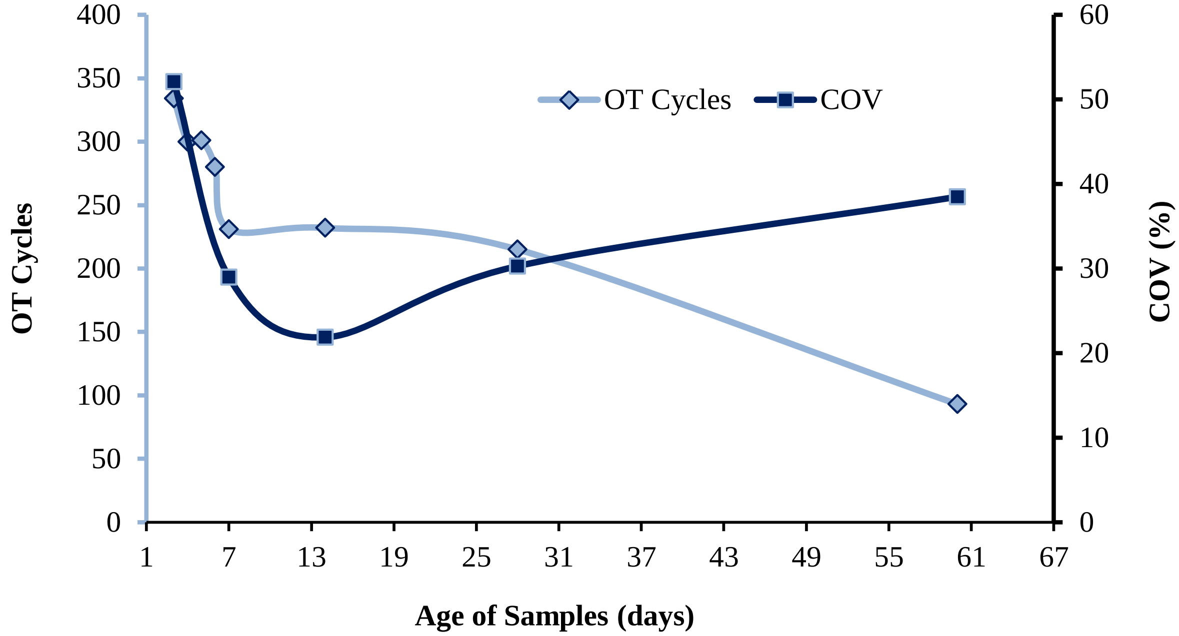


Figure 5-4. Effects of Sitting Time of the OT Results for Type D Mix.

The variation of the average OT cycles for the Type D mix (Figure 5-4) shows a trend very similar to what was observed in Figure 5-3 up to 15 days of sitting time. The samples kept beyond 28 days prior to testing showed greater decrease in the average OT cycle values due to the long-term oxidative aging effects. Once again, no definitive trend was observed in the case of the COV variation. The recommendation from this study is that all replicate samples should preferably be tested within 3 to 5 days from the day of sample molding to get consistent results and minimize the effects of initial oxidative aging on the OT crack performance.

The finding of this task poses a scope for one relevant investigation: how is variability in the OT test results affected if samples with different sitting times are tested and the results are presented together? The practicality of this investigation comes from the fact that sometimes it becomes difficult to test all replicate samples on the same day or same week and, therefore, test results from samples with different sitting times might necessarily be reported together. Especially test specimens of some of the more crack-resistant mixes (e.g., CAM) with higher average OT cycles might take too long to finish testing, and therefore, it might be difficult to test all replicates on the same day. Figure 5-5 shows variability of the OT test results when results from samples with different sitting times are combined; variability is reported for two mix types, namely Type C and CAM mixes.

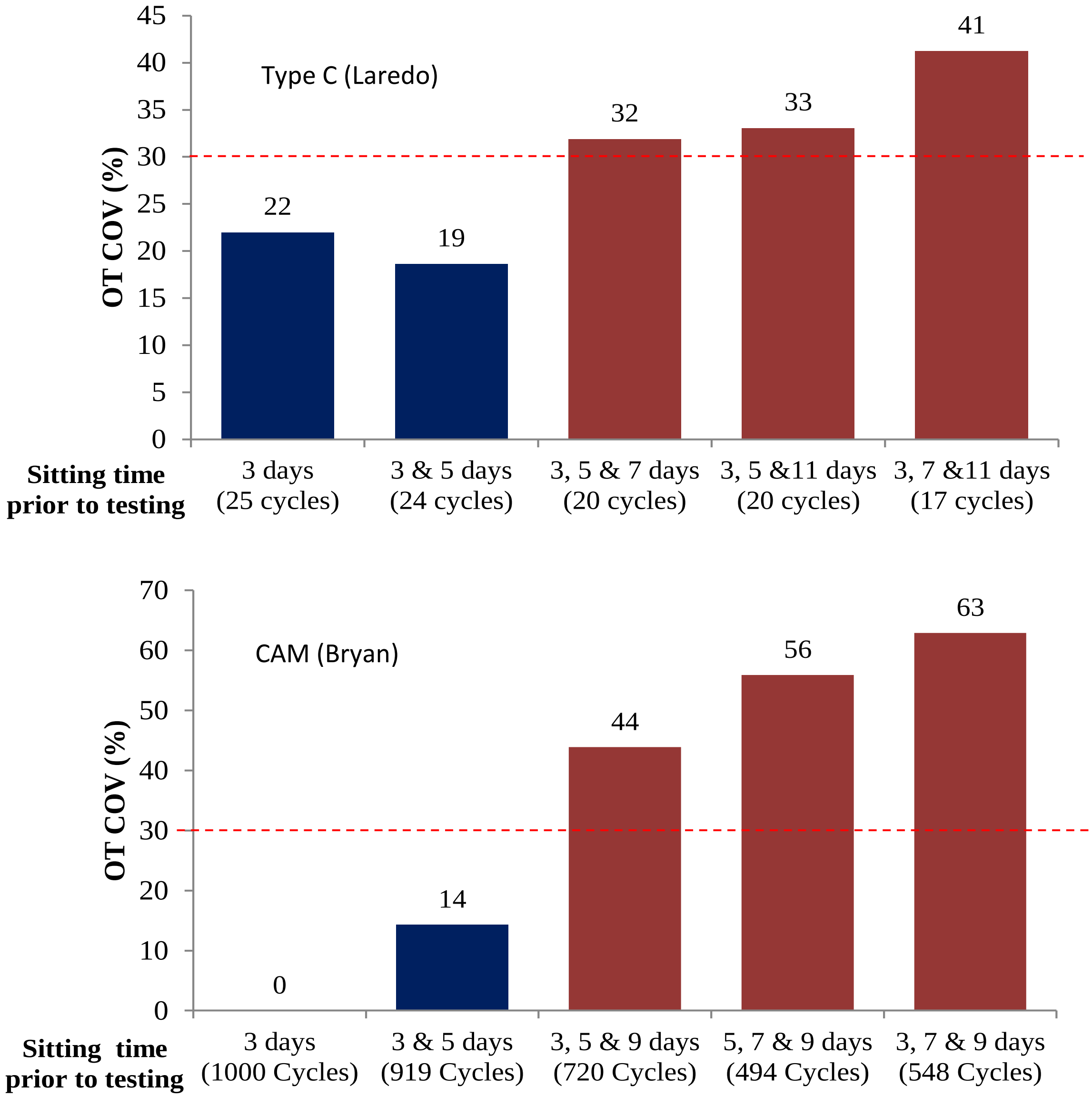


Figure 5-5. Effects of Mixed-Sample Sitting Time.

For both mix types, variability in the results is within acceptable limits (i.e., COV<30 percent) if all the samples are tested within 5 days of molding. Variability becomes very high when some of the replicate samples are rested for up to 7 days or more prior to testing. Conclusively, these results suggest that testing of all replicate specimens should preferably be completed within 5 days of molding to get more consistent results. That is, once molded, all replicate samples for a given mix, say mix A, should preferably be completed within 5 days. Otherwise, the time period from the day of molding to the actual day of testing of each specimen should be recorded and reported as part of the results.

As an integral part of this task, the source of the variations in the OT cycles as a function of the sitting time was also evaluated. Towards this goal, neat asphalt binders were subjected to the same heating and sitting conditions at ambient temperature as the OT samples and then tested in the dynamic shear rheometer (DSR) for the high temperature rheological property characterization. Results of these investigations for up to 40 days sitting time for the asphalt binders are shown in Figures 5-6 and 5-7.

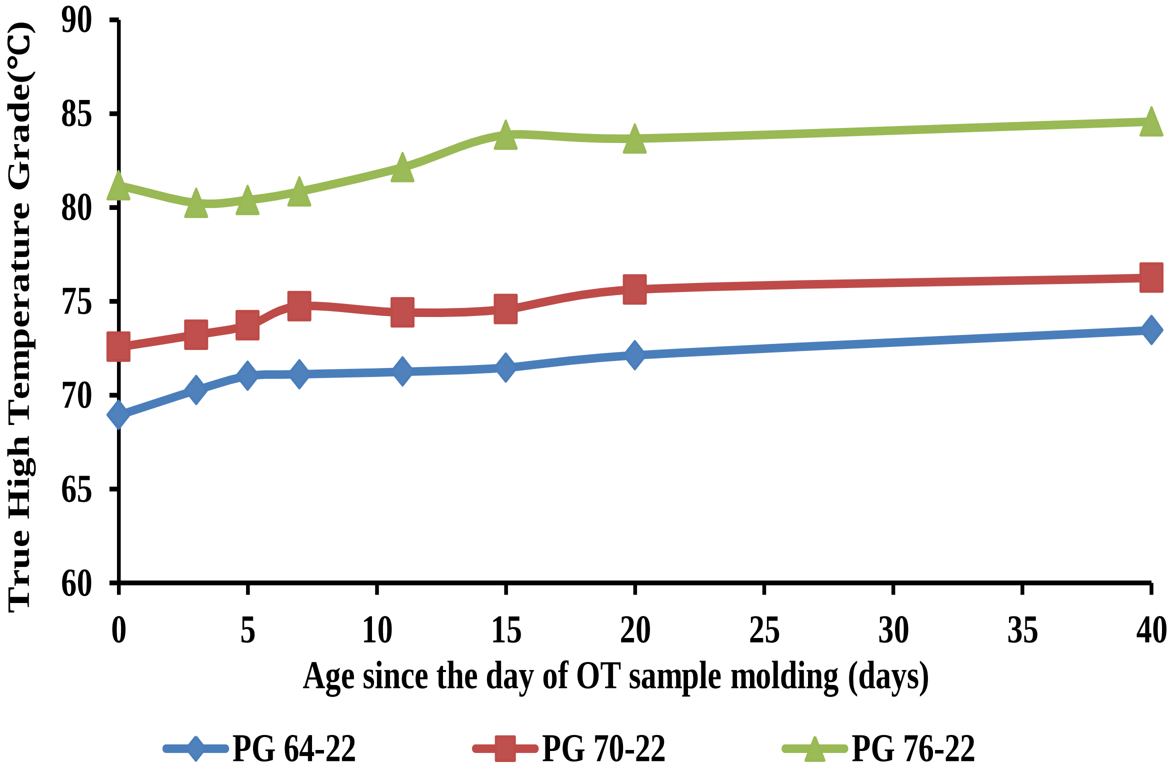


Figure 5-6. Asphalt Binder Shear Modulus as a Function of Sitting Time.

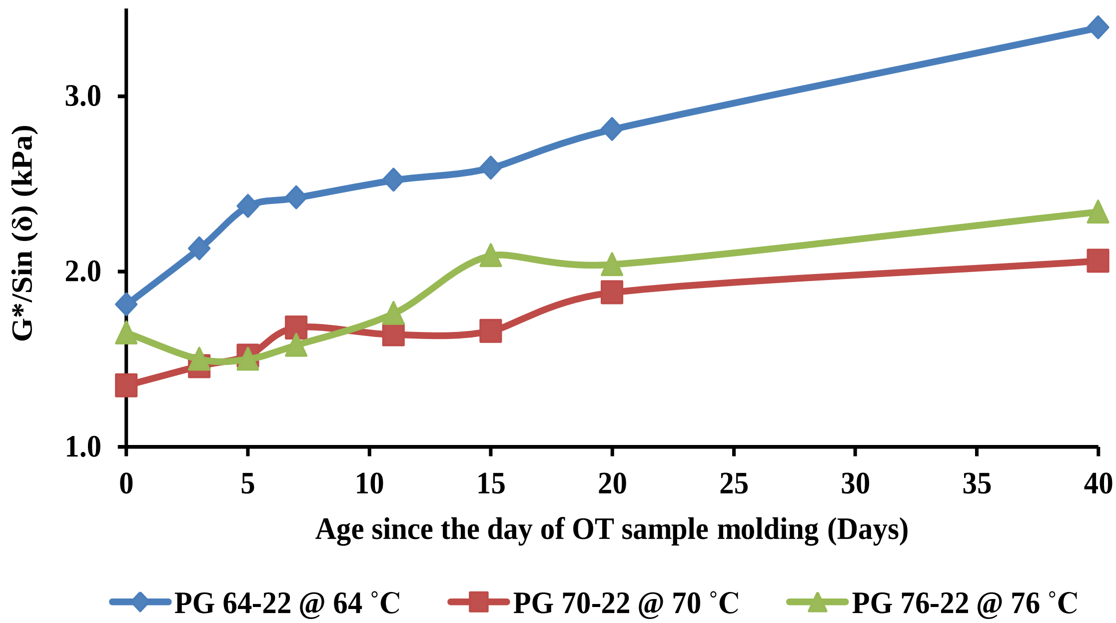


Figure 5-7. Asphalt Binder True High Temperature Grade as a Function of Sitting Time.

As the figures show, there is a considerable stiffening effect of the asphalt binder with an increase in the sitting time; both the complex shear modulus and the true temperature grade tend to increase with an increase in the sitting time of the asphalt binders. This is attributed to the initial oxidative aging of the asphalt binders, and clearly, the PG 64-22 exhibits more sensitivity. Due to the longer sitting time, the asphalt binders begin to oxidize and become stiffer (i.e., higher G* and true grade temperature values), thus making the overall mix stiffer and brittle with a decreased resistance to cracking, hence the decreasing number of OT cycles with increasing sitting time.

VARIATION IN THE AIR VOIDS

The typical target air-void level for lab-molded overlay samples is 7 ± 1 percent (TxDOT, 2004). But due to the heterogeneous nature of the HMA, sometimes it becomes difficult to maintain 100 percent uniformity in the OT specimen air voids, which is thought to be one of the major contributing factors toward the variability of the OT results. To better characterize the effects of specimen air voids on the OT result variability, researchers conducted a study by testing OT samples at different air-void ranges. Three mixes were considered for this study, and Table 5-3 presents the results.

Table 5-3. OT Results at Different Air-Void Ranges.

AV range	Chico Type D		Atlanta Type D		Laredo Type C	
	Average	COV	Average	COV	Average	COV
5.0%–5.5%	-	-	83	66%	-	-
5.5%–6.0%	-	-	176	0%	55	29%
6.0%–6.5%	89	11%	187	72%	49	13%
6.5%–7.0%	254	6%	116	6%	92	8%
7.0%–7.5%	80	9%	144	11%	53	23%
7.5%–8.0%	162	44%	188	25%	-	-
8.0%–8.5%	165	60%	-	-	-	-

From Table 5-3, it is evident that the test results are most repeatable when the AV ranges from 6.5 percent to 7.5 percent. It is also observed that in the case of the Atlanta Type D mix, the average OT cycles do not vary much between the AV range groups. This is also true for the Laredo Type D mix, with the exception of the AV range 6.5 percent to 7.0 percent where the average OT cycles is significantly higher than the other groups. The effect of specimen air voids on OT variability is better demonstrated in Figure 5-8.

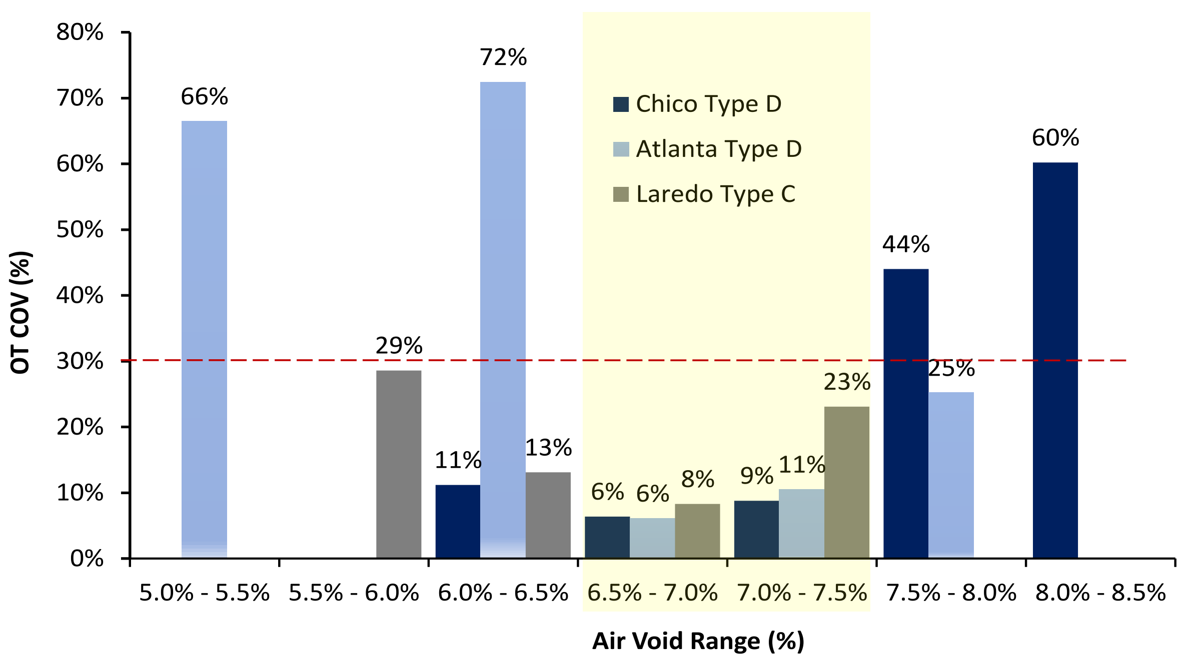


Figure 5-8. Effects of Specimen Air Voids on OT Variability.

Figure 5-13 reconfirms that OT specimens having AV values between 6.5 percent and 7.5 percent are the most repeatable with the lowest COV values. Only one Atlanta Type D specimen was tested at the AV range of 5.5–6.0 percent; therefore, a 0 percent COV value does not indicate zero variability in this case. More specimens need to be tested to determine the true OT variability at this AV level. The preliminary conclusion drawn from this study is that the target OT specimen AV should be 7 ± 0.5 percent. However, this tolerance limit may be considered to be too tight. For practicality purposes, 7 ± 1 percent may therefore still suffice.

GLUE TYPE, QUANTITY, AND GLUING METHOD

The current Tex-248-F OT testing procedure calls for using 2-part, 2-ton epoxy for gluing the samples to the OT testing plates. While Tex-248-F specifies the detailed properties of the glue type, it does not have any specific instructions on the amount of glue to be used or how the glue should be applied. To address this aspect, researchers investigated three different glue quantities (14, 16, and 18 g). Figures 5-9 and 5-10 show results for a CAM mix.

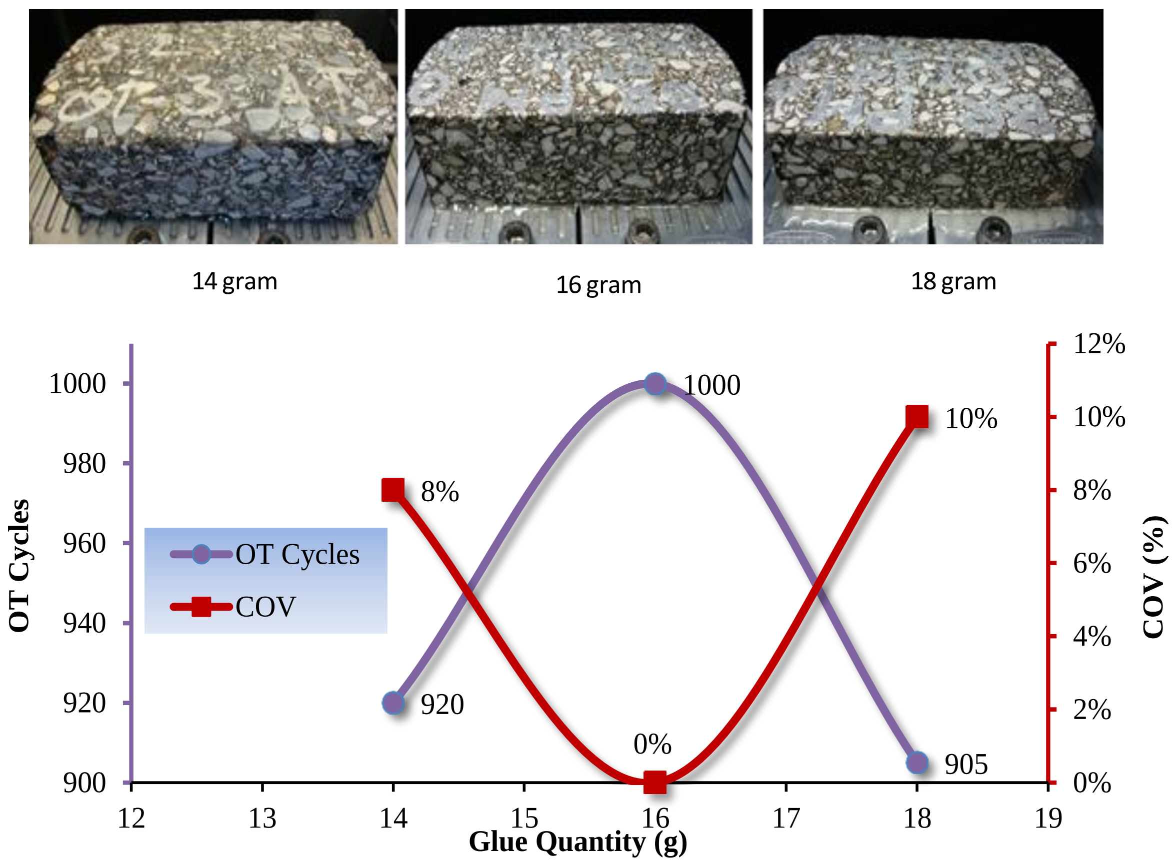


Figure 5-9. Effects of Glue Quantity on OT Cycle Variability.

It is very clear from Figure 5-9 that both the average OT cycles and COV reach optimum level when about 16 g of the 2-part, 2-ton epoxy is used to glue the samples to the OT plates. For the OT plates utilized, 14 g was found to be insufficient, while 18 g was too excessive and wasteful with too much spillage (Figure 5-9). Figure 5-10 shows the OT maximum loads for varying glue quantities, and it can be seen that the OT maximum load values are most repeatable when 16 g of glue is used.

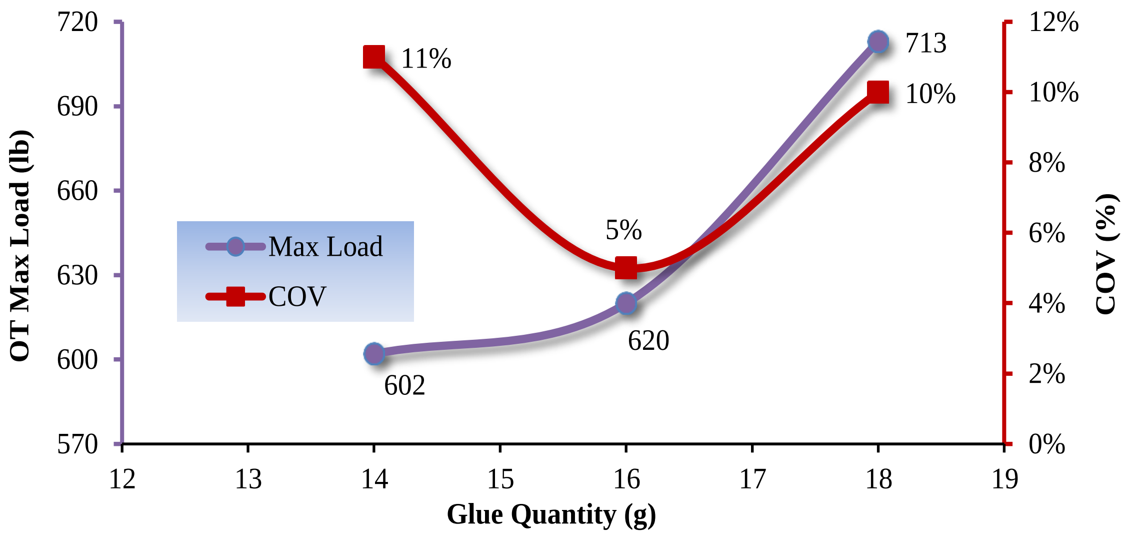


Figure 5-10. Effects of Glue Quantity on OT Max Load.

However, the 0 percent COV in the case of 16 g glue quantity does not necessarily represent zero OT cycle variability. The OT machines that are currently used in TTI labs are programmed to stop running once a sample has endured 1000 cycles of loading, which was the case for four of the five tested replicates. Therefore, to obtain the true OT cycle variability of the samples at 16 g glue quantity level, the samples need to be retested while allowing the machine to run beyond 1000 cycles or the data can be extrapolated to approximate the failure cycles. At this point, the researchers are planning to test more mix types to further study this issue.

To further investigate the overall process of attaching the specimen to the OT plates, the researchers tried using several other different glue types. Table 5-4 lists the glue types used for this study and their properties. From the preliminary observations, it is evident that the Devcon plastic steel epoxy putty is the least suitable of the three glue types. It is more expensive, and the curing time is considerably high. Also, workability issues have been reported by the laboratory technicians regarding this particular glue type (putty). The Devcon high strength epoxy, on the other hand, has a very low curing time but is almost twice as expensive as the Devcon 2-part, 2-ton epoxy and has considerably lower strength. Figures 5-11 and 5-12 present the results from OT tests for the different glue types.

Table 5-4. Properties of the Alternate Glue Types.

ITEM	 **Devcon Plastic Steel 5 Min Epoxy Putty**	 **Devcon High Strength Epoxy**	 **Devcon 2-Part, 2-Ton Epoxy S-31**
Strength (psi)	None listed	1500	2500
Curing time (to full strength)	16 hours (overnight)	15 minutes (overnight)	2 hours (overnight)
Price ($/item) @ time of report	43.00/1 lb container	6.25/tube (two sets)	3.50/tube (two sets)
Price ($/specimen) @ time of report	5.37	4.68	2.62
Quantity req. (grams/specimen)	64 ± 0.5	16 ± 0.5	16 ± 0.5
Comment	Workability issues with weighing, spreading, and cleaning, costly.	OK but relatively costly	OK

Figure 5-11 shows that for the mixes tested, the high-strength epoxy gives better overall OT performance marked by an increase in the average OT cycles and a decrease in OT variability, although one might argue that the high strength epoxy fails to distinctively differentiate between the two Type D mixes from two different sources. Also, the COV values for all the mixes are within acceptable limits for both the glue types; but with the former being about 79 percent more expensive than the later was at the time of this report. Due to the workability issues mentioned in Table 5-4, the ‘Plastic steel five minute epoxy putty’ was excluded from further evaluation; hence no results are reported in Figures 5-11 and 5-12. Based on the above test results and subsequent discussions, the 2-part 2-ton epoxy at 16±0.5 g (or 16±0.5 ml) is the best choice considering economy, workability, performance, and consistency in the OT results.

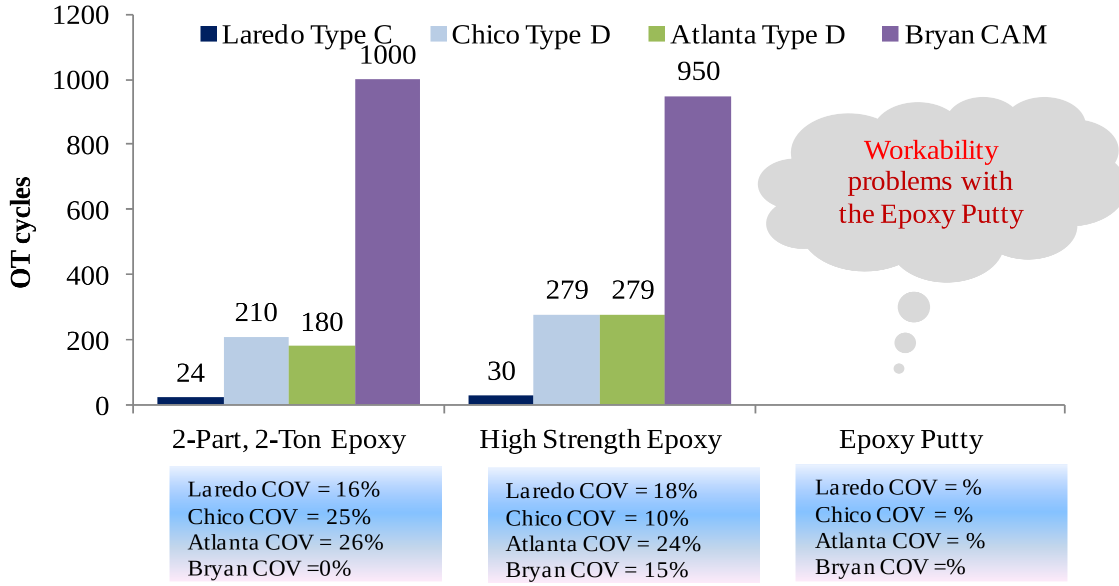


Figure 5-11. Effects of Glue Type on OT Cycles.

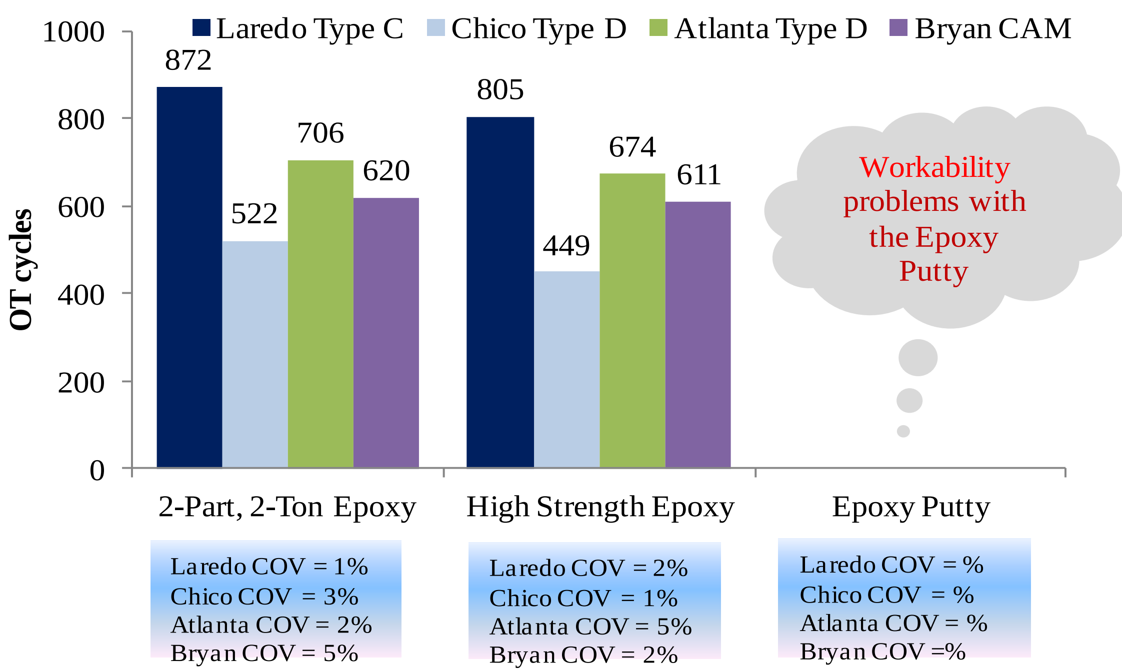


Figure 5-12. Effects of Glue Type on OT Max Loads.

TEMPERATURE VARIATIONS

According to the current OT test specification (Tex-248-F, 2009), OT tests are run at a temperature of 77 ± 1°F. To attain this temperature, the specimens are conditioned in a temperature-controlled room for about 24 hours. To study the effects of temperature on the variability of the OT test results, two mix types, namely, a Type C with 5.0 percent AC and a Type D with 5.1 percent AC were tested at five different temperatures (73, 75, 77, 79, and 81°F). Figures 5-13 and 5-14 present the OT results for the Type C mix and Type D mix, respectively. The corresponding changes in the OT peak loads with temperature for the same two mixes are presented in Figures 5-15 and 5-16.

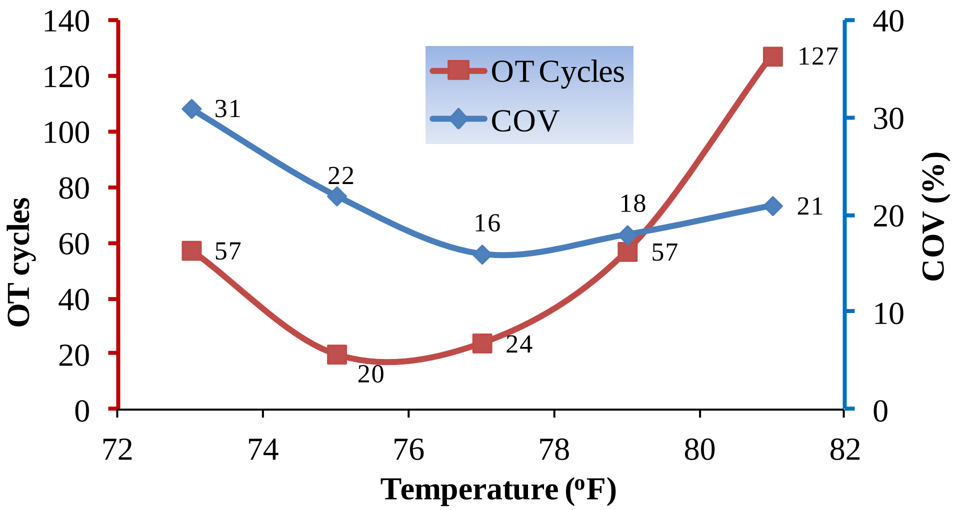


Figure 5-13. Effects of Test Temperature on OT Cycle Variability (Mix Type C).

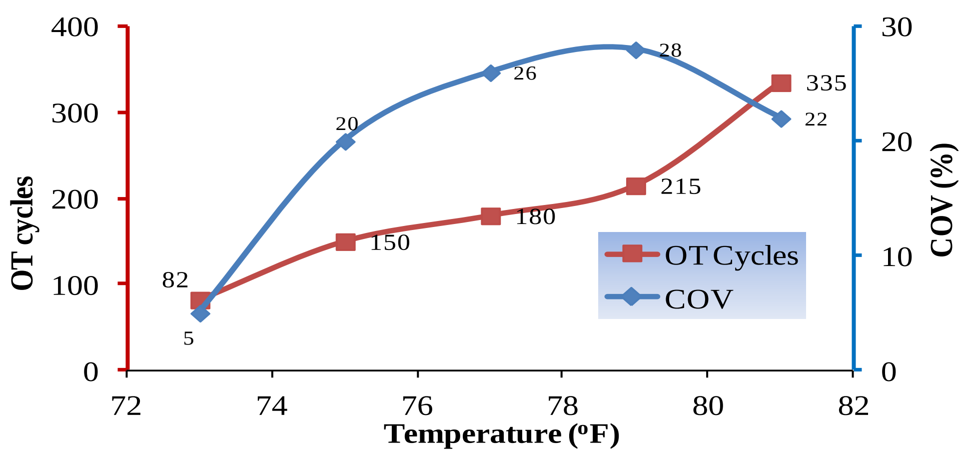


Figure 5-14. Effects of Test Temperature on OT Cycle Variability (Mix Type D).

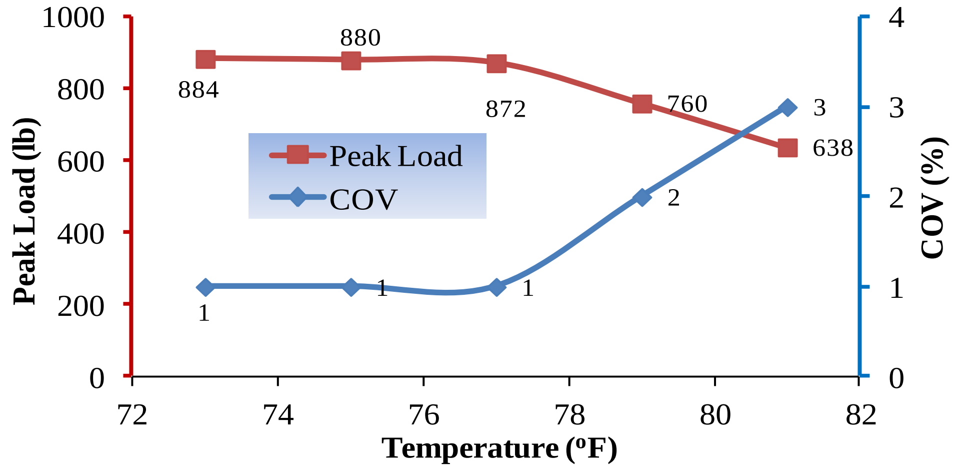


Figure 5-15. Effects of Test Temperature on OT Peak Load Variability (Mix Type C).

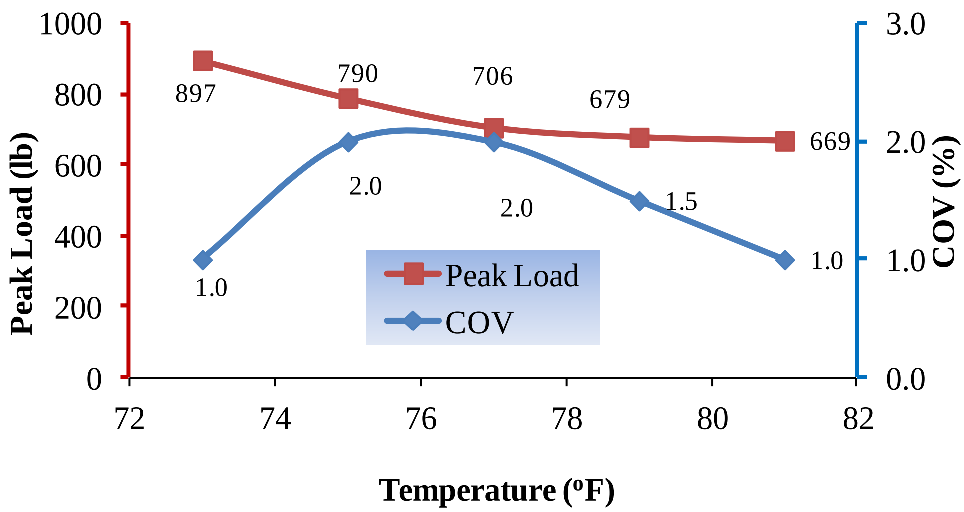


Figure 5-16. Effects of Test Temperature on OT Peak Load Variability (Mix Type D).

Analyzing the results shown in the Figure 5-13 through 5-16, the following conclusions can be drawn:

- In general, the OT cycles to failure show increasing trend with increasing temperature. This is somewhat expected behavior, since at higher temperatures the asphalt binder becomes softer and as such, the HMA mix displays a much more ductile failure mode. This change becomes very significant when the temperature differential exceeds ± 2°F.

- No definitive trend for the OT cycles variability (COV) is observed. In fact, the COV values display completely opposite trends with varying temperature for the two mixes that have been tested.
- The peak load decrease with increasing temperature as theoretically expected due to the mixes getting softer.
- Based on the above discussions, the researchers recommend continuing with the current practice of 77°F or any desired target test temperature for OT testing, but with a tolerance of ± 1°F and not to exceed ± 2°F. However, it should be noted here that the TTI OT machines are all programmed and set to operate within a temperature tolerance of ± 0.5°F.

TEST LOADING PARAMETERS AND REST TIME

Currently the OT test protocol specifies a 0.025 in. opening displacement for each loading cycle. In this study, the researchers tested the effect of the opening displacement on the OT results and OT result variability. A Type C plant mix (5.0 percent AC) was tested at three different opening displacements including the currently practiced 0.025 in. The other two opening displacements were 0.015 in. and 0.020 in, respectively. The results are presented in Figures 5-17 and 5-18.

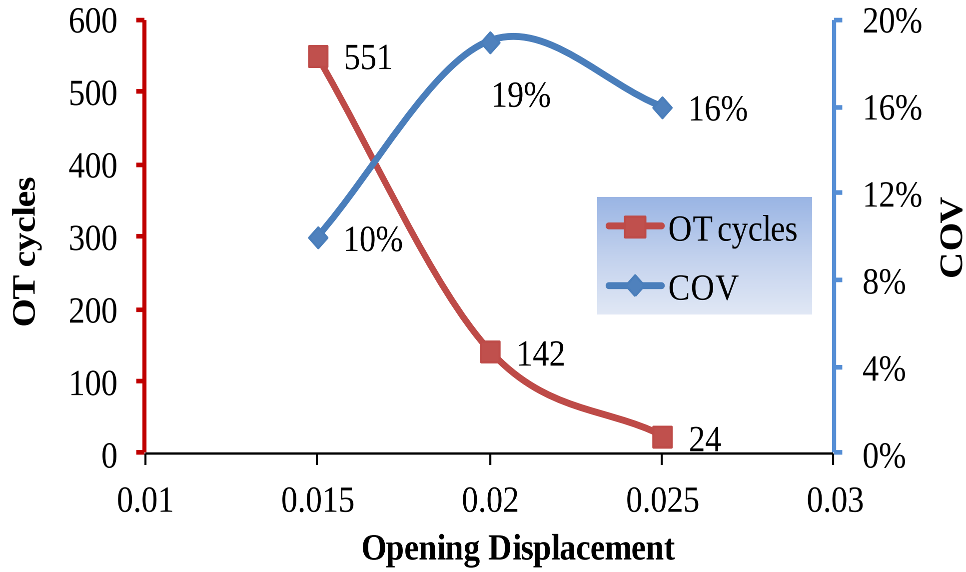


Figure 5-17. Effects of Opening Displacement on OT Cycle Variability (Mix Type C).

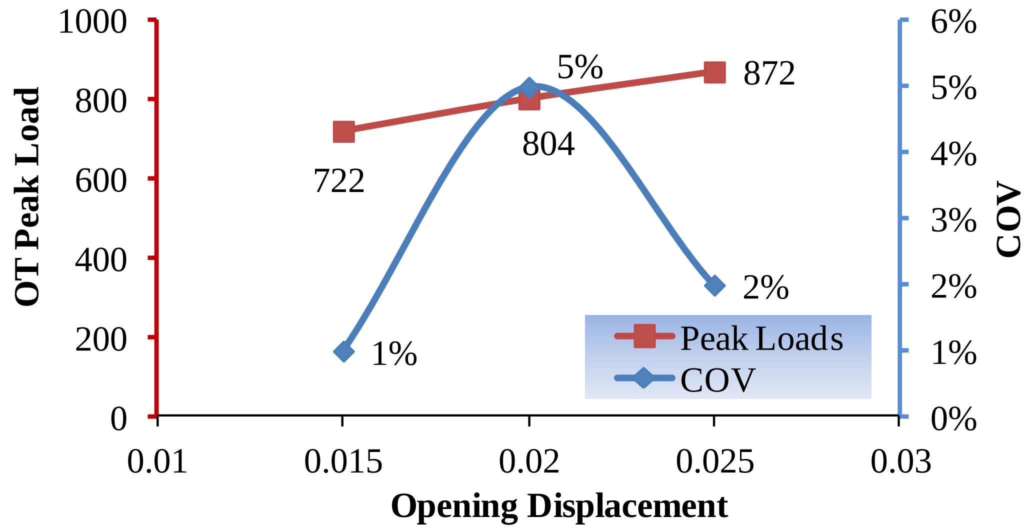


Figure 5-18. Effects of Opening Displacement on OT Peak Load Variability (Mix Type C).

From Figure 5-17, it is noticed that the OT variability does not show any definitive trend of variation with changing opening displacement. Also evident from the figure is that the average OT cycles decrease significantly with increasing opening displacement. From Figure 5-18, a marginal increasing trend is observed with increasing opening displacement. This behavior, however, is not unexpected. With smaller opening displacements, the specimens are less tortured at each loading cycle and hence, the cycle peak load would be less and the specimens would endure a much higher number of loading cycles before failing. However, it needs to be noted that this HMA mix (Type C 5.0 percent AC plant mix) usually has poor cracking performance (Table 5-1) at the regular OT testing with 0.025 in. opening displacement. Based on the results of this study, the researchers expect the average OT cycles to failure to be much higher (above 1000 cycles) in case of some of the more crack resistant mixes (e.g., CAM, Type D) when the opening displacement is reduced. In general, the following was concluded from this study:

- Decreasing the loading rate from 0.025 to 0.015 in. improves performance, but without major changes in the peak load or variability.
- However, reducing the test loading rate may erroneously pass poor crack-resistant mixes (i.e., majority of the Texas mixes may even last over 1,000 cycles) and also requires validation with field data.
- A similar trend was also observed for varying the loading and unloading time.

Overall, since changing the loading rate does not improve repeatability nor reduce variability in the OT test results and the fact that there is lack of field validation to support the proposal to the modified loading parameters; these researchers recommend maintaining the current load settings of 0.025 in. opening displacement and 10 sec/cycle.

Once the sample is bolted into the OT machine and temperature equilibrium has been reached, a rest period prior to actual testing needs to be defined to allow for elastic recovery due to tightening of the screws among other factors that may negatively impact the results. Rest periods of 5, 10, 30, and 60 minutes were investigated. Test results showed that a minimum rest period of 10 minutes (i.e., ≥ 10 minutes) was sufficient to yield consistent results. Automation of starting the OT test with a time counter is also recommended to optimize the efficiency of operations.

PLATE GAP

In the current practice of OT testing, the gap width between the pair of OT plates is 2 mm with the use of a 1/4 in. tape. A special arrangement of base-plate is used to achieve this plate gap width with a 1/4 in. tape used over the gap while the specimen is glued to the plates. In this study, the effects of plate gap width were examined along with a new set of OT plates were used for this study.

The two test arrangements tried for this study are shown in Figure 5-19. In the first arrangement, old plates were used with a 2 mm plate gap width and 1/4 in. (6.25 mm) wide black tape. The second arrangement had new plates at a gap width of 1/4 in. (6.25 mm) and a metal bar in between the plates as a seal. The test results are presented in Figures 5-20 and 5-21.

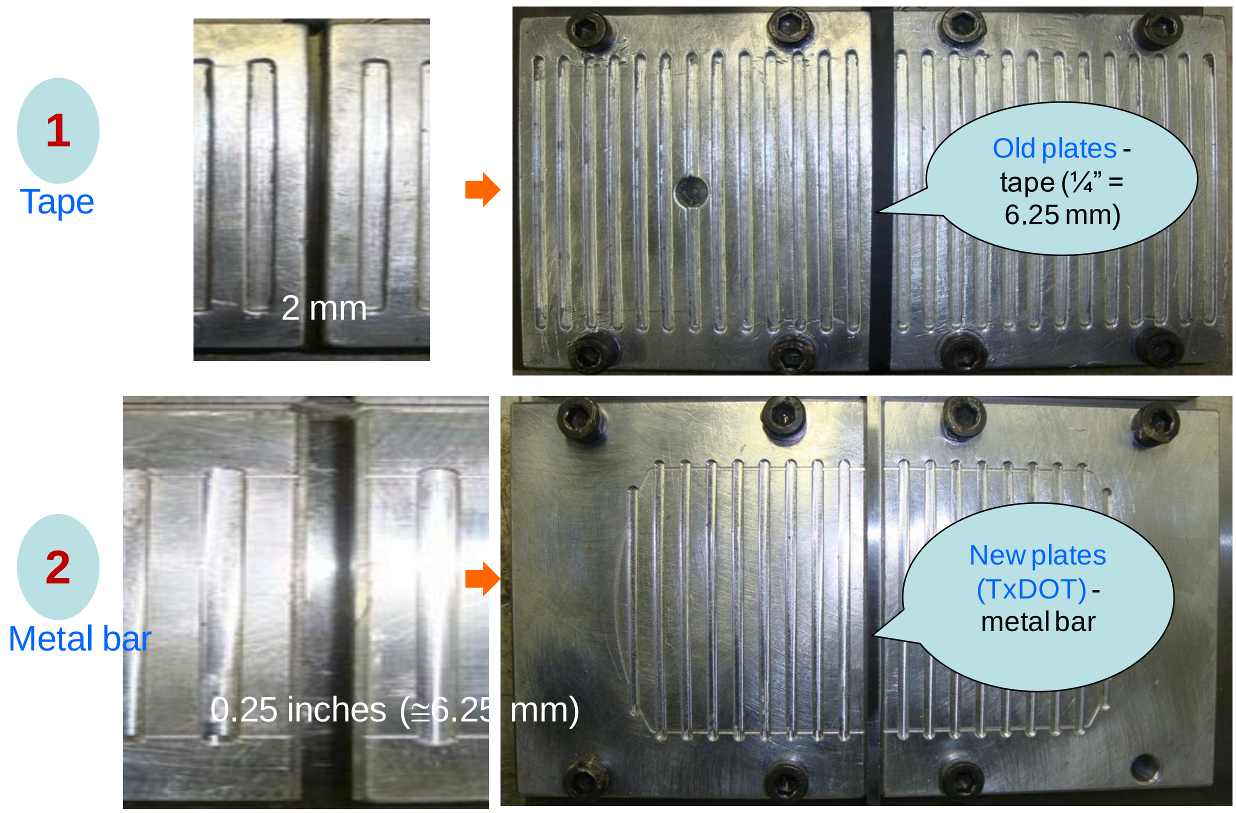


Figure 5-19. Plate Gap Width – Old Plates (Tape) versus New Plates (Metal Bar).

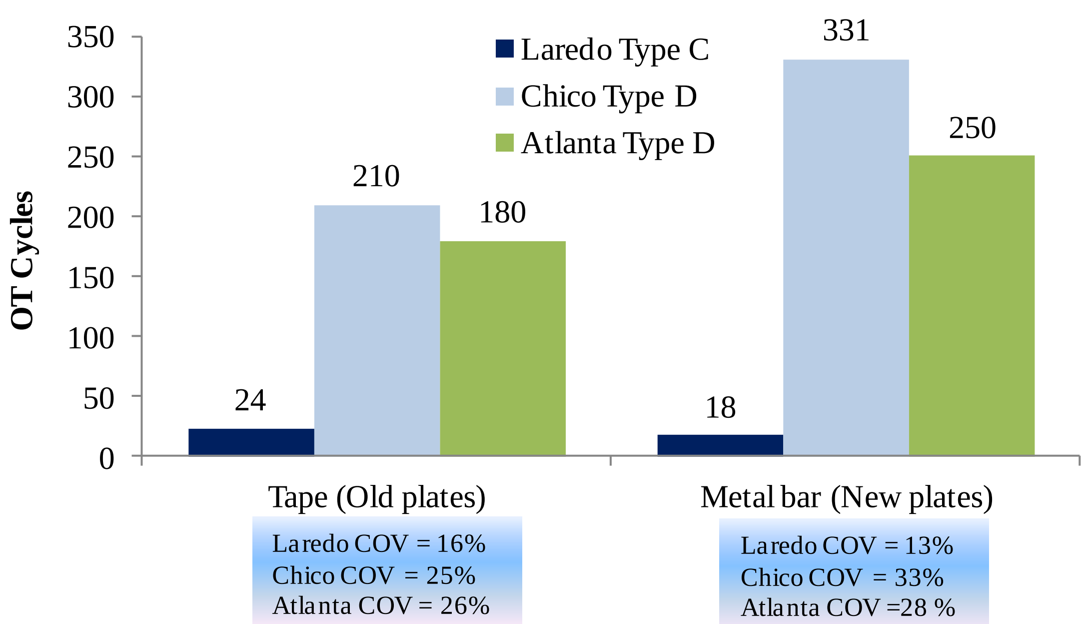


Figure 5-20. OT Test Results (Cycles) for Two Plate Gap Width/Type Arrangements.

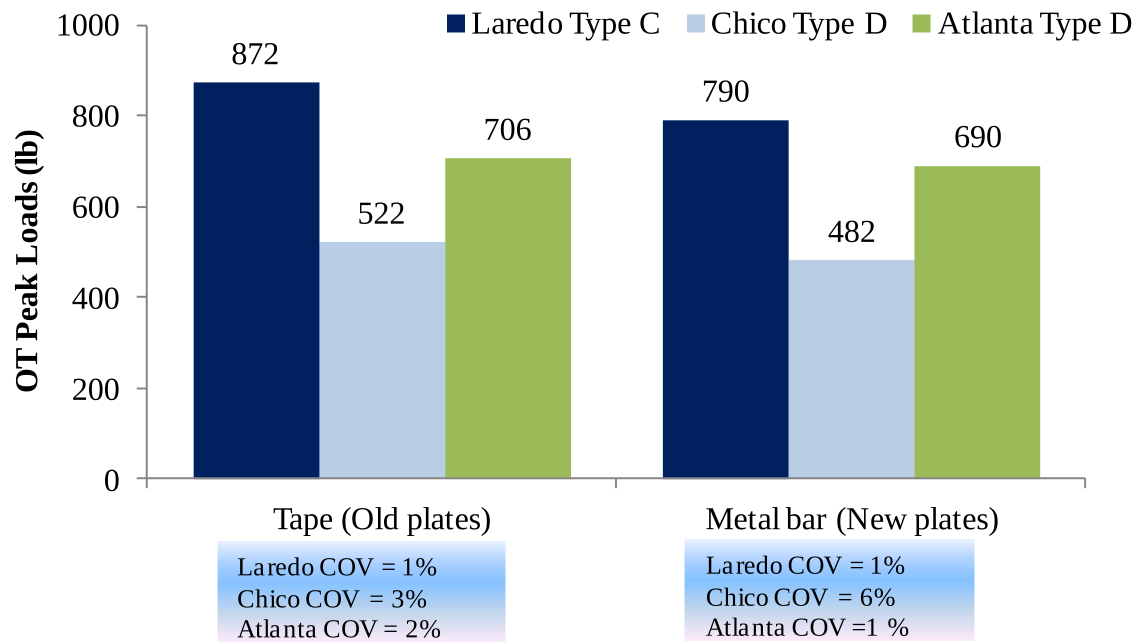


Figure 5-21. OT Test Results (Peak Load) for Two Plate Gap Width/Type Arrangements.

Three different mix types were used for this study, namely Type C plant mix from Laredo District and Type D plant mixes from Chico and Atlanta Districts. Analyzing the results, the following observations are made:

- In terms of statistical variability, the test results do not provide any conclusive evidence in favor of choosing either arrangement. However, from the workability point of view, the researchers recommend using the new TxDOT plates instead of the old plates. The new plates are more user friendly, easier to apply glue, and align the specimens centrally.
- The laboratory technicians have experienced difficulty while using the metal bar (difficult to remove after gluing).
- The researchers propose shifting to the new TxDOT plates with applying caution while using the metal bars and/or explore other techniques in lieu of using the metal bar.

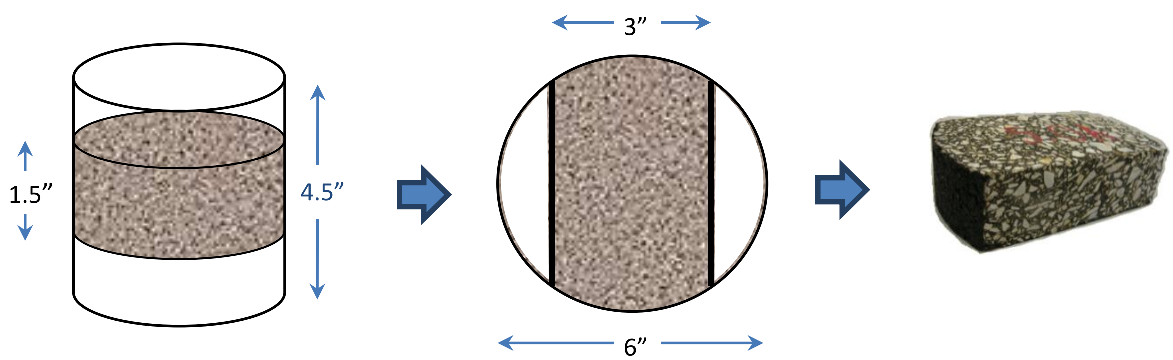
SUMMARY

This chapter discussed the findings of the sensitivity evaluation conducted on the key steps in the OT test procedure in view of minimizing OT test variability. Testing of several plant mixes and raw material mixes and their subsequent analysis helped the researchers to identify some key issues in the OT testing procedure that will help minimize the overall OT test variability. The findings of this chapter can be summarized in the following key points:

- Testing five or four replicate OT specimens and reporting the best three results instead of the current practice of testing three gives better repeatability. A set of best three replicates should be chosen based on the lowest COV considerations. As illustrated in the included CD, an easy to use macro was developed for automatically picking the best three test results out of four or five that are tested.
- Overnight oven drying of the OT specimens at a maximum temperature of 40 ± 3°C (104 ± 5°F) to constant weight is preferable to air drying.
- The specimens need to be tested within 5 days of molding, i.e., specimen sitting time between molding, and testing should not exceed 5 days.
- OT specimens having air-void values between 6.5 percent and 7.5 percent gave the most repeatable results.
- The use of 16.0 ± 0.5 g of Devcon 2-part, 2-ton epoxy for gluing the specimens to the OT testing plates is the most economical and gives the most repeatable results.
- The researchers didn’t find any conclusive effect of test temperature on OT result variability and as such, recommends the current setup. For any target test temperature, however, the tolerance limit should not be more than ± 2°F.
- The OT result variability does not show any definitive trend of variation with changing opening displacement. Using of the currently practiced 0.025 in. opening displacement is recommended.
- Consideration should be given to using the new TxDOT OT plates that are more user-friendly, but should exercise caution when using the metal bar as the gap spacer.

CHAPTER 6.
OT SAMPLE MOLD SIZE

Currently, for the lab-molded OT specimens, the test specification (Tex-248-F, 2009) specifies the molded samples to have a 6.0 in. diameter and a 4.5 ± 0.2 in. height; see Figure 6-1. The 4.5 in. sample height was a shift from the traditionally practiced molded sample height of 2.5 in. primarily as an effort to help address the OT variability issues. However, this shift did not address the variability issues; instead it just increased the work load and material wastage. Therefore, it was decided to revisit this aspect so as to optimize material usage and work load. To address this issue, researchers conducted a study under this project where the possibilities of using alternate OT sample mold sizes were considered and the OT test results were compared.



Molded Sample | Trimming Specimen’s Ends | OT Specimen

Figure 6-1. Trimming OT Specimen from Molded Samples.

The considered alternate approaches for sample molding were:

- Cutting two specimens from each molded sample of 4.5 in. height.
- Cutting two specimens from each molded sample of 5.0 in. height.
- Cutting one specimen from each molded sample of 2.5 in. height.

OT RESULT COMPARISON

Three mix types were tested for this study: two Type D plant mixes and a Type C mixed from raw materials. Tables 6-1, 6-2, and 6-3 present the results.

Table 6-1. Type D (Atlanta) Plant Mix Specimens for Different Sample Sizes.

Atlanta Plant Mix Type D		4.5" Sample (1 Specimen)	4.5" Sample (2 Specimens)	5.0" Sample (2 Specimens)	2.5" Sample (1 Specimen)
Peak Load (lb)	Average	706	676	581	890
	COV (%)	*2%*	*2%*	*22%*	*3%*
OT Cycles	Average	180	176	150	170
	COV (%)	*26%*	*24%*	*13%*	*27%*
Air Void (%)	Average	6.4	7.4	7.5	6.5
	COV (%)	*6%*	*3%*	*2%*	*7%*

Table 6-2. Type D (Chico) Plant Mix Specimens for Different Sample Sizes.

Chico Plant Mix Type D		4.5" Sample (1 Specimen)	4.5" Sample (2 Specimens)	5.0" Sample (2 Specimens)	2.5" Sample (1 Specimen)
Peak Load (lb)	Average	516	388	609	632
	COV (%)	*1%*	*1%*	*4%*	*4%*
OT Cycles	Average	210	230	203	89
	COV (%)	*25%*	*27%*	*28%*	*11%*
Air Void (%)	Average	7.3%	7.7%	7.8	6.4%
	COV (%)	*2%*	*11%*	*3%*	*1%*

Table 6-3. OT Test Results: Type C Raw Material Specimens for Different Sample Sizes.

Laredo Raw Material Type C		4.5" Sample (1 Specimen)	4.5" Sample (2 Specimens)	5.0" Sample (2 Specimens)	2.5" Sample (1 Specimen)
Peak Load (lb)	Average	618	542	578	687
	COV (%)	*2%*	*6%*	*3%*	*1%*
OT Cycles	Average	92	61	83	54
	COV (%)	*8%*	*11%*	*7%*	*20%*
Air Void (%)	Average	6.8%	6.5%	8.5%	6.0%
	COV (%)	*3%*	*9%*	*10%*	*7%*

It is evident from the results in these tables that the OT cycles to failure do not change much for the different approaches tried. The exception to this observation is the low average OT cycles for the Chico mix when one specimen is cut from a 2.5 in. tall molded sample. However, only three specimens were tested in this case instead of five, which might contribute to the low OT cycles. All the OT cycle COV values are within the 30 percent acceptable limit. The average peak loads are also comparable for the four considered options. This uniformity or comparability in the OT cycle and peak load results is fairly expected since the specimen AV values do not vary too much between the four different approaches. Figure 6-2 better illustrates the consistency of the OT cycles among these four mold size approaches.

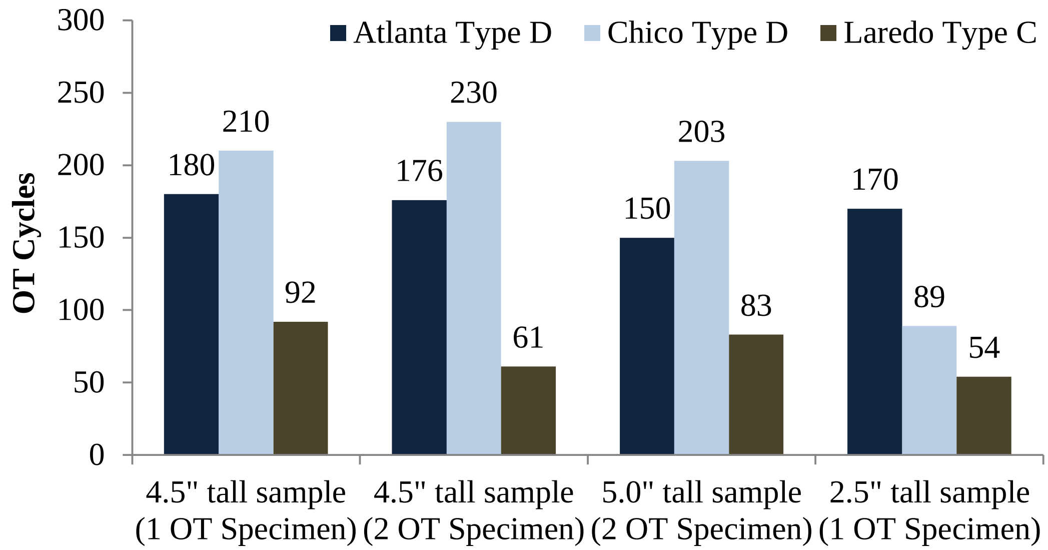


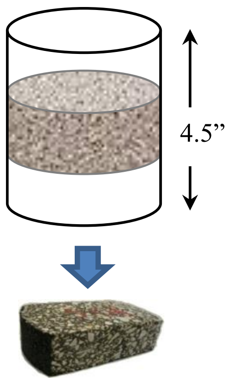
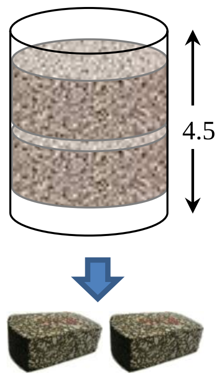
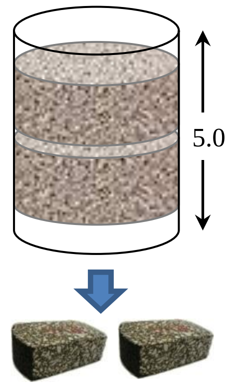
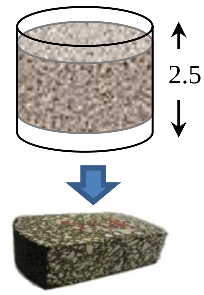
Figure 6-2. OT Cycles for Different Sample Molding Approaches.

From Figure 6-2, it is more evident that the OT cycles do no change considerably with changing sample mold size, with the exception of the Chico mix at 2.5 in. mold height. A logical conclusion from this observation is that any one of these four approaches can be used without having considerable effect on the test results. Therefore, a practical option will be to choose the approach that involves minimum material loss and at the same time the one that requires minimum time and workload.

MATERIAL WASTAGE FOR DIFFERENT SAMPLE MOLDING APPROACHES

Table 6-4 shows a comparison of the four approaches of sample molding based on respective volume-wise percent material wastage. Clearly evident is that the current practice of cutting one OT specimen from a 4.5 in. tall molded sample involves the most material wastage, whereas cutting two specimens from a 4.5 in. tall molded sample is the least wasteful approach.

Table 6-4. Comparison of Material Wastage for Different Sample Molding Approaches.

				
Molded Sample Volume (in.^{3})	118	118	132	66
OT Specimen Volume (in.^{3})	25	50	50	25
Material Wastage	80%	57%	60%	60%

The percent material wastage when two specimens are cut from a 5 in. tall molded sample and when one specimen is cut from a 2.5 in. tall sample is the same. However, considering the fact that between these two options, the former involves less laboratory time and workload; the researchers are inclined to recommend it.

AIR-VOID DISTRIBUTION FOR THE MOLDED SAMPLES

From the preceding discussion, it can be concluded that to minimize material wastage and time and effort in the laboratory, cutting two OT specimens from a 4.5 in. or 5.0 in. tall molded sample should be opted for instead of the current practice of cutting only one specimen from a 4.5 in. tall sample. Although based on material wastage considerations, using a 4.5 in. tall molded sample seems to be a slightly better option, there are concerns over the consistency of the resulting OT specimen air voids. To study how the air void is distributed over the height of the molded samples, researchers conducted an X-ray CT scan study under this project.

The X-Ray CT Scanner

Figure 6-3 shows the pictorial setup for TTI’s X-ray CT scanner. Details of the X-ray CT scanner including the test setup, test procedures, operational modes, and data analysis procedures are documented in Masad et al. (2009). In general, however, the test is typically conducted at ambient (room) temperature.

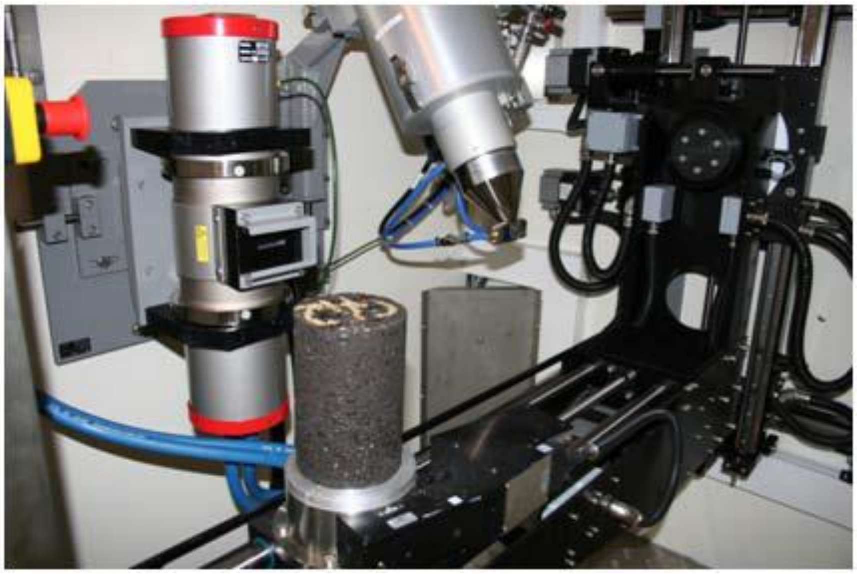


Figure 6-3. Pictorial Setup of TTI's X-Ray CT Scanner.

X-ray CT scanning of cylindrical molded samples of 2.5, 4.5, and 5 in. heights were done. Three replicate samples were scanned for each mix. An example of the cylindrically molded OT samples is shown in Figure 6-4.

Figures 6-5 through 6-7 present the results of the X-ray CT scans on 4.5 in. tall molded samples (one specimen per sample), 4.5 in. tall molded samples (two specimens per sample), 5 in. tall molded samples (two specimens per sample), and 2.5 in. tall molded samples (one specimen per sample), respectively.

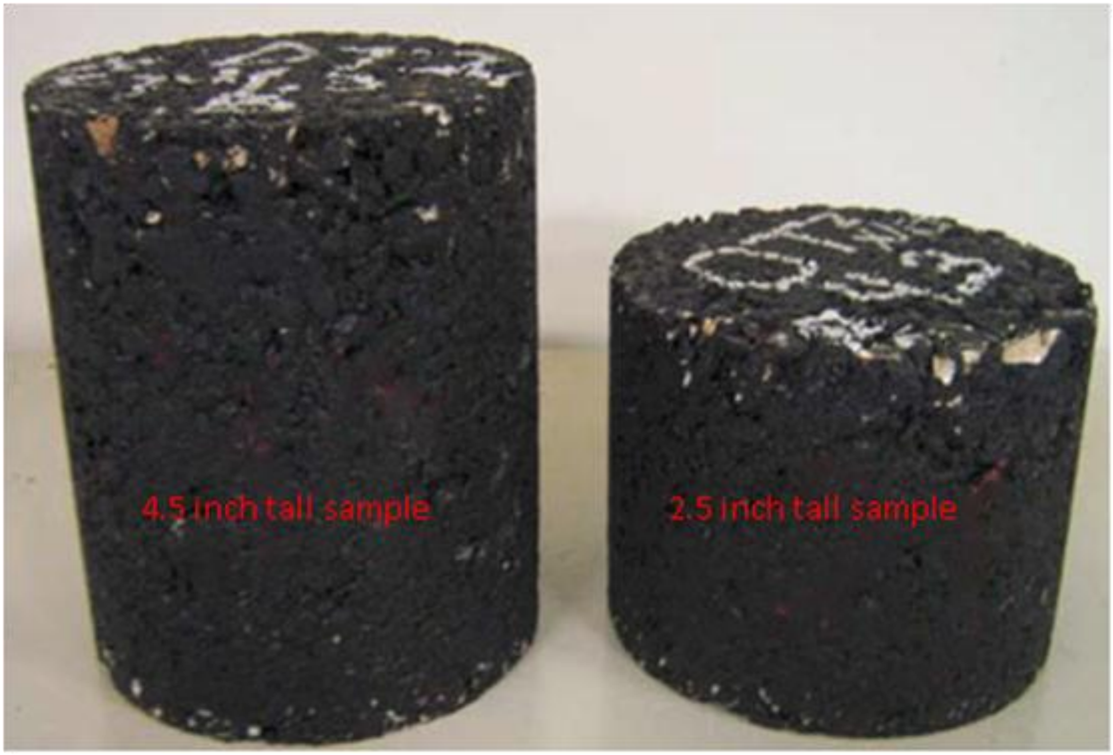


Figure 6-4. X-Ray CT Test Samples – SGC Lab Molded.

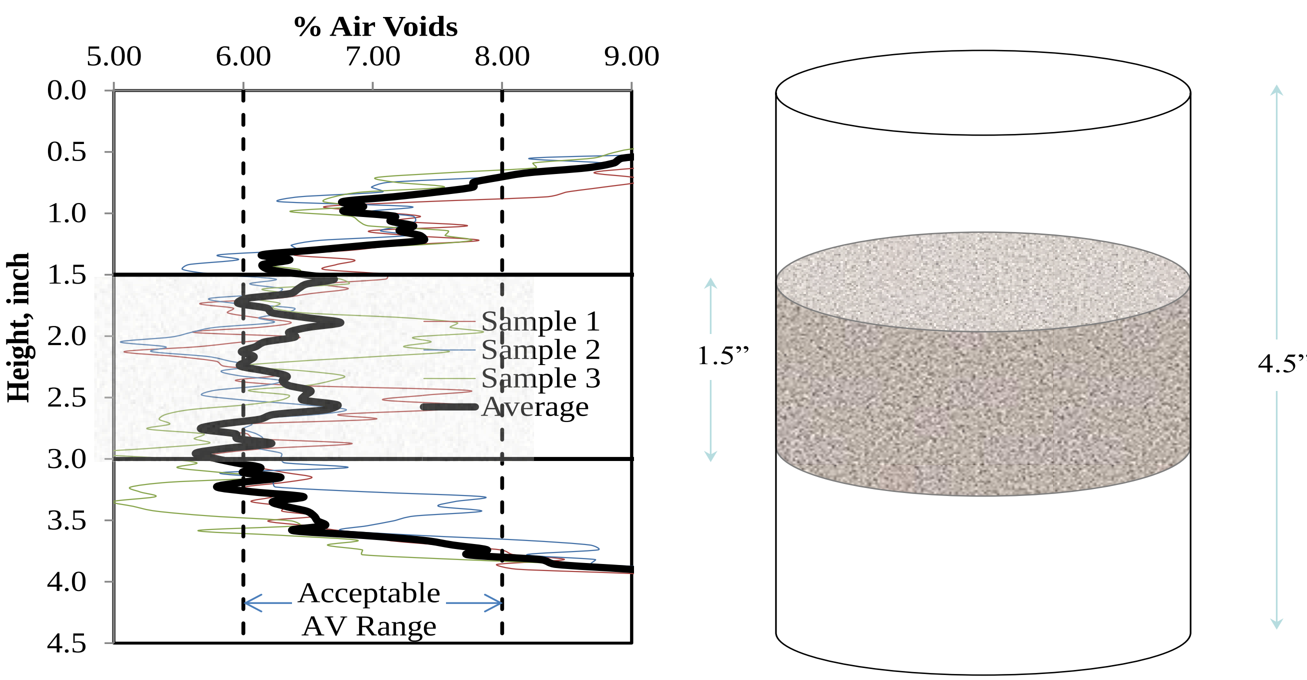


Figure 6-5. X-Ray CT Scan of 4.5 in. Tall Molded Sample (One Specimen per Sample).

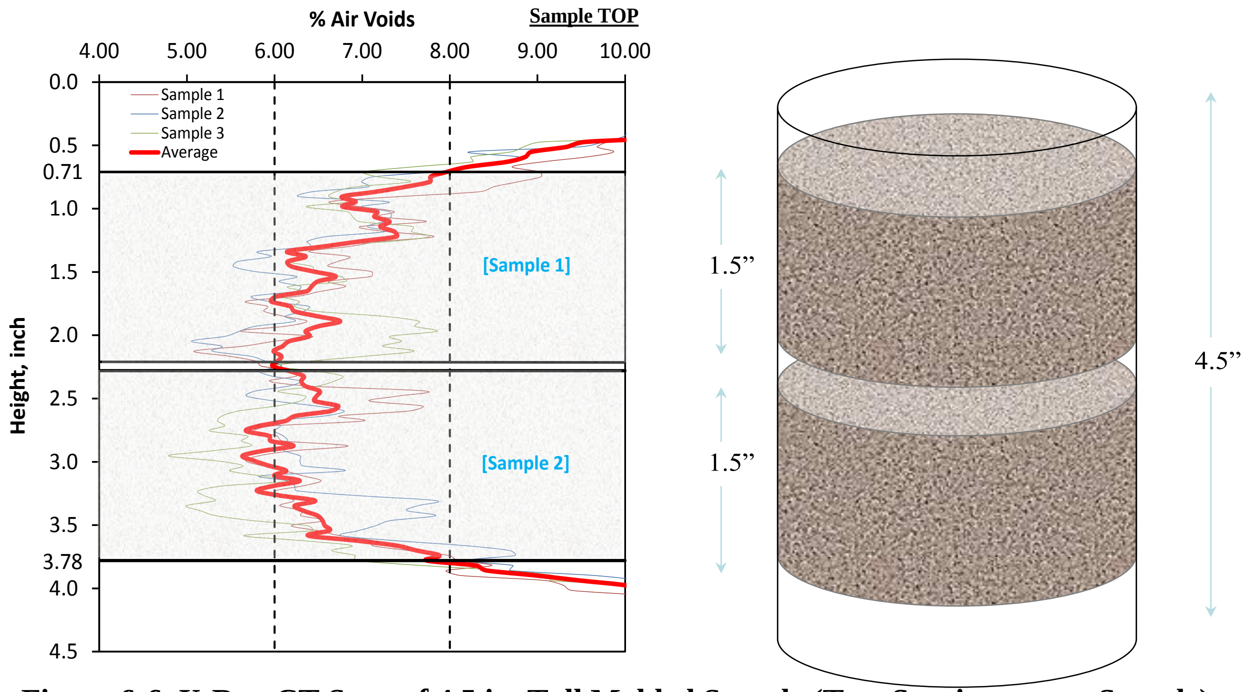


Figure 6-6. X-Ray CT Scan of 4.5 in. Tall Molded Sample (Two Specimens per Sample).

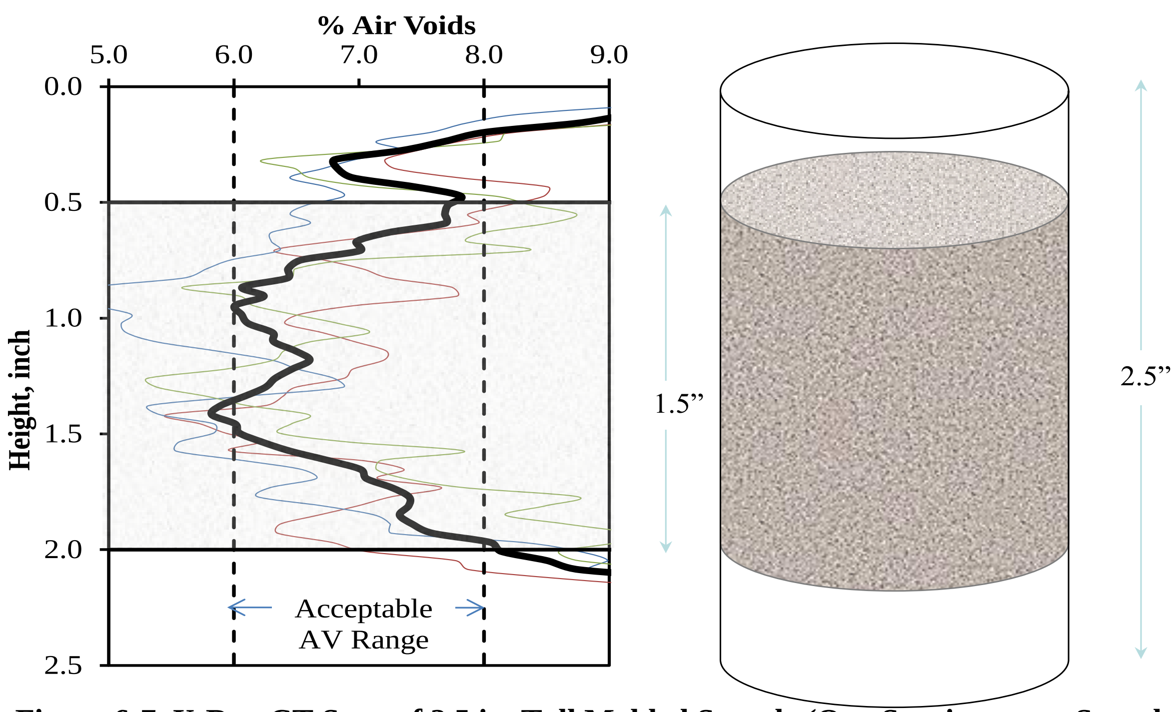


Figure 6-7. X-Ray CT Scan of 2.5 in. Tall Molded Sample (One Specimen per Sample).

The term *acceptable AV range* in Figures 6-5 through 6-7 is the specified compacted OT sample AV, 7 ± 1 percent (TxDOT, 2004). The objective of this X-ray CT scan was to ensure that the AV distribution across the height of the molded samples permitted the cutting of the desired OT specimens so that they had acceptable percent AV values. From the figures, it is evident that the AV distributions remain mostly within the acceptable range for the height levels where specimens are cut from. The exception to this is when two specimens are cut from the 4.5 in. tall molded sample where the specimens suffer from non-uniformity in AV distribution, particularly the specimens cut from the bottom. Also, from a practical point of view, it is rather tricky to cut two specimens from a molded sample of 4.5 in. height in the laboratory. A significant improvement is obtained when the molded sample height is increased to 5.0 in.

SUMMARY

In this chapter, the procedure of OT specimen preparation, from the molding of samples to sample trimming, was reviewed in view of addressing the issue of excessive material wastage associated with the currently practiced procedure. The key findings of the chapter can be summarized as follows:

- The molded sample height was shifted from 2.5 in. to 4.5 in. to help address the variability issues but this approach was not successful. As a result of this shift, the material wastage and the workload in the lab increased significantly.
- A comparison among several alternate sample mold sizes showed no significant difference in variability and OT cycles results.
- In order to minimize the material wastage and optimize the workload, these researchers propose the following alternatives: 1) make 5 in. tall sample and cut two specimens from the middle, or, 2) make 2.5 in. tall sample and cut one specimen from the middle.

CHAPTER 7.
OT ALTERNATIVE DATA ANALYSIS METHODS

As evident from the discussions in Chapter 2, the primary output of the OT test is the crack-resistance potential of an HMA mix, which is essentially quantified in terms of the number of cycles for the specimen to fail. The specimen is considered to have failed when it reaches a 93 percent reduction of the load measured on the first cycle. Often, researchers argue that this process fails to capture other important information that can be used to quantify the HMA crack-resistance potential. Furthermore, this approach (number of cycles) has in the past been associated with high variability in the test results, and hence, the need to seek other alternative methods of both analyzing and interpreting the data measured from the OT test. In this chapter, various alternative procedures, ranging from relatively simple to complex ones, were evaluated and include the following:

- Adding an additional up-front strain at break (single shot).
- Considering alternatives to the number of cycles to failure such as looking at the area under the load versus number of cycles to generate a strain energy statistic, the load reduction, and the rate of load decrease as a function of the number of cycles or time [i.e., change in slope]).
- Developing other engineering parameters from the results of the Overlay Test.

STRAIN AT BREAK AND FRACTURE ENERGY (SINGLE-SHOT MONOTONIC TEST)

The prospect of using the OT test setup to perform a monotonic loading test as a practical method for obtaining the tensile strength, ductility characteristics, modulus/stiffness, and fracture energy of HMA mixes as a means to characterize their cracking-resistance potential were evaluated as a part of this study. HMA mixes that are typically used on Texas highways were tested at a monotonic loading rate of 0.125 in. per minute at a temperature of 77°F. The trial testing results and selection of the 0.125 in./min loading rate are illustrated in Appendix H.

During monotonic OT testing, the measurable parameters are similar to those in a repeated OT test (applied load, opening displacement, time, and test temperature). The primary output of the OT monotonic test is the stress-strain behavior of HMA. Figure 7-1 provides an illustration of a typical monotonic OT test output data.

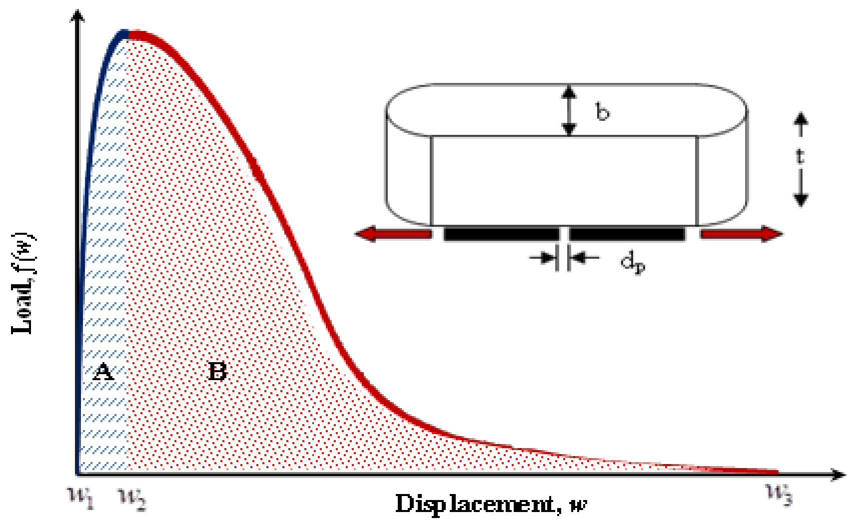


Figure 7-1. Crack Initiation and Propagation during a Typical Monotonic OT Test.

From the figure, one observes that there are two distinct phases in the reflective cracking process of HMA pavement systems: the crack initiation phase (part A in the load-displacement curve) and crack propagation phase (part B in the load-displacement curve).

The fracture parameters measured from the test are the specific fracture energy, G_f, HMA tensile strength, σ_t, the tensile strain at peak failure load (ductility potential), ε_t, and HMA tensile modulus (stiffness), E_t. These fracture parameters are calculated using the following equations:

$$G_f = \frac{\text{Work}}{\text{Area of Cracked section}} = \frac{1}{tb}\int f(w)\,dw \qquad \text{(Equation 7-1)}$$

One can write expressions for specific fracture energy for the two phases of the OT_M test. Specific fracture energy required for crack initiation following Equation 7-1 is:

$$G_{f,A} = \frac{1}{tb}\int_{w_1}^{w_2} f(w)\,dw \qquad \text{(Equation 7-2)}$$

and

$$G_{f,B} = \frac{1}{tb}\int_{w_2}^{w_3} f(w)\,dw \qquad \text{(Equation 7-3)}$$

Therefore, the total specific fracture energy of an HMA overlay from an OT monotonic test is:

$$G_{f,T} = G_{f,A} + G_{f,B} = \frac{1}{tb}\int_{w_1}^{w_3} f\left(w\right)dw \qquad \text{(Equation 7-4)}$$

The HMA tensile strength measured from a monotonic OT test is expressed as follows:

$$\sigma_t = \frac{Peak\ Load}{Cross\ Section\ Area} = \frac{P_{\max}}{tb} \qquad \text{(Equation 7-5)}$$

And the tensile strain at peak failure load (ductility potential) is defined as follows:

$$\varepsilon_t = \frac{D_{P\max} - D_o}{d_p} \qquad \text{(Equation 7-6)}$$

Then, the HMA tensile modulus (stiffness) can be computed as follows:

$$E_t = \frac{\sigma_t}{\varepsilon_t} \qquad \text{(Equation 7-7)}$$

Where, t is the OT sample thickness, b is the OT sample width or breadth, d_p is the opening of the base plate, $D_{P\max}$, and D_o are displacements measured at the peak load and at the start of the test, respectively, and E_t is the HMA tensile modulus or stiffness.

Monotonic OT Test Results and Analyses

Several different mix types were tested using the monotonic OT setup and were analyzed to measure HMA fracture properties using the developed expressions. The load-displacement response obtained from the tests were used as a starting point for analyzing the results, and understanding these curves provided insight into the HMA fracture process. As an example, Figure 7-2 presents the load-displacement curves from monotonic OT tests for six different mix types. Three replicate samples were tested for each mix, and the graphs in Figure 7-2 represent the average for each mix. In general, three replicates were utilized for all monotonic OT testing, and the results represent an average of the three.

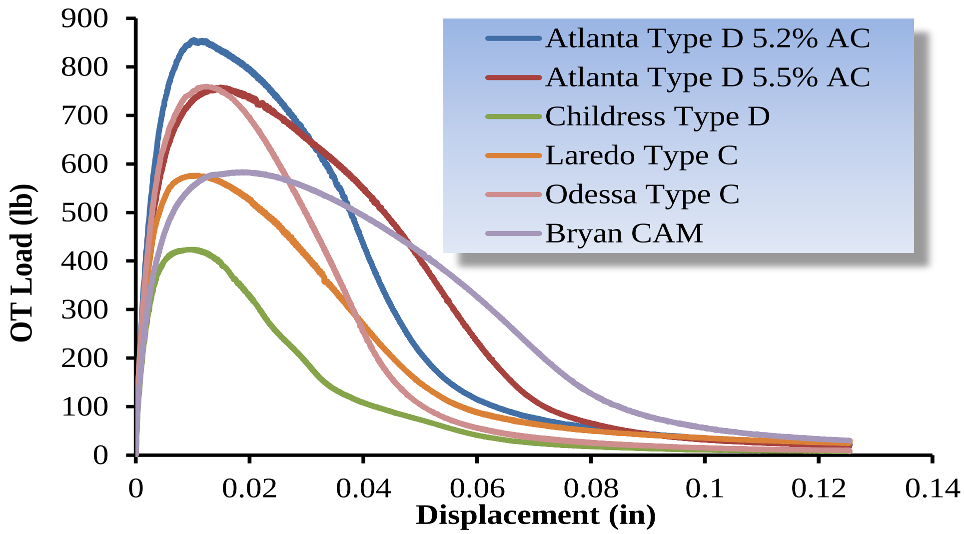


Figure 7-2. Example of Monotonic OT Load-Displacement Curves.

All the specimens for these tests were subjected to a monotonic loading rate of 0.125 in. per minute at a temperature of 77°F. For each mix type designation, three replicate samples were tested, and the load-displacement responses were averaged. The wide variation in the curve shapes indicates the potential of the monotonic OT test to distinguish between different mix designs. Researchers analyzed these load-displacement curves to calculate the specific fracture energy (G_f) using the models derived in Equations 7-1 through 7-7. Table 7-1 presents a summary of the fracture parameters obtained from the analysis.

Table 7-1 shows that most of the tensile strength values calculated for different mixes from the monotonic OT test are within the acceptable range for HMA tensile strengths (85 ~ 200 psi); and are consistent with the values reported for the other test methods by other researchers (Walubita et al., 2010). Additionally, the mixes have fairly low variability with COV values less than 30 percent, which is comparable to data found in the literature for other monotonic fracture tests, i.e., IDT (4 percent ~ 15 percent [Walubita et al., 2010]), DSCTT (4 percent ~ 25 percent [Wagoner et al., 2005]), and SCB (15 percent ~ 34 percent [Li and Marasteanu, 2004]) tests.

Table 7-1. Fracture Parameters from OT Monotonic Tests.

Mix Designation	P_{max} (lb) Average	COV	D_{Pmax} (in.) Average	COV	σ_t (psi)	G_f (J/m^2) Average	COV
CAM (PM)	587	3.1%	0.017	19.4%	131	1479	1.3%
CAM (Raw)	559	3.7%	0.021	2.2%	124	1504	3.6%
Type D 5.2% AC	868	7.9%	0.012	27.0%	193	1475	14.8%
Type D 5.5% AC	760	3.0%	0.015	4.2%	169	1620	4.6%
Type D 4.9% AC	433	24.4%	0.011	33.6%	96	572	20.4%
Type C 5.0% AC	583	10.4%	0.010	24.4%	130	1152	28.8%
Type C 5.8% AC (Raw)	763	3.3%	0.012	3.6%	170	1150	3.1%
Type C 4.6% AC	589	8.7%	0.012	23.7%	131	905	7.0%
Type C 5.8% AC (PM)	986	2.5%	0.015	1.2%	219	1382	10.6%

Sensitivity to Changes in Asphalt-Binder Content

One notable observation from the fracture energy results of Table 7-1 is that the monotonic OT test result is sensitive to different mixes and varying asphalt-binder contents. One can consider the Atlanta Type D mixes, for example. Figure 7-3 shows the load-displacement response curves for a Type D mix at three different asphalt-binder content (AC) levels. Three replicate specimens were tested at each AC level.

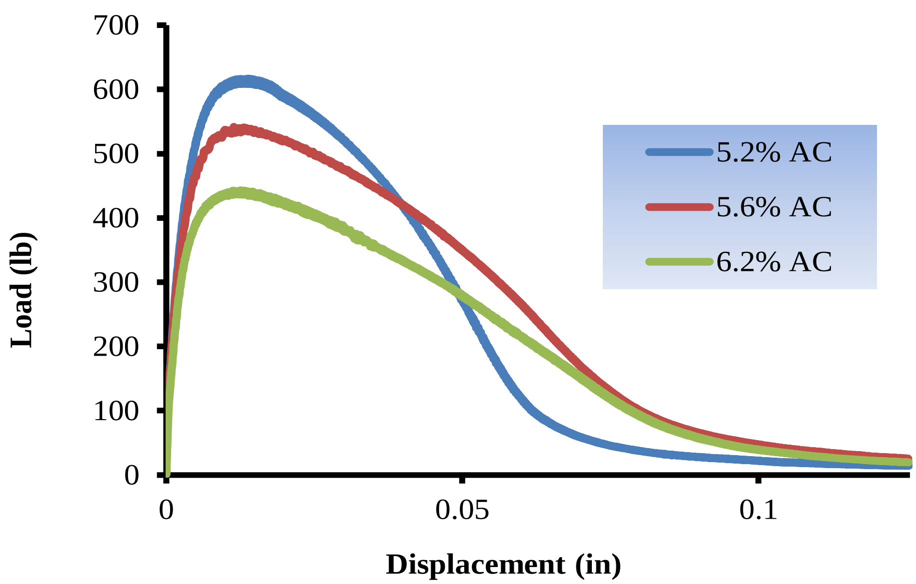


Figure 7-3. Load-Displacement Curves for Varying Asphalt Contents (Mix Type D).

The immediate observation from these three curves depicts two characteristics of the HMA mix. First is the fall in peak load values with increasing percentages of AC levels, which clearly marks the decrease in the HMA tensile strength. The second characteristic is that the curves become more widespread as the percentages of AC level increase, which is a clear indication of increased ductility of the HMA mix at higher percentages of AC levels. These two characteristics pose two opposing trends on the total area under the load-displacement curve such that an increase in area due to a higher peak load at lower AC is somewhat compensated by a decrease in area due to lower ductility, i.e., shorter elongation prior to failure. Since specific fracture energy of the HMA mix is directly proportional to the area under the load-displacement curve, the total fracture energy value will not be able to capture the actual effects of AC percentage change in the HMA mix effectively. However, if the fracture energy for crack initiation (Phase A) and crack propagation (Phase B) are considered separately, they should be able to show some trends with changing AC content. Table 7-2 and Figure 7-4 show the variation of specific fracture energy for a Type D mix (Atlanta) as a function of the asphalt-binder content.

Table 7-2. Variation of Fracture Parameters as a Function of Asphalt-Binder Content.

AC (%)	P_{max} (lb) Avg.	P_{max} (lb) COV	ε_{Pmax} (in./in.) Avg.	ε_{Pmax} (in./in.) COV	σ_t (psi)	E_t (psi)	Fracture Energy (J/m²) $G_{f,A}$	$G_{f,B}$	$G_{f,T}$	COV ($G_{f,T}$)
5.2	619	8%	0.165	18%	138	836	247	942	1189	6%
5.6	547	4%	0.154	7%	122	792	206	1093	1299	11%
6.2	445	4%	0.166	5%	99	596	188	862	1050	5%

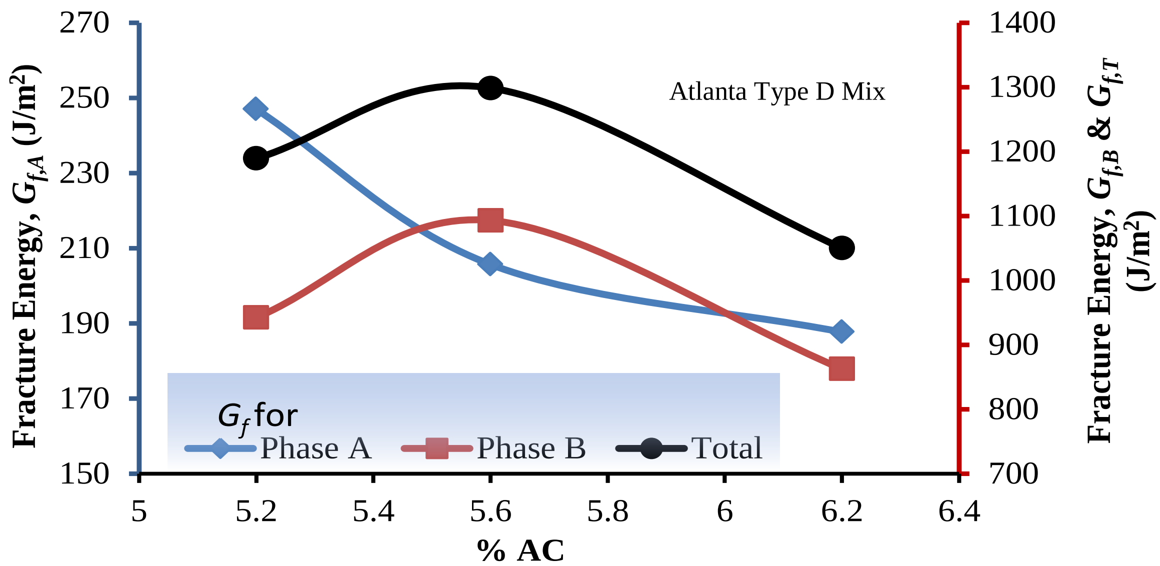


Figure 7-4. Effect of %AC on Monotonic OT Fracture Energy.

Figure 7-4 shows that the fracture energy required for initiating the crack decreases with increasing AC level and is following a similar trend as the peak load. This behavior is as expected, since at higher AC levels, the HMA is more flexible (softer and less stiff). Also during this phase, the predominant governing parameters in defining the fracture energy, according to Figure 7-3, are the peak load and the stiffness of the mix. Fracture energy required for crack propagation (phase B), on the other hand, does not show any definitive trend with the change in AC level. Theoretically, however, one would expect the specific fracture energy for crack propagation to increase with an increase in the asphalt-binder content. The argument behind this is that increased asphalt-binder content in the HMA would mean increased ductility and, therefore, a larger area bound under the load-displacement curve, which in turn would result in a higher specific fracture energy value. Theoretically, the concern is that since fracture energy is an area function of the load (Y-axis) and displacement (X-axis), an increase in the load for stiff mixes (low AC in this case) means a decrease in displacement (less ductility and elongation) and vice versa for softer mixes (high AC level in this case). Therefore, the load (Y-axis) and displacement (X-axis) always seem to compensate each other and, as a result, the total area (fracture energy) does not seem to vary much with changes in the AC levels. Further study is required to investigate this behavior and/or establish better analysis models.

Figure 7-5 shows a comparative study of the effect of the asphalt-binder content change on the total fracture energy (monotonic loading) and the number of OT cycles to failure (repeated loading) for the same Type D mix. Once again, the figure clearly shows the inability of the fracture energy (from monotonic loading) to successfully capture the effect of changing AC on the HMA performance, whereas the OT cycles (from repeated loading) show a clear increasing trend with an increase in the AC level, as would be theoretically expected.

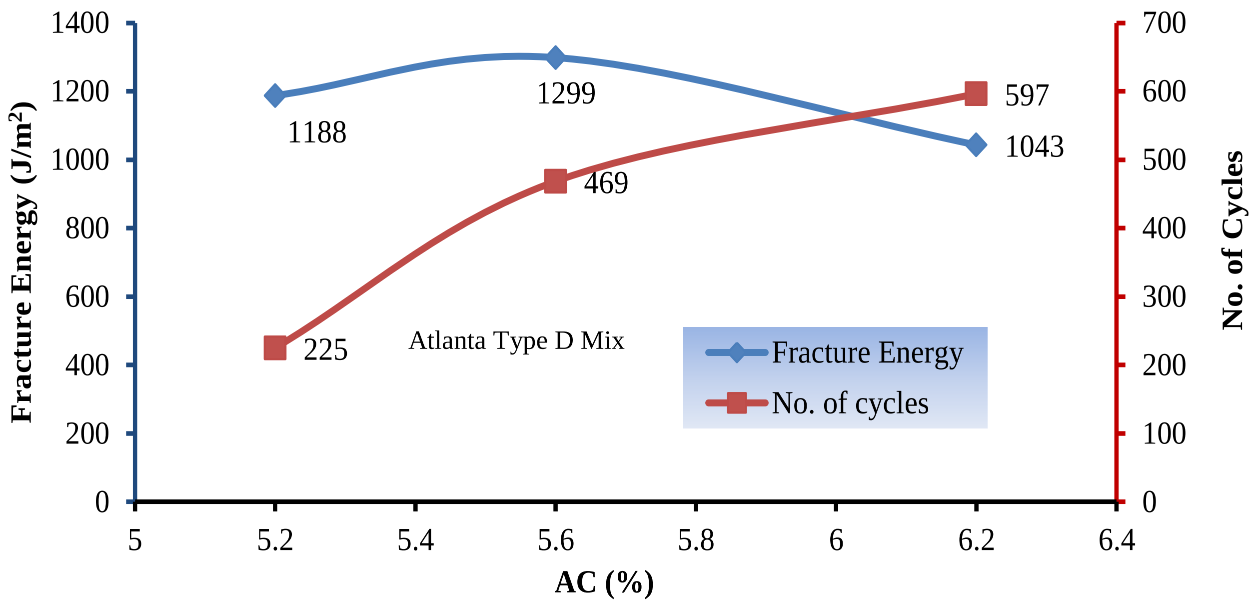


Figure 7-5. Change in Specific Fracture Energy and OT Cycles with Asphalt-Binder Content.

Sensitivity to Changes in Temperatures

The researchers also conducted a similar study to investigate the effects of temperature variations on the fracture parameters calculated from the monotonic OT test. The samples tested for this study were from a Type C mix. Three sample replicates were tested at each temperature level at a loading rate of 0.125 in. per minute, and Figure 7-6 shows the load-displacement response curves.

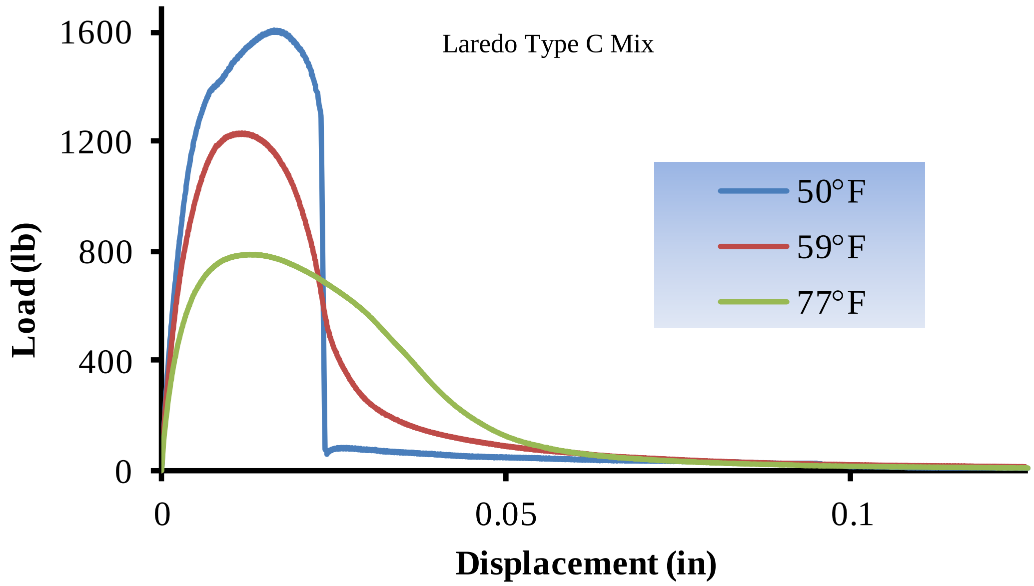


Figure 7-6. Monotonic OT Load-Displacement Curves for Varying Temperature (Mix Type: C).

The curves in the above figure bear testimony to the fact that at lower temperatures, the HMA mixes become stiffer and more brittle, resulting in instantaneous crack failure under tensile loading. The sudden drop in load for the sample at 50°F marks the sudden complete failure, whereas the samples at higher temperatures (59°F and 77°F), with some elasticity, show smooth load-displacement behavior stretching over a relatively larger displacement range, indicating better ductility at elevated temperatures. Figure 7-7 and Table 7-3 present the fracture parameters calculated from the results of this study.

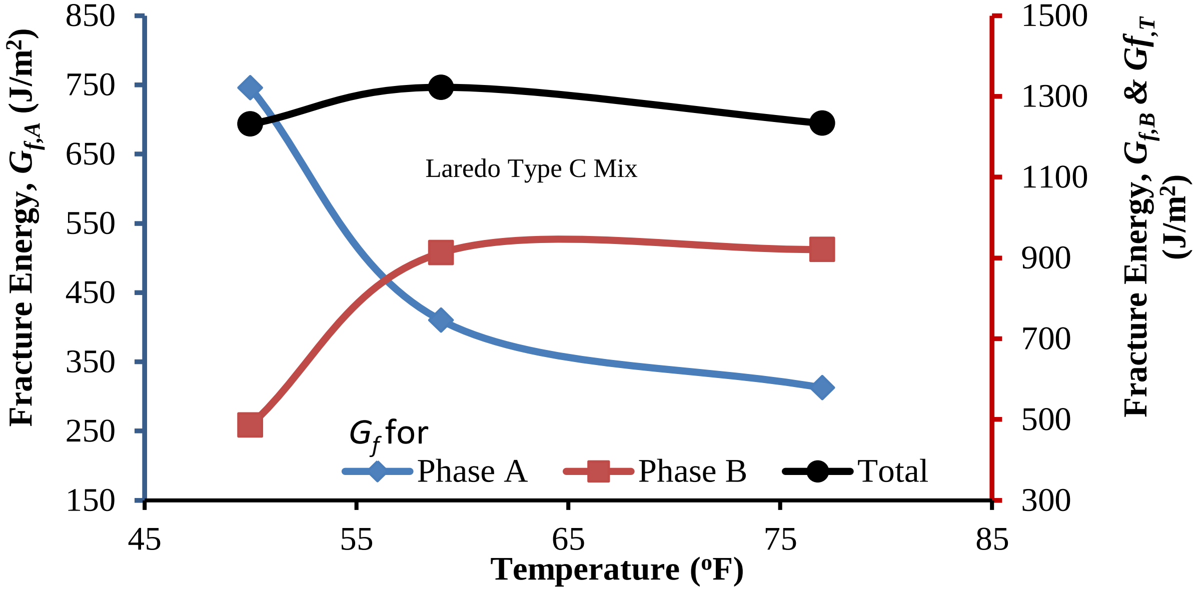


Figure 7-7. Effects of Temperature Variation of the Monotonic OT Fracture Energy.

Table 7-3. Variation of Fracture Parameters as a Function of Temperature Change.

Temp (°F)	P_{max} (lb) Avg	P_{max} (lb) COV	ε_{Pmax} (in./in.) Avg	ε_{Pmax} (in./in.) COV	σ_t (psi)	E_t (psi)	Fracture Energy (J/m²) $G_{f,A}$	$G_{f,B}$	$G_{f,T}$	COV($G_{f,T}$)
50	1630	13%	0.193	6%	362	1876	746	486	1231	13%
59	1240	16%	0.147	3%	277	1884	410	913	1323	16%
77	796	6%	0.162	15%	177	1093	312	921	1233	10%

The results clearly indicate that the total fracture energy is unable to capture the complete behavioral change of the HMA mix with varying temperature. Once again, this is considered to be due to the opposing trends shown by the peak load and HMA ductility with temperature change, just like for the change in AC level.

The significant decrease in crack initiation fracture energy with increasing temperature can be explained using the concept of HMA stiffness. Higher temperature leads to lower HMA stiffness (softer material), hence the reduction in required specific fracture energy, which in this phase is predominantly a function of the peak load. In case of the crack propagation phase, however, an increase in specific fracture energy is observed with increasing temperature. At lower temperatures, cracks tend to propagate through both aggregates and mastic, whereas at higher temperatures, cracks tend to propagate around the aggregates, thereby making the samples effectively more ductile against cracking. The result is a higher energy requirement for crack propagation in case of higher temperature. However, the temperature change does not seem to have any significant effect on fracture energy beyond 65°F due to the same reasons stated earlier, i.e., the load decreases while the displacement increases. The net result is that the area (product of load and displacement) is barely affected. The authors recommend further studies to better understand this behavior and/or develop better analysis models.

Figure 7-8 compares the effects of temperature change on the total fracture energy and number of OT cycles to failure for the same Type C mix; based on an average of three replicate test specimens. The extreme low OT cycle values at the low temperature are due to the high degree of stiffness and brittleness of the HMA mix, which is consistent with theoretical expectations. Although this particular Type C mix is a poor mix in terms of cracking resistance, the effect of temperature on the number of OT cycles is nonetheless clearly evident. Studies are currently ongoing to evaluate other mixes with better cracking performance properties.

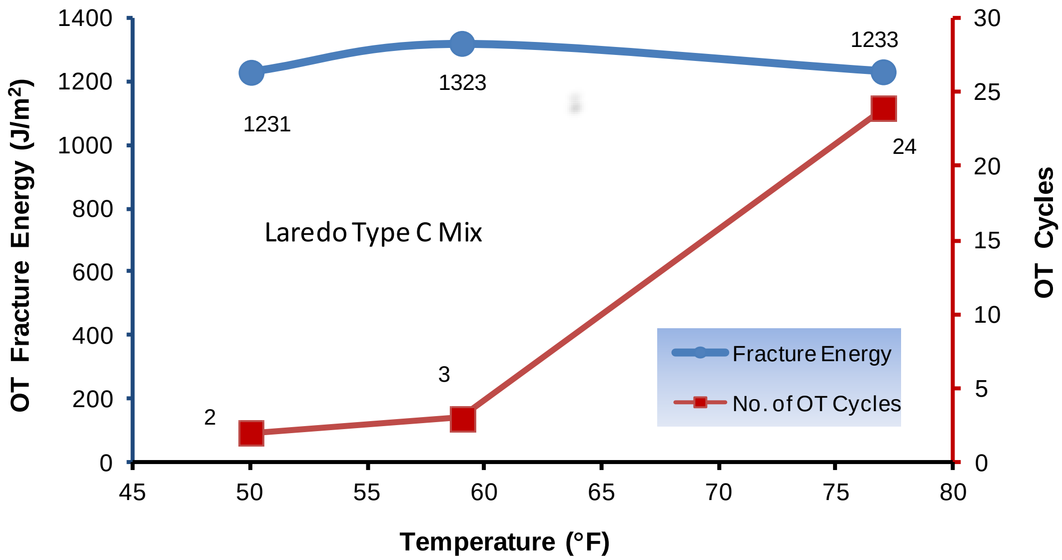


Figure 7-8. Change in Specific Fracture Energy and OT Cycles with Temperature Variations.

Comparison of OT Fracture Energy to Regular Repeated OT Loading Cycles

Figure 7-9 shows the comparison of specific fracture energy values from monotonic OT tests with OT cycles of the same mixes. Although the results in Figure 7-9 seem to support the assumption that higher specific fracture energy means better crack-resistance potential, there is no clear distinction in the magnitude of the fracture energies between the different mixes. Additionally, this would also be in contrast to the results shown previously for the Phase A fracture energy, i.e., crack initiation. The number of OT cycles from the repeated loading, on the other hand, shows a definitive trend that is consistent with both theoretical expectations and the historically observed field performance of these mixes on the Texas roads. For instance, the 5.0 percent AC Type C mix from Laredo showed a significantly high specific fracture energy value while having a relatively low OT cycles to failure. Also, the 5.8 percent AC Type C plant mix has a fracture energy that is not significantly different from that of the CAM plant mix.

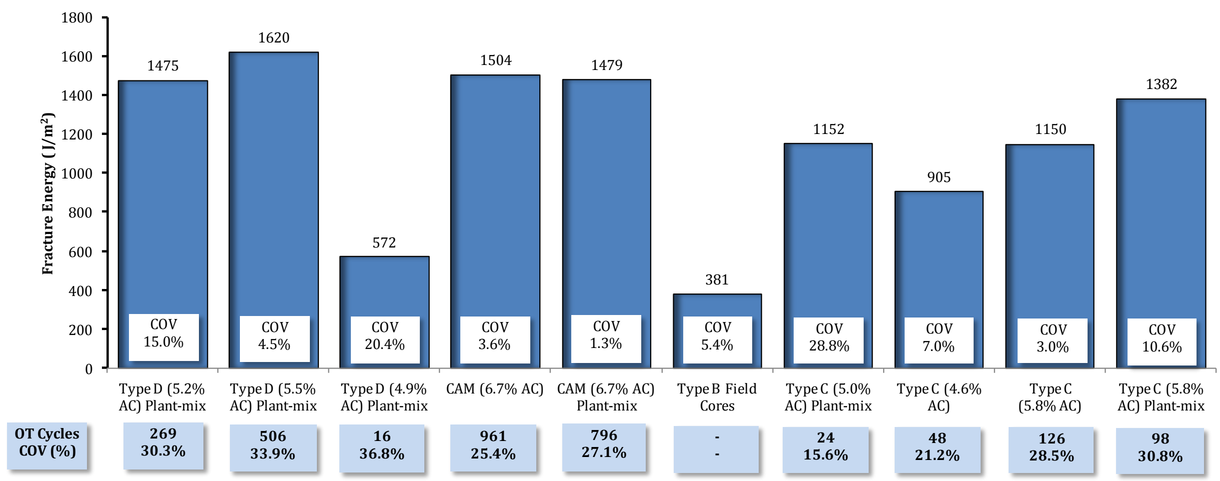


Figure 7-9. Comparison of Monotonic and Repeated OT Loading Tests: Fracture Energy and OT Cycles.

However, the fracture energy values show significantly lower variability than the OT cycles. This indicates that the monotonic OT is a much more repeatable test than its repeated loading OT counterpart. Although the variability is relatively higher in the OT repeated loading, the number of cycles to failure, as evident in Figure 7-9, still remains the best screener and discriminator of HMA mixes. To better illustrate this, Table 7-4 summarizes discriminatory ratios for selected mixes.

Table 7-4. Discriminatory Ratios for Selected Mixes.

Mixes	Designation	Repeated OT Cycles	Mono-Strength (psi)	Mono-Strain (in./in.)	Mono-Stiffness (psi)	Mono-FE (J/m^2)
CAM (Raw)	(Very Good, VG)	961	124	0.267	464.4	1504
Type D (5.2% AC)	(Good, G1)	269	193	0.152	1269.7	1475
Type D (5.5% AC)	(Good, G2)	506	169	0.191	884.8	1620
Type D (4.9% AC)	(Poor, P1)	16	96	0.140	685.7	572
Type C1	(Poor, P2)	60	130	0.127	1023.6	1152
Type C4	(Poor, P3)	98	219	0.191	1146.6	1382
Discriminatory Ratio (DR)	*VG/G1*	*3.57*	*0.64*	*1.76*	*2.70*	*1.02*
	VG/P1	*60.06*	*1.29*	*1.91*	*1.47*	*2.63*
	G2/G1	*1.88*	*0.88*	*1.26*	*1.43*	*1.10*
	G2/P2	*8.43*	*1.30*	*1.50*	*1.16*	*1.41*
	VG/P3	*9.81*	*0.57*	*1.40*	*2.44*	*1.09*
	G1/P3	*2.74*	*0.88*	*0.80*	*0.90*	*1.07*
	G2/P3	*5.16*	*0.77*	*1.00*	*1.30*	*1.17*
Comment					*Reciprocal DR*	

The ability of the OT cycles to failure to better serve as a screener becomes clearly evident from the results listed in column 3 of Table 7-4. For instance, the OT cycles show a significant difference in performance between the Type D 5.2 percent AC mix and the Type D 5.5 percent AC mix (i.e., a ratio of about 1.9), while the fracture energy shows negligible difference (i.e., a ratio of 1.09). Likewise, the OT cycles show a significant difference between Type C mixes with 5.0 percent and 5.8 percent AC, whereas the fracture energy does not. This distinction is most vivid when the CAM (raw) and the Type D (4.9 percent AC) mixes are compared. While the OT cycles show a discriminatory ratio of about 60, the same for the fracture energy is only 2.6. In general, the discriminatory capabilities of the monotonic tensile strength, strain, stiffness, and fracture energy between different mixes are also not as effective as that of the number of OT cycles from repeated loading mode. Also, in most cases, while comparing two mixes, the mix with the higher OT cycles has a lower tensile strength. One possible explanation of this behavior is that mixes with higher tensile strength tend to be stiffer and more brittle and, as such, fail earlier in the repeated loading OT test.

Fracture Energy Index as an HMA Mix Screener

It is evident from the preceding discussions that the fracture properties derived from an OT monotonic test (i.e., HMA fracture energy) is much more repeatable than the OT cycles to failure from a repetitive OT test but it lacks the ability to discriminate between different HMA mixes. To address this issue, the researchers explored the Fracture Energy (FE) Index concept as an alternative fracture parameter to characterize and differentiate the cracking resistance potential of HMA mixes subjected to the OT under monotonic loading in the laboratory. Mathematically and as shown in Equation 1, the FE Index was derived and defined as a parametric ratio of the total fracture energy (G_f) to the HMA tensile strength (σ_t) and tensile strain (ε_t) at peak failure load under the OT monotonic testing. The terms associated with the derivation of Equation 7-8 are discussed in the subsequent text.

$$FE\ Index = 1\times 10^3 \frac{G_f}{t\sigma_t}\varepsilon_f \qquad \text{(Equation 7-8)}$$

where, G_f, t, σ_t, and ε_t are defined in Equations 7-1, 7-5, and 7-6, respectively.

The nine mixes that were tested using the OT monotonic test setup were further analyzed using Equation 7-8 to calculate the FE Index values, and the results are presented in Figure 7-10 along with the corresponding OT cycles to failure results. From Figure 7-10, it is immediately noticed that the FE Index values for the different mixes are fairly consistent with their respective repeated OT test performance. The CAM mixes have the highest FE Index values which corresponds to their high OT cycles to failure, whereas the Type B field core and the 4.9 percent AC Type D mixes lie on the lower end of the FE Index array, which is justified by their low OT cycles to failure values. Only exception to this trend is the two Type C (5.8 percent AC) mixes, but again the numbers are insignificantly different. This observation highly enhances the prospect of the FE Index as a surrogate HMA fracture property for differentiating and screening HMA mixes in the lab; an aspect that the Fracture Energy failed to show (Figure 7-9 and Table 7-4).

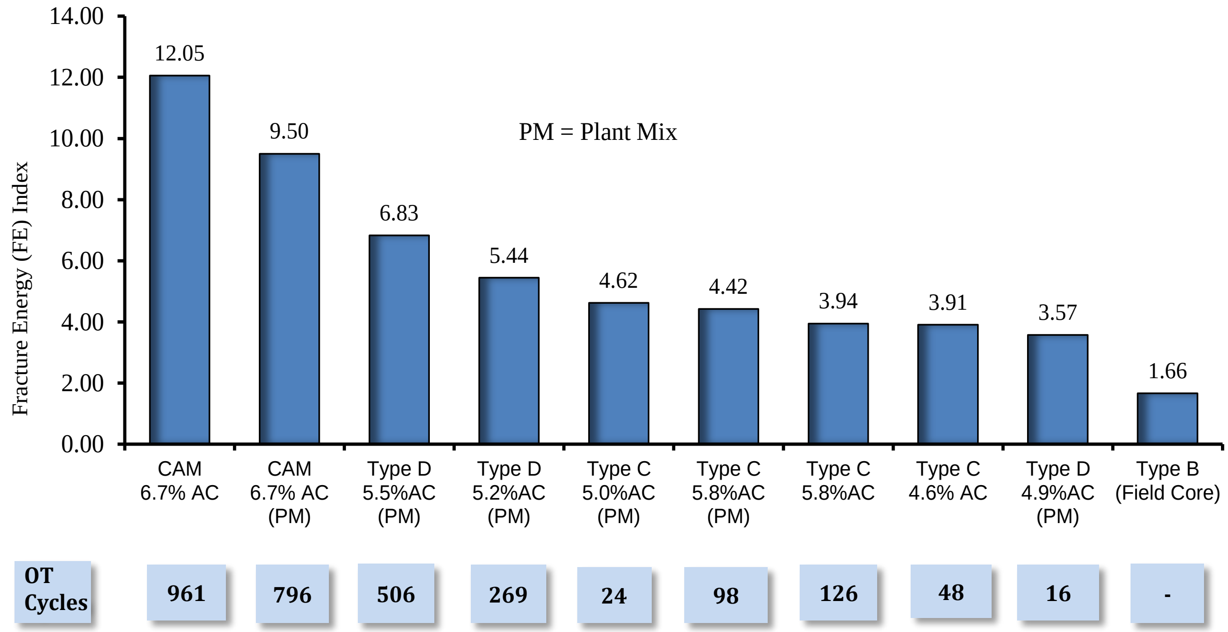


Figure 7-10. FE Index Ranking of HMA Mixes.

Sensitivity to Changes in Asphalt-Binder Content

It is interesting to notice from Figure 7-10 is that this FE Index parameter is able to discriminate among the same mix types based on the asphalt-binder content variations. To further investigate this phenomenon, a Type D mix (PG 64-22 + Quartzite + 20 percent RAP; ⅜″ NMAS, dense- to fine-graded) with three different asphalt-binder contents was tested, and the resulting FE indices were calculated. The results are presented in Figure 7-11 along with the corresponding OT cycles to failure.

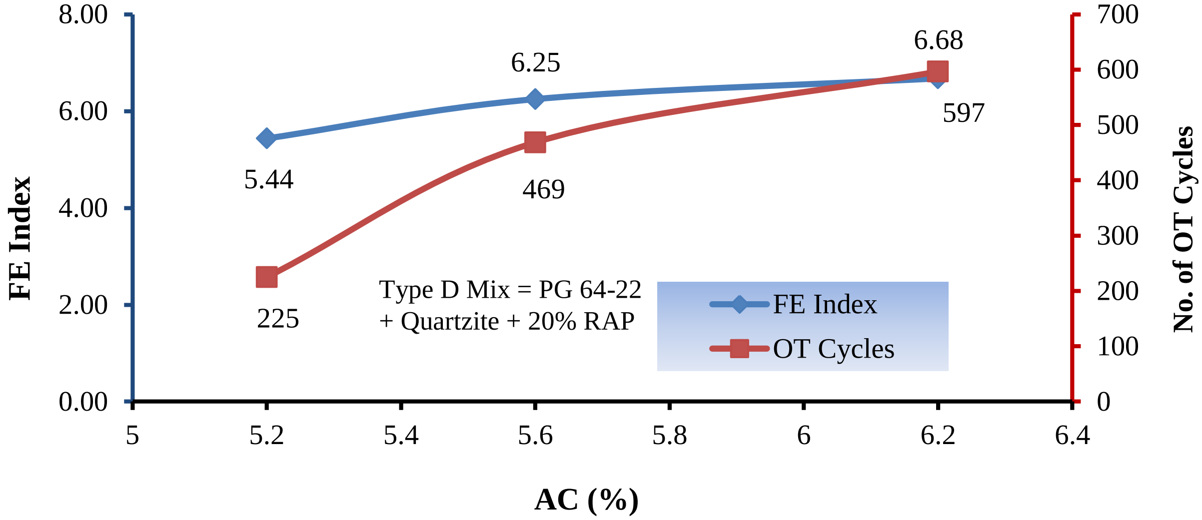


Figure 7-11. FE Index Sensitivity to AC Level.

Figure 7-11 further demonstrates the ability of the FE Index parameter to act as a surrogate HMA mix screener in terms of the effects of AC variations. Both the number of OT cycles and the FE Index values show similar increasing trends with increasing AC. This behavior, however, is quite expected and can be easily explained. Increased asphalt-binder content in the HMA would mean increased ductility and, therefore, a larger area bound under the load-displacement curve, which in turn would result in a higher specific fracture energy (G_f) value. Additionally, because of the increased HMA ductility, the tensile strain (ε_t) at peak failure load or elongation prior to crack failure is also expected to increases in the magnitude. On the other hand, at higher AC levels, the HMA is more flexible (softer and less stiff) and hence, the peak load decreases with increasing AC levels, which in turns decreases the HMA tensile strength (σ_t). From Equation 7-8, it can be clearly seen that the FE Index is directly proportional to the specific fracture energy (G_f) and tensile strain (ε_t); and is inversely proportional to the HMA tensile strength (σ_t). Therefore, both an increase in the former and a decrease in the later values result in an overall increase in the FE Index value; which is evident in Figure 7-11.

However, in terms of the degree of sensitivity, Table 7-5 shows that the number of cycles measured from the repeated loading OT test is more sensitive to changes in the AC levels than the FE Index measured from the OT monotonic “single shot” test; for the particular mix that was evaluated. The change in the OT cycles as a function of AC is over 100 percent while it is below

25 percent for the FE Index. Between the two parameters and if given a choice, the number of OT cycles from the repeated load OT test would thus be preferred.

Table 7-5. Degree of Parametric Sensitivity to AC Variation.

AC Level	OT Cycles (Repeated Loading)		FE Index (Monotonic Loading)		Comment
	Value	% Change	Value	% Change	
5.2%	225	-	5.44	-	
5.6%	469	108%	6.25	15%	OT cycles more sensitive
6.2%	597	165%	6.68	22%	

Sensitivity to Temperature Variations

A similar study was also conducted to investigate the effects of temperature variations on the FE Index values calculated from the monotonic OT test. The samples tested for this study were from a Type C mix (5.0 percent PG 64-22 + Crushed Gravel + 20 percent RAP; ¾″ NMAS, dense-graded). Three replicate samples were tested at each temperature level at a loading rate of 0.125 in. per minute and the resulting FE Index values are shown in Figure 7-12 along with the results from the repeated OT test.

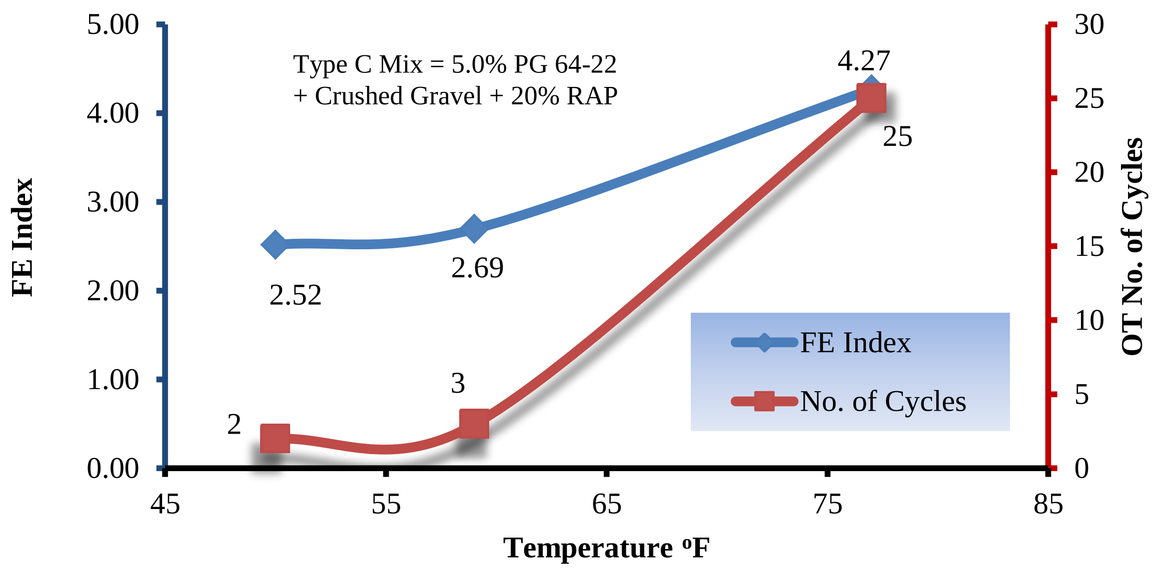


Figure 7-12. FE Index Sensitivity to Temperature.

Once again, Figure 7-12 shows very similar trends for the FE Index and the OT cycles to failure values. At low temperatures, the FE Index values obtained were significantly low (less than one) as were the OT cycles to failure. The curves in Figure 7-12 bear testimony to the fact that at lower temperatures, the HMA mixes become stiffer and more brittle; resulting in instantaneous crack failure under both monotonic and repeated tensile loading. Similar to the case of AC level change, this behavior can also be explained based on the two opposing trends shown by the peak load and HMA ductility with temperature change. Higher temperature leads to lower HMA stiffness (softer material), hence the peak load is reduced, resulting in a reduced HMA tensile strength (σ_t), which is divisor in Equation 7-8.

The dependence of G_f on temperature, however, is not so straight forward as it is on AC and thus, must be interpreted cautiously. Theoretically, an increase in temperature increases the HMA ductility. At lower temperatures, cracks tend to propagate through both the aggregates and the asphalt-binder mastic; whereas at higher temperatures, cracks tend to propagate around the aggregates, thereby making the samples effectively more ductile against cracking. This results in a more widespread HMA load-displacement curve. However, this does not necessarily indicate a direct increase in the G_f value. For the fracture energy, which is an area function of the load (Y-axis) and displacement (X-axis), an increase in the load for stiff mixes (low temperature in this case) means a decrease in displacement (less ductility and elongation) and vice versa for softer mixes (high temperature in this case). Therefore, the load (Y-axis) and displacement (X-axis) always seem to compensate each other and as a result, the total area (fracture energy) may not change significantly as a function of temperature variation. Therefore, while calculating the FE Index using Equation 7-8, the HMA tensile strength and strain values govern the response behavior of the HMA mix with varying temperature and hence, a net increase in the FE Index with increased temperature.

Like for the AC, Table 7-6 again shows that the number of OT cycles measured from the repeated loading OT test is much more sensitive to temperature variations than the FE Index measured from the OT monotonic “single shot” test; for the particular mix that was evaluated. Given a choice between the two parameters, the number of OT cycles from the repeated loading OT test would thus be preferred.

Table 7-6. Degree of Parametric Sensitivity to Temperature Variation.

Temp.	OT Cycles (Repeated Loading)		FE Index (Monotonic Loading)		Comment
	Value	% Change	Value	% Change	
50 °F	2		2.52		
59 °F	3	50%	2.69	7%	OT cycles more sensitive
77 °F	25	1150%	4.27	70%	

Variability in the Test Results

For the FE Index to be considered as an effective HMA fracture property and an HMA mix screener, the variability should be within an acceptable range. Figure 7-13 presents the COV results based variability of the FE Indices for the nine mixes tested in a monotonic OT test setup along with the variability of the corresponding OT cycles to failure from the standard repeated OT test.

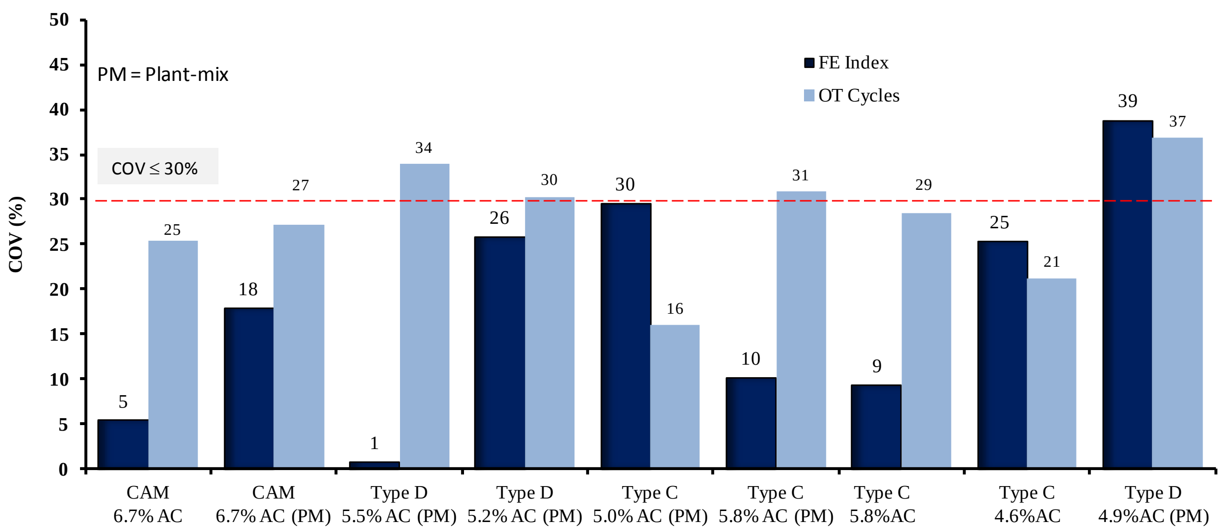


Figure 7-13. Comparison of HMA Mix Variations (FE Index and OT Cycles).

The mixes in Figure 7-13 are assembled following the FE Index ranking (Figure 7-10) and no definitive trend of variability change for either the FE Index or the OT cycles is observed with respect to their cracking performance ranking. However, the Type D (4.9 percent AC) mix does show the highest variability in both in the FE Index and OT cycle values, which corresponds to the mix's poor performance in both monotonic and repeated OT tests. A COV value of less than or equal to 30 percent (i.e., COV ≤ 30 percent) is usually considered as acceptable for OT cycles variability. As evident in Figure 7-13, only two out of nine HMA mixes exhibit COV values that are significantly higher than this threshold level. The average of the OT cycle COV values for the nine mixes presented in Figure 11 is 28 percent with a range of 16 percent to 37 percent, whereas the average FE Index COV for the same mixes is 18 percent with a range of 1 percent to 39 percent.

Variability in the 'effects of AC level change' and 'effects of temperature variation' test results were also calculated based on their respective COV values and the results are presented in Figures 7-14 and 7-15.

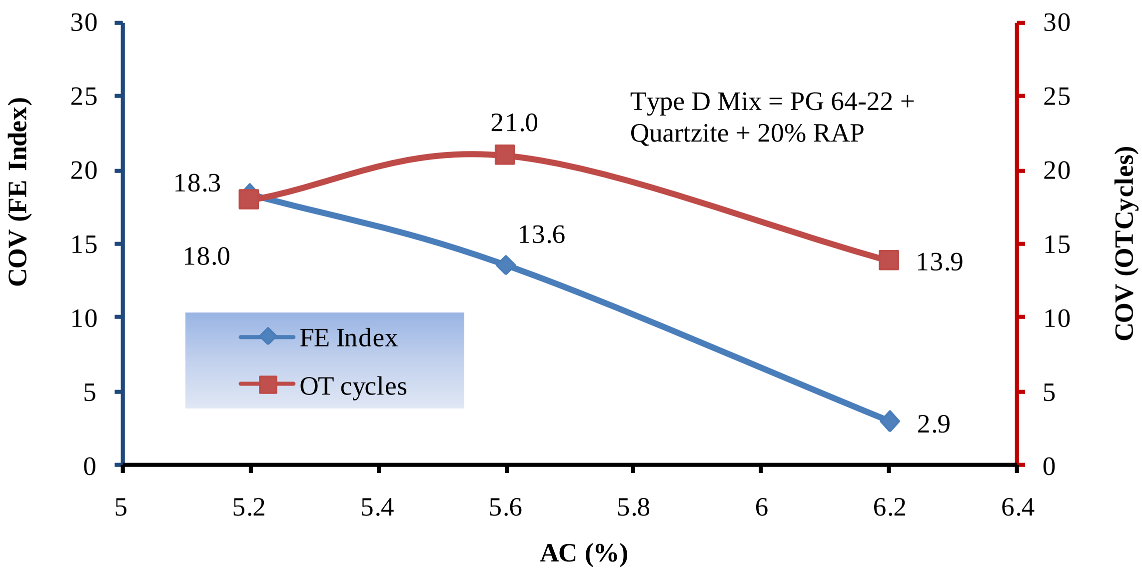


Figure 7-14. Effects of AC Changes on Variability (FE Index and OT Cycles).

Figure 7-14 shows the effects of change of AC levels on the test result variability. The figure shows that the FE Index test results become more repeatable with an increase of AC level. One possible explanation of this response behavior is the increased HMA stiffness at low AC that gives rise to more brittle and unpredictable specimen failure patterns, hence the higher variability. At higher AC content, on the other hand, the OT specimens are less stiff and hence, the failure is of a more ductile mode, which somewhat increases the uniformity in the test results.

Following the same arguments, one would expect the OT cycles to failure results to follow similar trends and become more repeatable. However, from Figure 7-14 no definitive trend for the OT cycle variability is observed. Further study is recommended for understanding of this issue. Intuitively, this result may suggest that variabiliy in the repeated OT test is not only a function of the HMA response behavior but that sample fabrication and test setup may also play a role. Note in Figure 7-15 that while a total of five replicate samples were tested at each temperature for the OT cycles, only the best three results with the lowest COV were plotted in the figure. For FE Index, only three replicate samples were tested at each temperature.

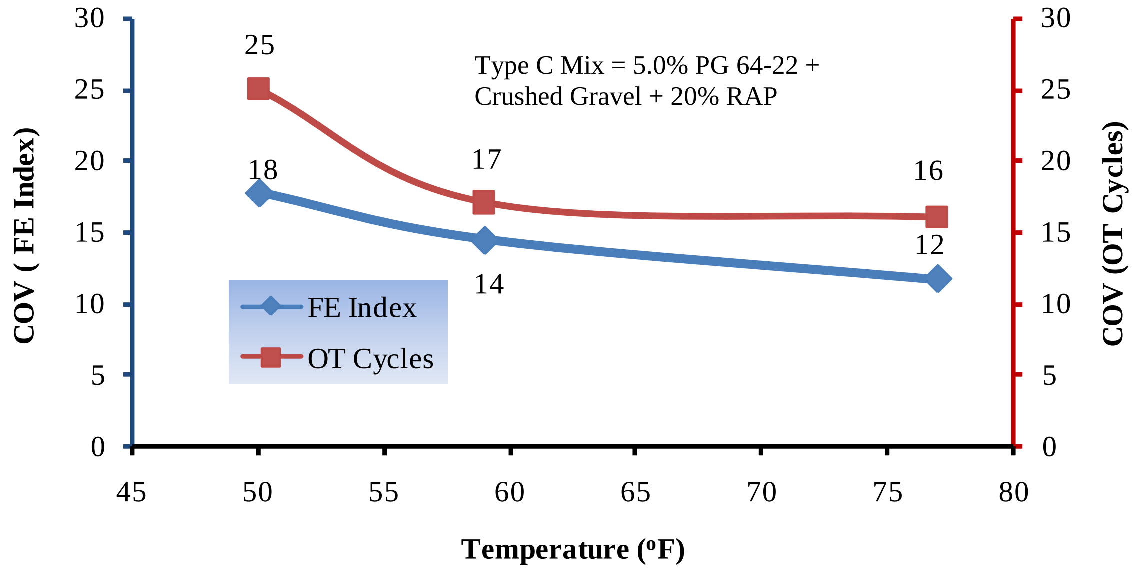


Figure 7-15. Effects of Temperature Changes on Variability (FE Index and OT Cycles).

Figure 7-15 presents the effects of change of specimen temperature on the test result variability based on COV values. The figure shows that variability for both FE Index and OT cycles decreases with increasing temperature. At lower temperatures, the mixes tend to be stiffer and the resulting failure patterns are more brittle and unpredictable, hence the higher variability. The opposite is true when the specimens are tested at a higher temperature, i.e., less stiff mix, more ductile and uniform failure mode and therefore, more variability in results. However, more mix types need to be tested to further validate these observations. In general, the following key findings can be concluded from this particular task:

- In addition to testing in repeated loading mode and measuring the number of OT cycles as a means to quantify the HMA crack resistance potential, the current OT setup can also be run in monotonic loading "single shot" test configuration to characterize the HMA crack resistance potential in terms of measuring the following fracture properties: HMA tensile strength, tensile strain at peak failure load, HMA tensile modulus (stiffness), fracture energy (FE), and FE index.
- Compared to the repeated loading OT, the monotonic OT loading single shot test is more repeatable with very low variability in the test results (i.e., COV ≤ 30 percent), which is comparable to other monotonic fracture tests such as the IDT, SCB, or DSCTT.
- Compared to its repeated counterpart and just like any other monotonic crack test evaluated by these researchers, the OT monotonic test (single shot) was not as effective in screening and discriminating mixes; but it is a fairly shorter test to run when compared to its repeated loading counterpart. However, as only a limited number of mixes were evaluated, further research with more mixes is strongly recommended to substantiate these findings.
- For the mixes evaluated, the fracture energy measured from the OT monotonic loading single shot test was less sensitive and unable to readily capture the effects of changes in the asphalt-binder content and temperature variations. However, the FE index exhibited promising potential, but not as effective as the number of OT cycles (repeated loading mode).
- The peak load, tensile strength, and tensile modulus measured under OT monotonic loading single shot test exhibited some degree of sensitivity to both changes in the AC level and temperature; but were not as good as the number of OT cycles (from repeated loading) in terms of differentiating mixes based on the discriminatory ratios that were compared.
- Of all the fracture parameters evaluated, the FE index (Figure 7-10) appeared to be the best parameter next to the OT cycles to use as supplementary or surrogate fracture parameters for screening, discriminating, and ranking HMA mixes in their order of superior cracking resistance performance. Consideration should be given to explore this parameter further.

ALTERNATIVES TO NUMBER OF CYCLES TO FAILURE

As mentioned earlier, in the current OT test procedure, a specimen is deemed to have failed once the cycle peak load is 7 percent or below that of the first loading cycle. It is based on the assumption that at the 7 percent retained load level; the cracks have propagated through the entire thickness of the specimen. However, there is a wealth of other information that is not used in summarizing the information from any particular test. In this subtask, the research team evaluated other potential methods of defining the cracking resistance of the mix under the repeated loading OT test. Three options were considered as an alternative to the current practice:

- Area under the load versus cycles curve as an indicator of pseudo fracture energy.
- Number of cycles to reach 50 percent, 75 percent, and 85 percent load reductions from the first cycle load. Ultimately, this will also address the issue of whether the current failure criterion is sufficiently applicable to all mixes, needs to be modified, or should be different for different mixes.
- Rate of load decrease as a function of time or the number of OT cycles to failure, i.e., change in slope.

Area under the Load versus Cycles Curve

The plot of OT cycle peak load versus number of cycles (Figure 7-16) is used to measure the pseudo fracture energy of the OT test, which is defined as the work done to propagate the crack through the thickness of the sample. Table 7-7 presents the calculated pseudo fracture energy values, as a function of the opening displacement and the OT specimen X-cross sectional area, for six HMA mixes along with the corresponding regular OT results.

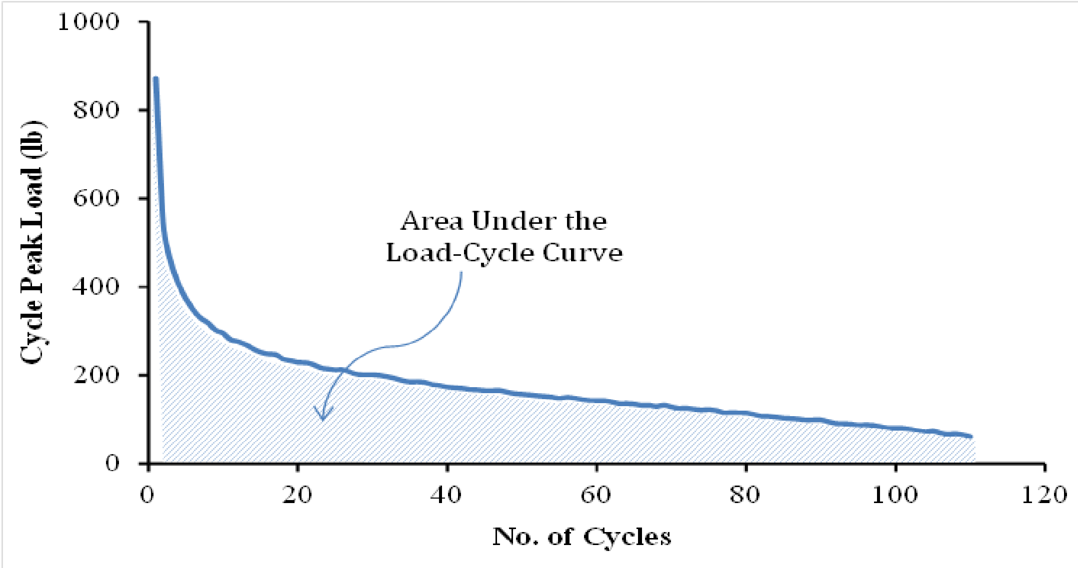


Figure 7-16. Cycle Peak Load vs. No. of Cycles Curve for a Typical OT Test.

Table 7-7. Area under Load-Cycle Curve (Pseudo Fracture Energy).

Mix	OT Cycles		Area under Load-Cycle Curve	
	Avg	COV	Avg (lb-in/in^2)	COV
Type D 5.2% AC (Plant Mix)	239	32.3%	183	33.6%
Type D 5.5% AC (Plant Mix)	404	41.9%	328	35.4%
CAM 6.9% AC PG 76-22 (Valero) + Capitol Limestone	834	4.7%	425	7.5%
CAM 6.9% AC PG 76-22 (Martin) + Capitol Limestone	168	40.4%	115	43.5%
Type D 4.9% AC (Plant Mix)	559	7.5%	205	11.4%
Type C 5.0% AC (Plant Mix)	43	44.3%	38	52.5%

From the results in Table 7-7, it is evident that no significant improvement in variability is achieved through this approach. The COV of the pseudo fracture energy is higher than that of OT cycles, with the exception of Type D 5.5 percent AC (plant mix). The reason behind the similarity in corresponding COV values for the different mixes is easily understandable, since by definition, the pseudo fracture energy values are directly proportional to the OT number of cycles, i.e., the higher the OT cycle, the higher the pseudo fracture energy.

Number of Cycles at Auxiliary Load Drop Points

As an alternative to calculating the number of cycles for 93 percent load drop, the researchers considered three alternate load drop points: 50 percent, 75 percent, and 85 percent. The initial assumption was that the number of cycles to reach these load drop levels would yield more repeatable results than the current practice. Figure 7-17 explains the procedure for two HMA mix types.

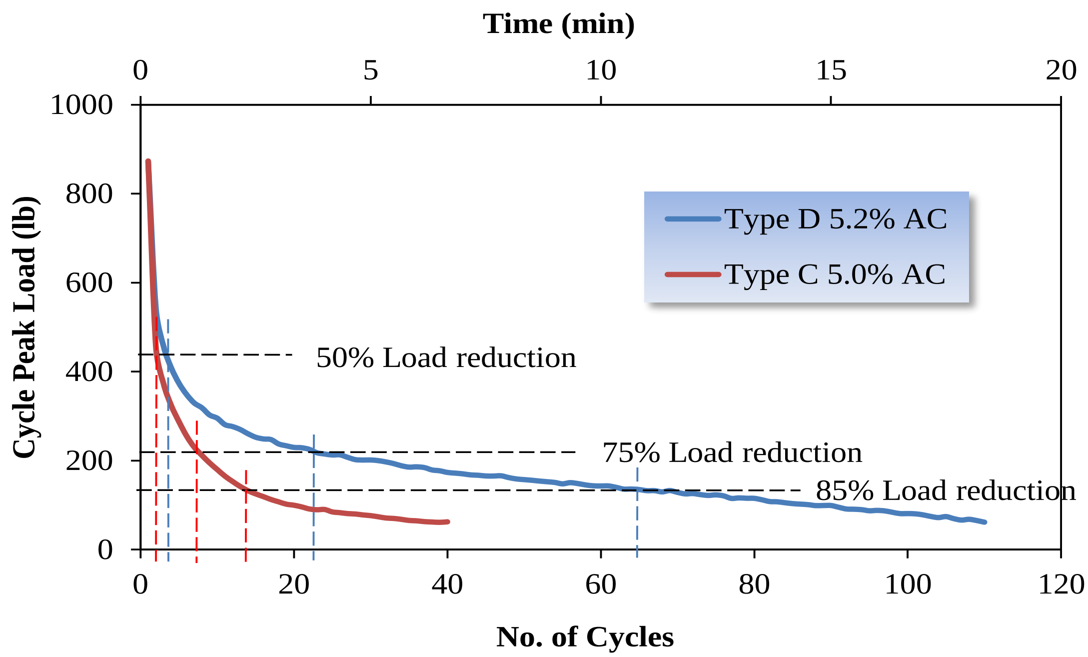


Figure 7-17. Load-Time Cycle Graphs: Number of Cycles at Auxiliary Load Drop Points.

OT results for four mixes were analyzed using this approach for both air-dried and oven-dried samples. Table 7-6 presents the results along with the regular OT cycle results at failure (93 percent load drop).

Table 7-8. Number of OT Cycles at Auxiliary Load Drop Points.

Mix	Drying Method	Average No. of OT Cycles to Load Reduction of-							
		50%	*COV*	75%	*COV*	85%	*COV*	93%	*COV*
Type D 5.2% AC (Plant Mix)	Air	3	*0.9%*	21	*8.9%*	58	*10.4%*	92	*8.5%*
	Oven	3	*1.7%*	22	*5.2%*	70	*8.4%*	118	*6.3%*
Type D 5.5% AC (Plant Mix)	Air	7	*4.4%*	70	*10.5%*	390	*1.9%*	527	*26.1%*
	Oven	4	*4.3%*	40	*21.3%*	185	*21.0%*	520	*19.5%*
Type D 4.9% AC (Plant Mix)	Air	2	*6.2%*	19	*17.2%*	62	*14.7%*	176	*31.6%*
	Oven	3	*3.9%*	22	*9.8%*	106	*16.2%*	560	*7.5%*
Type C 5.0% AC (Plant Mix)	Air	2	*3.1%*	5	*19.8%*	8	*15.5%*	25	*22.3%*
	Oven	2	*5.4%*	7	*9.2%*	13	*12.1%*	24	*15.6%*

From the table, it is evident that for the same mix, the 50 percent load drop point yields the most repeatable results, while a 93 percent load drop is associated with the highest COV values and COV at 75 percent and 85 percent load drop lie in between. Despite being highly repeatable, the OT cycles at 50 percent and 75 percent load drops are too small to sufficiently differentiate or screen mixes and hence, present no meaningful interpretation of the results. Figure 7-17 shows that these two load drop points are associated with very sharp load drops and hence, a small number of cycles. The 85 percent load drop gives reasonable repeatability, and the numbers of cycles are reasonably large enough to provide meaningful interpretation and screen mixes. However, the biggest challenge in using these alternative load drop points is defining their proper physical interpretation and associating them with field data. Studies have shown that at 93 percent load drop, the specimens are completely failed, which is marked by the propagation of the crack throughout the entire thickness of the specimen, but the other load drop points cannot be associated with any such interpretations. More studies and tests are needed before any reasonable conclusion can be drawn from this sub-study along with field validation.

Rate of Load Decrease (Slope Change)

This aspect was tried, but it yielded inconclusive results. There were problems in determining and defining the point of sharp change in slope beyond 50 percent load reduction for most mixes. Beyond 50 percent load reduction, the curves tendered to exhibit a constant slope with hardly any definable point of change.

OTHER ENGINEERING PARAMETERS FROM THE RESULTS OF THE OT TEST

Since Majidzadeh et al. (1970) introduced fracture mechanics concepts into the field of pavements, the fracture mechanics approach has been widely used in predicting pavement cracking (fatigue, low temperature, and reflective) analysis. Paris and Erdogan (1963) proposed the generally accepted crack propagation law in the form of Equation 7-9. Many researchers have successfully applied it to asphalt concrete for the analysis of experimental test and prediction of reflective cracking and low temperature cracking.

$$\frac{dc}{dN} = A(\Delta K)^n \qquad \text{(Equation 7-9)}$$

where

c = Crack length.

N = Number of loading cycles.

A, n = Fracture properties of asphalt mixture determined by experiments.

ΔK = Stress intensity factor (SIF) amplitude, depending on the geometry of the pavement structure, fracture mode, and crack length.

Equation 7-9 can be used to calculate the number of load cycles, N_f, needed to propagate a crack through the asphalt overlay thickness of h as illustrated in Equation 7-10:

$$N_f = \int_o^h \frac{dc}{A(\Delta K)^n} \qquad \text{(Equation 7-10)}$$

From the above equation, it is evident that to calculate the number of load cycles to failure, SIF and the two fracture parameters (*A*, *n*) need to be known. These two fracture parameters depend primarily upon the compliance and the tensile strength of the mix, and the surface energies of the asphalt-aggregate mixture. This finding has given rise to several useful simplifying and empirical relations that permit fairly accurate estimates of the fracture properties on the basis of simpler laboratory tests. The OT has proved success in directly measuring the *A* and *n* properties and is currently being implemented at TTI (Cleveland et al., 2003).

SUMMARY

This chapter discussed possible data analysis procedures that could utilized as alternatives to the currently practiced number of cycles to OT specimen failures. Three alternative approaches were considered in this respect, the first of which was to run the OT test in a single-shot monotonic loading mode. While this approach was successful in measuring several critical HMA fracture properties, it was somewhat unsuccessful as an effective HMA mix screener in comparison to the repeated loading OT test. However, the OT monotonic "single shot" test exhibited potential as a supplement (or surrogate) crack test to the standard repeated loading OT test, particularly in terms of the FE index.

The second alternate data analysis approach presented in this chapter was calculating the area under the load versus the cycles curve from a repeated OT test as a measure of the pseudo fracture energy. This approach was unsuccessful in minimizing variability. Lastly, some alternatives to the use of the 93 percent load drop point to calculate OT cycles to failure were proposed. Whereas some of them (50 percent and 75 percent) produced very low repeatability, questions remained over their practicality and correlation to field data. However, 85 percent load drop seemed to be a reasonably good choice as an alternative to the currently practiced load drop of 93 percent; but this still requires validation with field performance data.

CHAPTER 8.
OT SPECIFICATION MODIFICATIONS

This chapter contains a summary of the findings of the preceding chapters and researchers' proposed modifications to the existing OT specification Tex-248-F. Appendix I presents a complete draft of the proposed modifications, and this chapter cites the key components warranting modifications including the following:

- Modifications to the current OT testing procedure.
- Modifications to the OT data analysis procedure.

MODIFICATIONS TO THE OT TESTING PROCEDURE

The researchers proposed modifications to the current OT test procedure specification Tex-248-F based on the sensitivity evaluation of the critical OT steps (Chapter 5) and experience gained from past studies. A brief discussion of the principal modifications is presented below:

- Based on the discussion in Chapter 5, researchers proposed testing four or five replicate specimens to replace the current practice of testing three (Appendix I—Section 5.1.1). The OT cycles to failure of the best three replicates should be presented. A set of best three replicates should be chosen based on the lowest COV considerations. Toward this goal, an Excel Macro was developed to automatically pick the best three results based on the lowest COV. The Macro will be included as an integral part of the modified Tex-248-F specification.
- Oven drying of the OT specimens at a maximum temperature of 40 ± 3°C (104 ± 5°F) for a minimum of 12 hrs to constant weight was proposed (Appendix I—Section 5.2.3). The specified drying temperature in the current specification is 60 ± 3°C (140 ± 5°F), which is deemed to be too high for some mixes (e.g., mixes with PG 58-28 and/or PG 64-22 asphalt binder).
- The current OT specification does not specify the allowable sitting time of the specimens after molding. To address this issue, a recommendation was made in the proposed modified specification to test the specimens within 5 days of molding (Appendix I—Section 4.1).
- The modified specification proposed the use of Devcon two-part, 2-ton epoxy for gluing the specimens to the OT testing plates, and the glue quantity is specified to be

16.0 ± 0.5 g or 16 ± 0.5 ml, i.e., two-third of the two-part tubes (Appendix I—Section 5.3.2). Additional instructions are included in Section 5.3 to make sure that the gluing procedure is consistent.

- The mounting procedure of the specimen assembly to the testing device and the steps to be followed prior to starting the OT test are prescribed in detail in the proposed modification (Appendix I—Section 5.6 and 5.7). The proposed modifications include ensuring that the machine is in displacement mode before placing the specimen assembly, putting the specimen assembly in the machine with one of the dowel pins aligned in the sleeve in the fixed plate, and waiting for a minimum of 10 minutes prior to starting the test for specimen relaxation.
- The maximum allowable number of cycles for an OT specimen that does not reach a 93 percent load drop is reduced from 1200 cycles to 1000 cycles in the proposed modification. Also, a visual count of the number of cracks (zero, single, or more) at the top of a failed specimen was proposed to be included in the test report.

Table 8-1 presents a list of the proposed modifications to the OT test specification (Tex-248-F, 2009).

Table 8-1. Proposed Modifications to Tex-248-F.

Item	**Current Spec**	**Proposed Modification**	**Comment**
5.2.3	"Dry the trimmed specimen at a maximum temperature of 60 ± 3°C (140 ± 5°F) to constant weight. Maximum drying time should be 24 hours. Discard all samples that are in the oven more than 24 hours."	"Dry the trimmed specimen at a maximum temperature of 40 ± 3°C (104 ± 5°F) to constant weight. Oven temperature should be kept constant throughout the sample drying process. Minimum drying time should be 12 hrs and should not exceed 24 hrs. Discard all samples that are in the oven more than 24 hrs."	Currently still evaluating the quicker Core Dryer (< 20 minutes per sample)
4.1 & 5.1.1	"Make three cylindrically molded (6-in by 4.5-in)	1) Make two or three (6-in by 5-in) molded samples and trim 2 OT specimens from each, or.	

	specimens according to Section 4. and trim 1 OT sample from each."	2)Make four or five (6-in by 2.5-in) molded samples and trim 1 OT specimen from each.	
6.2		"For the final analysis and reporting, pick the results of the best 3 replicates out of 5 or 4 based on the lowest COV (can use Macro if needed) and report the following additional data: - The average peak load - The average OT cycles - The Stdev and COV"	This is an addition
5.3.3		"Glue the specimens individually and use 16 ± 0.5 g (16 ±0.5 ml or 2/3 tube) on the old plates or 14 ± 0.5 g (14±0.5 ml) on the new TxDOT plates of the 2-part 2-ton epoxy resin per specimen. Cover the majority of both the base plates with the epoxy including the metal strip. Secondly, apply some glue (remaining from the 16 ± 0.5 g) to the specimen surface that will be attached to the base plates. Glue the trimmed specimen to the base plates."	
4.1		"Note 2 – It is recommended that the specimens be tested within 3 to 5 days from the day of molding. And once testing has started, similar replicates should preferably be completed within 48 hrs. Otherwise, the time period from the day of molding to the day of testing each specimen should be recorded and reported as part of the results."	Addition of "Note 2".
5.7.2 & 6		In addition to the number of cycles, consider using OT for measuring tensile strength, strain, and fracture energy index as supplement or substitute to IDT.	

MODIFICATIONS TO THE OT DATA ANALYSIS PROCEDURE

The current OT test specification (Tex-248-F, 2009) does not specify any instruction for the analysis of the reported test data. The OT test setup automatically reports essential test data, i.e., peak load, number of cycles to failure (93 percent drop from the first cycle load), and test temperature, and a mere average number of cycles and peak load is reported as a means to measure the cracking susceptibility of a mix. Also, the OT cycle COV is reported as a check for the test variability. Attempts were made to establish alternative data analysis procedures to gain a better insight into the HMA cracking process and to collect additional information on an HMA mix through the OT test. Single-shot monotonic tests were run using the OT setup as an alternative and/or supplement to the traditional HMA fracture tests, e.g., the IDT and SCB. While this approach was successful in measuring several critical HMA fracture properties and exhibited very good repeatability with low variability in the test results, it was somewhat less effective as an HMA mix screener when compared to the repeated OT test. However, both the tensile strain and FE index from the OT monotonic test exhibited promising potential as supplementary or surrogate fracture parameters for quantifying the HMA cracking resistance properties.

Attempts were also made to use some alternatives to the 93 percent load drop point to calculate OT cycles to failure. Whereas some of them (50 percent and 75 percent) produced very low repeatability, questions remained over their practicality. However, 85 percent load drop seemed to be a reasonably good choice as an alternate to the currently practiced load drop of 93 percent. Lastly, as an alternative to the number of cycles, the use of a pseudo fracture energy, which is necessarily the area under the cycle peak load versus the number of cycles curve, was tried. This approach was unsuccessful in minimizing variability.

While some of these attempted alternative data analysis procedures had encouraging findings that will surely lead to improvements in the OT test in the future, at this point, the researchers are not able to propose any modifications to the OT test specification based on these studies. More tests and thorough studies are required before any concrete conclusions can be reached regarding these issues.

SUMMARY

This chapter listed the focal points of the modifications that were proposed to the OT test specification. These modifications are based on a thorough study of the OT testing procedure, which comprised of extensive laboratory testing and the subsequent data analysis. The proposed modifications are expected to improve the overall consistency of the OT repeated test throughout the different laboratories using the OT and make it a much more repeatable test for evaluating the HMA cracking susceptibility. For a supplementary or surrogate crack test, the OT monotonic test with the FE index parameter may be considered.

CHAPTER 9.
CONCLUSIONS AND RECOMMENDATIONS

The OT test is a fast and effective means for evaluating the cracking susceptibility of HMA in the laboratory. The OT test effectively simulates the reflective cracking mechanism of the opening and closing of joints and/or cracks, however, the repeatability and variability of the test results have been major areas of concern. To address this issue and to refine the overall applicability of the OT test, researchers undertook a study to commence a step-by-step evaluation of the OT testing procedure. The findings of this study were presented in detail in the preceding chapters of this report. This final chapter summarizes the overall theme of this report and highlights the major findings of the study.

MAJOR FINDINGS OF THE STUDY

The findings of this study are presented in the following subsections.

Findings from the OT Survey and OT Users' Group Meeting

In order to have an in-depth consensus understanding of the key issues/problems related to the OT and formulate appropriate remedial strategies/work plans, researchers sent a survey questionnaire to various OT users both locally and nationally. The key findings from this preliminary level of the study were:

- The OT test has a wide range of advantages that are accepted by the different laboratories using the OT; these advantages include but are not limited to speed and reliability, ability to test both lab-prepared samples and field cores, correlation with field performance data, and ability to perform as an HMA mix screener.
- There are several challenges associated with the OT test, most critical of which are the complicated sample preparation process and high variability in test results.
- Some critical remedial measures that might improve the robustness and repeatability of the OT test include (a) modifying the OT test parameters (i.e., loading rate, test temperature, acceptable OT cycles) appropriately as needed for different materials/mixes; (b) using more than three replicate samples to get acceptable results; (c) modifying the molded sample dimensions to reduce the wastage of materials; (d)

standardizing and clearly quantifying the necessary glue amount per sample; and (e) preferably testing the OT samples within 5 days of molding.

Findings from the OT Sensitivity Evaluation

Researchers conducted a step-by-step evaluation of the current Tex-248-F OT test procedure so as to have an in-depth understanding of the key issues related to the OT testing procedure and to find ways to improve the overall test performance. The major findings from this study were as follows:

- Testing five or four replicate OT specimens and reporting the best three results instead of the current practice of testing three gives better repeatability. A set of best three replicates should be chosen based on the lowest COV considerations. As indicated in the included CD, an easy to use macro was developed to aid in picking the best three out of four or five total replicate samples.
- Overnight oven drying of the OT specimens at a maximum temperature of 40 ± 3°C (104 ± 5°F) for a minimum of 12 hrs to constant weight is preferable to air drying.
- OT specimens having air-void values between 6.5 percent and 7.5 (i.e., 7±0.5%) percent gave the most repeatable results. For practicality, however, 7±1 percent may still suffice.
- The specimens need to be tested within 5 days of molding, i.e., specimen sitting time between molding and testing should not exceed 5 days.
- The use of 16.0 ± 0.5 g or 16.0 ± 0.5 ml (i.e., two-third) of Devcon 2-part, 2-ton epoxy for gluing the specimens to the old OT testing plates is the most economical and gives the most repeatable results.
- No conclusive trend was displayed by the OT variability with changing test temperatures. However, the tolerance limit should not exceed ± 2°F.
- The OT result variability showed a slight improvement in repeatability with decreasing opening displacement. However, changing these loading parameters also requires validation with field performance data. Therefore, the current practice of 0.025 in. opening displacement is recommended.

- The new TxDOT OT plates are easier to use as compared to the old plates and therefore, consideration should be given to using these new plates. However, caution should be exercised when using the metal bars as the gap spacer.

Findings from the Evaluation of Alternate OT Sample Mold Sizes

Material wastage associated with the current practice of OT specimen preparation from a 4.5 in. tall molded sample is a major issue of concern. This approach (one specimen from 4.5 in. tall molded sample) has failed to address the OT variability issues. Researchers thus conducted a study to evaluate alternative sample molding approaches, and the findings from this study are presented below:

- Three alternative sample molding approaches were evaluated in addition to the current practice. They were (a) cutting two specimens from a 4.5 in. tall molded sample, (b) cutting two specimens from a 5.0 in. tall molded sample, and (c) cutting one specimen from a 2.5 in. tall molded sample.
- The OT test results and specimen air voids do not show considerable variation with the different specimen preparation approaches.
- The current practice of cutting one OT specimen from a 4.5 in. tall molded sample involves the most material waste (but without minimizing variability), whereas cutting two specimens from a 4.5 in. tall molded sample is the least wasteful. However, the later approach has workability issues, which are minimized by slightly increasing the molded sample height to 5.0 in.
- The percent material wastages when two specimens are cut from a 5 in. tall molded sample and when one specimen is cut from a 2.5 in. tall sample are the same. However, the former involves less laboratory time and work.

Findings from the Evaluation of Alternative Data Analysis Methods

Various possible data analysis procedures as alternatives to the currently practiced number of OT cycles to specimen failures were evaluated. The findings were as follows:

- A single-shot monotonic test run in the OT test setup can successfully evaluate HMA fracture properties, and this test can be used as an alternative and/or supplement to the traditional HMA fracture tests, e.g., IDT and SCB. Although the FE index exhibited promise potential, this test still requires more work and refinement, and hence, cannot act as a complete replacement to the repeated OT test. As only a limited number of mixes were evaluated, further research with more mixes is strongly recommended to substantiate these findings.

- Pseudo fracture energy can be calculated from the load versus cycle curve generated from a repeated OT test. However, its variability level is indifferent from that of the number of OT cycles to failure; and hence, no need to implement it.
- Auxiliary percent load drop points can be used in addition to or as an alternative to the current practice of using 93 percent load drop point to calculate the number of OT cycles to failure. Whereas some of them (50 percent and 75 percent) produced very low repeatability, questions remained over their practicality. However, 85 percent load drop seemed to be a reasonable option; however, the major challenge is correlating and validating this criterion (85 percent) with field performance data.

Supplementary or Surrogate Crack Tests

Based on the data presented in this interim report, the OT monotonic "single shot" test is a viable option as a supplementary and/or surrogate crack test, but not as a complete replacement to the standard repeated loading OT test. The fracture parameters of consideration from the OT monotonic test should be the FE index.

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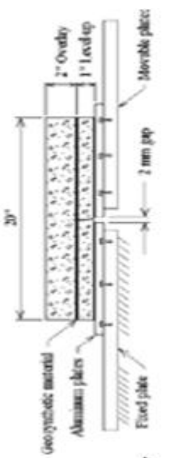
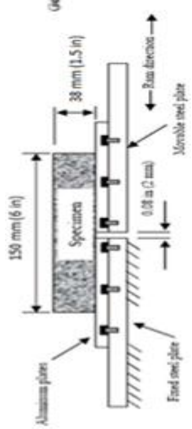
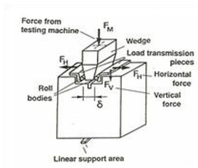
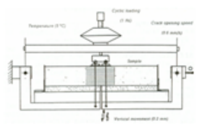
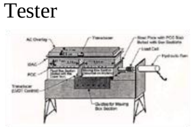
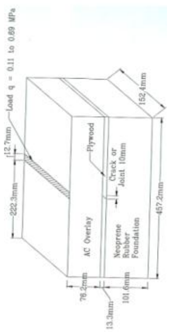
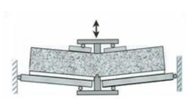
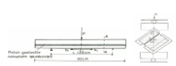
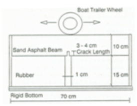
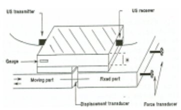
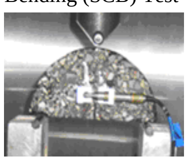
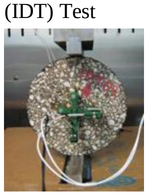
APPENDIX A. LIST OF CRACK TESTS REVIEWED

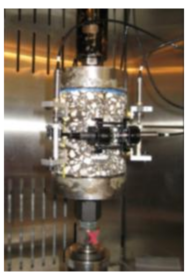
#	Test Type & Schematic	References	Materials, Sample Prep, & Dimensions	Test Loading Parameters	Output Data & Results	Reported Advantages	Reported Disadvantages	Used In
1	OT: TTI Upgraded Overlay Tester 	Loria-Salazar. (2008)	– Cores: 6 in. diameter – Beams: 6×3×2 in.	– Tentative pass/fail criterion on reflective cracking resistance is 300 cycles. – Temp: 77ºF (25ºC) – Displacement: 0.025 in (0.64 mm). – Triangular cyclic load. – 10 seconds/cycle. – When a rich bottom layer is used, the reflective cracking life in the Overlay Tester should be at least 750 cycles.	– Number of repetitions versus crack length – Number of repetitions versus testing time – Load – Time	– Consistency between the mixtures' test results and their corresponding field performance	– Sensitive to the testing temperature, opening displacement, asphalt-binder content and grade, and air voids.	-
		Hajj et al. (2010)	– Spec T-248-F – Short-term aging: 275°F, 4 hours prior to compaction. – Long-term aging: 185°F, 5 days prior to compaction. – Mix type: four mixes with PG64-28NV and PG 76-22NV binders. – NDOT T2C, NDOT T3, – TX CAM, & UTSRC	– Temperature : 77 F Max 0.025" displacement , 1200 cycles (min 750) – 50 F max, 0.018" displacement , 4000 cycles allowed – 5s loading/ 5 s unloading – Failure criteria: 93% drop in peak load – 21 lbf torque force for tightening the screws/bolts –	– One sample 105 cycles – TX CAM and UT SRC interlayer mixes better than NDOT T2C mixes – Regardless of the binder grade used, the UT SRC interlayer mixes were found to have significantly better resistance to reflective cracking than the other interlayer mixes.	– Testing the mixes at 50°F, 0.018" displacement, and for 4000 loading cycles was found to be appropriate for the type of mixes and binder grades used in Nevada.	– Performing the TTI OT test at 77°F and for only 1200 cycles was not enough to capture the differences in mix resistances to reflective cracking for NV mixes.	Reno, Nevada, USA
		Bennert (2009) Bennert and Dongré (2010) Bennert et al. (2011) Bennert and Ali (2008) Bennert et al. (2009)	– Spec T-248-F – Mixes: RAP, surface mixes, NJDOT mixes, WMA, SMA, interlayer mixes, Superpave mixes, etc.	– T-248-F – 59°F, 0.025" displacement for surface mixes.	– > 300 cycles – Load vs. displacement curve	– Reliable test for evaluating crack resistance of HMA – Field cores or gyratory compacted – Relatively quick – Results found correlated to flexible and composite pavements – Sensitive to RAP content and WMA additive/technology	– Sample prep (gluing and cutting)	Rutgers, NJ, USA

#	Test Type & Schematic	References	Materials, Sample Prep, & Dimensions	Test Loading Parameters	Output Data & Results	Reported Advantages	Reported Disadvantages	Used In
	TTI – OT	Zhou and Scullion (2003) Tex-248-F, (2009)	– Tex-248-F	– Tex-248-F	– Tex-248-F	– Tex-248-F	– Tex-248-F	Texas, USA
2	Technical University of Vienna, Austria—Wedge Splitting  	Loria-Salazar (2008)	– Cubical or prismatic	– Static monotonic loading – Loading rate 0.05 in/min – Three temperatures: 8°C, -0.5°C, and -21°C	– Horizontal force versus displacement – Maximum vertical force versus temperature – Fracture energy versus temperature	– The specific fracture parameter can better describe the fracture behavior of the material.	– The maximum splitting force is not an appropriate parameter to differentiate between HMA mixes since two different mixes can have the same maximum splitting force and different fracture behavior. – No field data	Vienna, Austria
3	LPR-Tester 	Loria-Salazar (2008)	– Beams: 24×2.8×2.8 in.	– Cyclic vertical load: 1 Hz – Static horizontal load: – 0.024 in/hr – Constant temperature (5°C)	– Crack initiation time & length – Crack propagation time & length – Breaking time	– The behavior of stress absorbing membrane interlayer (SAMI) is more similar to that of paving fabrics.	– No field data	France
4	University College of Dublin—Accelerated Simulative Wheel Tracking 	Loria-Salazar (2008)	– Beam: Bottom-up cracking: 5.5×11×2.0 in. – Beam: Top-down cracking: 5.5×10.2×2.0 in.	– Cyclic wheel load: 21 cycles/min – Test temperature: 25°C	– Number of wheel loading repetitions versus crack length – Deformation of the slabs over the central 8 in. throughout the test	– None reported	– No field data – Still no tests performed	Dublin
5	University of Illinois Tester 	Loria-Salazar (2008)	– HMA layer on top of a PCC slab of 6×90×2.7 in.	– Cyclic uniaxial load: frequency 0.0016 in/min (triangular) – Temp: −1.1°C	– Strain in HMA overlay as a function of test – Crack length versus time – Load cycles	– The interlayer stress – Absorbing composite – ISAC had a much better performance than other commercial products when it was tested in the proposed test device.	– No field data	Illinois, USA
6	Aeronautical Technological Institute, ATI, Brazil	Loria-Salazar (2008)	– Beams: 18×6×3 in.	– Sinusoidal load: 20 Hz	– Permanent strain versus number of load cycles – Tensile stress versus	– The HMA overlay reinforced with geogrid had a life up to six times higher than an HMA overlay	– No field data	Brazil

#	Test Type & Schematic	References	Materials, Sample Prep, & Dimensions	Test Loading Parameters	Output Data & Results	Reported Advantages	Reported Disadvantages	Used In
					crack length	without it.		
7	Florida Atlantic University, USA 	Loria-Salazar (2008)	– Beams: 18×6×7.5 in.	– Static – Cyclic (sinusoidal) load: 2 Hz	– The load value or number of repetitions to first reflected crack – The load value or number of repetitions for crack propagation to half way of overlay	– At the same load ratio, the slabs having geogrids embedded at the bottom showed better resistance to reflection cracking compared to specimens in which the geogrid was simply attached to the bottom with a tack coat. – It was found that geogrid embedded at mid-height was more effective than geogrid embedded at the bottom of overlay.	– No field data	Florida , USA
8	Polytechnic University of Madrid, Spain— Wheel Reflective Cracking Device 	Loria-Salazar (2008)	– Beams: 12×12×2.4 in.	– Cyclic wheel load – Static traction force: 0.001 to 50 μm/hr – The test can be performed in a range of temperatures between 0°C and 20°C	– Vertical length of the crack with time – Vertical displacement with time – Relative movement between crack edges	– None reported	– No field data	Madrid, Spain
9	Regional Laboratory of Pont et Chausses, France—MEFISTO 	Loria-Salazar (2008)	– Beams: 2×2×26 in.	– Static (horizontal load) – Cyclic (vertical load): sinusoidal 10 Hz – The test is conducted at 5°C and the applied vertical load is 1.9 kips (8.5 kN)	– Number of repetitions versus vertical force or dissipated energy – Number of repetitions versus crack length	– None reported	– No field data –	Chausses, France
10	Cracow University of Technology, Poland 	Loria-Salazar (2008)	– Beams: 12×3×3 in.	– Static bending load: loading rate 0.47 in/min – Repeated haversine bending load: 5 Hz – Static shearing: loading rate 4×10-2 in/min – The samples were tested at a temperature of 20°C	– Static bending: cracking time, max force & bending strength – Dynamic bending: number of repetitions – Static shear: max shear force & stress	The bending test under repeated load indicates that HMA overlays reinforced with geotextiles exhibited a greater resistance to the crack development. – The shearing test showed that the presence of a	– No field data –	Poland

#	Test Type & Schematic	References	Materials, Sample Prep, & Dimensions	Test Loading Parameters	Output Data & Results	Reported Advantages	Reported Disadvantages	Used In
						geotextile diminished more than two times the adhesion between the asphalt layers.		
11	Technion-Israel Institute of Technology, Israel 	Loria-Salazar (2008)	– Beams: 28×4×4 in.	– Cyclic wheel load – The device was located in a temperature-controlled room at a constant temperature of 25C	– Number of wheel loading repetitions to failure – Crack length versus number of repetitions and testing time	– The evaluated geotextile fabric had a resistance to reflective cracking four times greater than other techniques.	– No field data – It was shown that the resistance to reflective cracking of the monolithic HMA beam and the HMA sample compacted in two layers was greater than the other geotextile felts.	Israel
12	Geo-Materials Laboratory, ENTPE, France— Fissurometer 	Loria-Salazar (2008)	– Slabs	– Static: rate of 0.05 to 0.22 in/hr – Cyclic uniaxial	– Measure of energy transmitted by an ultrasonic wave train	– N/A	– Reverse order with field performance; probably because the fissurometer only simulates thermal shrinkage.	France
13	Semi-Circular Bending (SCB) Test 	Huang et al. (2005)	– Tennessee DOT Type D mixes, RAP mix – PG64-22 & PG 76-22 binder – One type of mix with two types of asphalt binder, two types of aggregate, and four RAP contents – 150 mm diameter – 25 mm thickness	– Tensile strength – Loading rate: 51 mm/min – 25°C – Air void 5.0±0.5%	– COV within 13% – SCB tensile strength 3.8 times than IDT – The tensile strengths from IDT and SCB tests were different due to their different stress states under loading. – The results from SCB and IDT test were fully comparable and convertible.	– Test setup is simple. – The potential lateral inhomogeneity of the material during the fabrication of specimens can be eliminated by sawing the circular specimen into two halves.	– A comprehensive investigation to look into SCB test and compare its results to those from other tests is necessary. – Only one type of mix was used in the study. More types of mixes are needed to compare the tests of SCB and IDT.	US (Tennessee DOT) Introduced by European and South African researchers

#	Test Type & Schematic	References	Materials, Sample Prep, & Dimensions	Test Loading Parameters	Output Data & Results	Reported Advantages	Reported Disadvantages	Used In
	SCB 	Li & Marasteanu (2004)	– Materials: three asphalt binders & two aggregates.	– Fracture energy	– 90 SCB specimens – All COV values for both fracture energy and peak load were less than 25%, and this indicates a satisfactory repeatability of this type of test. – 4% target air-void specimens overall resulted in higher fracture peak load and fracture energy than the 7%. – Loading rate was found to have influence on the fracture energy.	– Experimental plots and low coefficient of variation values from three replicates show a satisfactory repeatability from the test.	– None reported	USA
	SCB 	Walubita et al. (2010)	– Coarse/Fine/Dense-graded mixes (Type B, C, & D) – 150 mm diameter – 25 mm thickness – 76.2 mm height – Sample notch: 6.35 mm	– Temperature: 25°C – Monotonically increasing compressive loading @ 1.27 mm/min – Repeated loading @ 10 Hz @ 50% of max SCB peak load under monotonic testing	– HMA tensile strength, strain @ max load, & cycles to crack failure	– Simplicity of setup – Easy-to-test field cores – Short test time – Simplicity of data analysis – Results repeatable for monotonic loading (COV < 30%) – Potential to characterize HMA mix fracture & strain energy	– Need for notching – Lack of validation with field performance data – Lack of better data analysis model – No pass-fail criterion – Inability to sufficiently screen mixes – Need for MTS type of setup – Concentration of loading at supports	TTI, USA
14	Indirect Tension (IDT) Test 	Walubita et al. (2010)	Specimen type: Superpave coarse and fine mixes, mixtures, & field cores – Specimen size: 150 mm (diameter) × 25 mm (thickness)	– Temperature: 10°C – Creep test: 100 sec. – Tensile strength test: 10 sec. – Resilient modulus test: 5 sec.	– m-value & creep compliance – Resilient modulus – Total fracture energy & dissipated creep strain energy to failure – Stress intensity factor – Effective crack length – Crack growth rate	– The test system does not require the direct measurement of crack growth during testing. – Simple to conduct. – The interpretation of the data does not require the use of the properties (e.g., stiffness or poisson ratios) that have to be determined independently from	– Permanent deformation under the loading strip is undesirable. – Only controlled stress testing may be performed. – High stresses at the supports in IDT may cause local failure at these points.	Florida, USA

#	Test Type & Schematic	References	Materials, Sample Prep, & Dimensions	Test Loading Parameters	Output Data & Results	Reported Advantages	Reported Disadvantages	Used In
						other tests on the mix.		
	Indirect Tension (IDT) Test 	Walubita et al. (2010)	– Coarse/Fine/Dense-graded mix – Specimen size: 150 mm (diameter) × 25 mm (thickness)	– Temperature: 25°C – Monotonic increasing compressive loading rate: @ 51 mm/min – Repeated loading @ 1 Hz & 20–50% of max IDT load measured under monotonic loading	– HMA tensile strength, strain @ max load, & cycles to crack failure	– Simplicity of setup – Simplicity of sample preparation – Easy-to-test field cores – Short test time – Simplicity of data analysis – Potential to characterize HMA mix fracture & strain energy – Repeatable with acceptable variability in test results when run in monotonic loading (COV< 30%)	– Lack of validation with field performance data – Lack of better data analysis model – No pass-fail criterion – Inability to sufficiently screen mixes – Need for MTS type of setup – Concentration of loading at supports – Existing of complex stress-state within specimen	TTI, USA
15	Direct Tension (DT) Test 	Walubita et al. (2010)	– Specimen type: TxDOT Type C mixture – Specimen size: cylindrical specimens with 100 mm (diameter) × 150 mm (height)	– Tensile strength test: 5 min – Relaxation modulus test: 25 min – Repeated Direct Tension Test: 20 min	– Number of load cycles to crack initiation, N_i – Number of load cycles to crack propagation, N_p – Paris' law coefficients, A&n	– Direct measurement of tensile loading – Short test time – Simplicity of setup	– No field data	TTI, USA
		Walubita et al. (2010)	– Coarse/Fine/Dense-graded mix – Specimen size: cylindrical specimens with 100 mm (diameter) × 150 mm (height)	– Temperature: 25°C – Monotonically increasing tensile loading @ 1.27 mm/min – Repeated tensile loading @ 1 Hz in strain mode	– HMA tensile strength and strain @ max load – Cycles to failure	– Direct application of tension to the specimen – Direct measurement of tensile strength – Simplicity of data analysis – Repeatability in monotonic mode – Potential to characterize HMA mix fracture & strain energy	– Laborious sample preparation – Inability to test field cores – No field validation – No pass-fail criterion – Need for MTS type setup – Not readily applicable for routine use	TTI, USA

#	Test Type & Schematic	References	Materials, Sample Prep, & Dimensions	Test Loading Parameters	Output Data & Results	Reported Advantages	Reported Disadvantages	Used In
			–	–	–	–	–	
17	Repeated Flexural Bending Test (3-Point or 4-Point Bending Test) 		–	–	–	–	–	

APPENDIX B. THE DSCTT TEST SETUP AT TTI'S MCNEW LAB

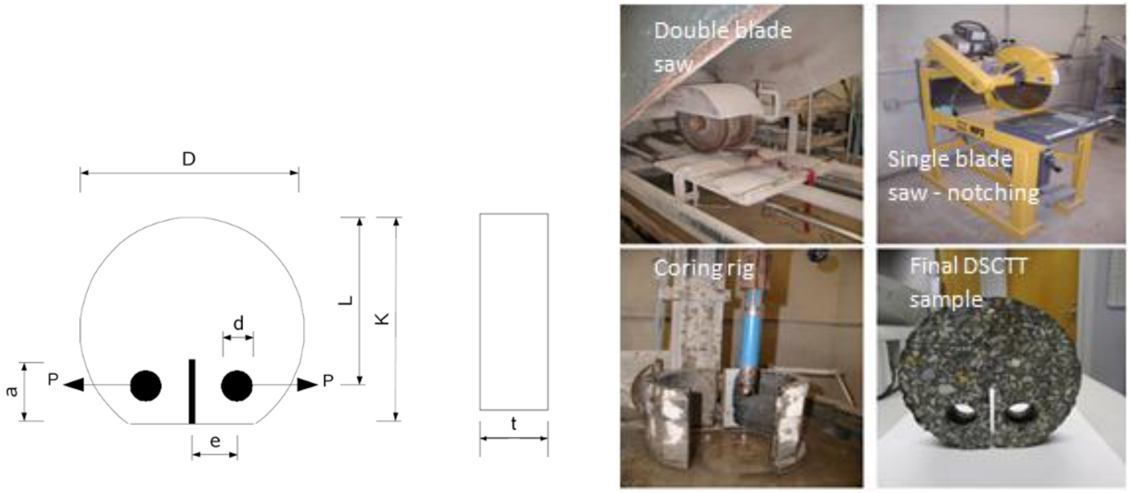


Figure B-1. Example of DSCTT Sample Fabrication Jigs and a Fabricated DSCTT Sample @ TTI.

Table B-1. DSCTT Sample Dimensions.

Dimension (in.)	ASTM D7313	Illinois (IL)	South Africa (RSA)	TTI
a (in.)	2.5 ± 0.2	2.5	2.8	2.5 ± 0.20
d(in.)	1.0 ± 0.04	1.0	1.0	1.0 ± 0.04
e (in.)	1.0 ± 0.1	1.0	1.0	1.0 ± 0.10
L (in.)	4.3 ± 0.1	4.3	4.3	4.3 ± 0.10
K (in.)	5.7 ± 0.2	5.7	5.7	5.7 ± 0.20
D (in.)	5.9 ± 0.4	5.9	5.9	5.9 ± 0.40
Sample thickness (t) (in.)	2.0 ± 0.2	2.0	2.4	2.0 ± 0.20 (will also try 2.5)

Table B-2. DSCTT Test Loading Parameters and Data Analysis Models

Parameter	ASTM	IL	RSA	TTI
Temp (°C)	5.0 to 20.0 (41 to 68°F)	30.0 to −30 (86 to −22°F)	5.0 (41°F)	5 to 25 (41 to 77°F)
Loading rate (in./min)	0.04	0.004/0.04/0.2/0.39	0.04	Will try 0.004, 0.04, 0.05
Air void %	-	7.0 ± 1	5.8	7 ± 1
Temp conditioning period (hr)	Min = 2 hr Max = 16 hr	-	-	≥ 2 hr
Seating load (kN)	0.20 (45 lbf)	-	-	0.1 (45 lbf)
Test completion criterion (kN) (post peak load level)	0.10 (22 lbf)	-	-	Till sample cracks through or load reduces to zero
Load cell capacity (lbf)	≥ 4500 lbf	-	-	5000 lbf
Load-displacement curve	Load applied to fracture specimen in tension versus the crack mouth opening displacement (CMOD)			Will use same approach as ASTM, IL, & RSA.
Data analysis model—fracture energy (G_f)	$G_f = \frac{Area}{t(k-a)}$ ***Area*** = area under load CMOD curve ***t*** = specimen thickness (in.) ***K-a*** = initial ligament length (in.); see Figure B-1			Will use the same model as ASTM, IL, & RSA and modify accordingly if need be.

APPENDIX C. EXAMPLE OT SURVEY QUESTIONNAIRE RESPONSE—TXDOT DISTRICT LAB X

Overlay Tester (OT) Survey Questionnaire and Response—TxDOT District Lab X

Project Details:	**TxDOT Project 0-6607: Search for a Test for Fracture Potential of Asphalt Mixes**
Objectives:	One of the primary objectives of this study is to improve the robustness and repeatability of the Overlay Tester, particularly in regards to minimizing variability in the test results.

With this background, you are humbly requested to assist in answering the following survey questions! Your assistance in this regard will be highly appreciated.

Please note that if you are using the TxDOT Tex-248-F specification, you may omit most of these questions or simply respond by typing/writing "Tex-248-F." Also, if you are not sure or do not know the exact response, you may just leave it blank!

OT Test Procedure and Specifications

1) What test procedures and specifications are you using in your lab? If you are following Tex-248-F, you can skip several of these questions. However, if you are making modifications to any of the items below (sample prep, loading parameters, etc.), please let us know by completing the sections below.
RESPONSE: 248-F; we do have our machine set to cut off at 1000 cycles.

2) What software type and version do you have?
RESPONSE: Shed Works 1.0.8

3) Does your OT machine have any extra or improvised features such as external LVDTs, camera, etc.?
RESPONSE: No, not to my knowledge.

4) What calibration protocols do you follow, and what is the frequency of checking/calibrating your equipment?
RESPONSE: None

5) What are you using the OT for? (i.e., routine mix design and screening, verifying designs, testing plant mixes from contractors, forensic investigations, others, etc.)
RESPONSE: We have used it for mix-design verifications, mix-design screening, testing plant mix for the contractor, and to monitor production mixes.

OT Sample Preparation

6) What specifications and procedures do you follow when preparing the OT samples (i.e., Tex-248-F)?
RESPONSE: 248-F

7) To what dimensions do you mold the SGC samples prior to cutting (i.e., height of 2.5 or 4.5 in.)? And from one molded SGC sample, how many replicate specimens would you typically cut?
RESPONSE: 4.5 in.

8) What is the typical target or range of the air voids final OT test specimen? (i.e., 7±1%)
RESPONSE: 7 ± 1%

9) How do you dry your samples after wet cutting (air, fan, or oven dried)? And for how long? If oven dried, what is the drying temperature?
RESPONSE: Air dry in front of a fan.

10) What type (i.e., Devon 2-ton epoxy) and quantity (in ml or grams) of glue do you use for gluing the samples?
RESPONSE: Devcon 2-ton epoxy all purpose. We use approximately half a tube to glue down each specimen. This tube is 25 ml in volume.

11) What is your curing procedure in terms of the curing weight (i.e., 10 lb) and curing time (min 12 hr)?

RESPONSE: We glue 1 day & cure overnight every time. We use the 10 lb weights that Lubinda furnished us with.

12) On an average, how much time do you typically take from the day of molding the samples up to the day of testing? (i.e., 4, 5, 6 days, etc.)
RESPONSE: It depends on the workload of the lab. Best case is 5 days.

13) At what temperature are the samples conditioned after gluing prior to testing? (i.e., room temperature or 77°F?)
RESPONSE: 77°F (condition in the chamber)

OT Loading Parameters and Test Conditions

14) Are there any other modifications you have made to theTex-248-F test setup or test procedures? If so, what are they and are there any improvements compared to the standard setup?
RESPONSE: We follow 248-F. We used to oven dry the specimens in a 140°F oven until Lubinda recommended that we air dry the specimens after cutting in front of a fan.

15) When fastening the sample-plate assembly into the machine, how much torque force (lbf) do you use? (i.e., Tex-248-F specifies 15 lbf)
RESPONSE: 248-F

16) What is the opening displacement loading rate that you use (i.e., is it the standard 0.025 in.)?
RESPONSE: Standard 0.025 in.

17) What is the test temperature and the tolerance that you allow?
RESPONSE: 248-F

18) What rest time do you typically allow after specimen setup and temperature equilibrium prior to start of the actual test?
RESPONSE: 1 hour

HMA Materials and Test Results

19) What type of mixes do you often test in the OT? (dense-graded, fine-graded, etc. [or Type A, B, C, D, etc., for Texas labs)?
RESPONSE: dense-graded mixes

20) What type of results do you typically get?
    a. Range of cycles to failure (i.e., 10 [coarse-graded mixes] to 1200 [fine-graded rich mixes]): It depends, usually all over the place. Warm mixes are all over the place also.
    b. Range of peak load on first cycle (i.e., 400–500 lbf): Have not tracked this information.

21) What is the level of repeatability and statistical variability in the test results for the mixes you have tested so far?
    a. Standard deviation (Stdev; i.e., 5–250): We do not calculate this information, we just use the average for the three specimens
    b. Coefficient of Variation (COV; i.e., 5–50%): see above.

22) In addition to the number of cycles and/or peak load, which other parameters do you recommend to look at when analyzing the OT data and characterizing the fracture crack resistance potential of HMA mixes?
RESPONSE: We also look at the tensile strength numbers.

OT Problems

23) What are the general problems you have experienced with the OT machine?
    RESPONSE: Deviation between specimens from same sample.

24) If you have been able to address these problems, how?
    RESPONSE: We have not always been able to get real close numbers. We have the same person to glue and break the samples and the same person to mold and cut the specimens.

25) What general problems, if any, have you experienced with the OT results? And what are your suggestions of how these problems can be addressed or minimized?
    RESPONSE: Consistency is key. All tolerances need to be tight.

OT Improvement

26) What other applications, if any, are you using the OT machine for in your lab?
    RESPONSE: Just the ones mentioned above.

27) From your experience with the OT, how can it be improved particularly with respect to minimizing variability in the test results?
    RESPONSE: None

28) Any other comments regarding the OT operations and applications will be gratefully appreciated.
    RESPONSE: None

APPENDIX D. EXAMPLE OT SURVEY QUESTIONNAIRE RESPONSE—STATE X (OUTSIDE OF TEXAS)

Overlay Tester (OT) Survey Questionnaire and Responses—State X (Outside of Texas)

Project Details: TxDOT Project 0-6607: Search for a Test for Fracture Potential of Asphalt Mixes

Objectives: One of the primary objectives of this study is to improve the robustness and repeatability of the Overlay Tester, particularly in regard to minimizing variability in the test results.

With this background, you are humbly requested to assist in answering the following survey questions! Your assistance in this regard will be highly appreciated.

Please note that if you are using the TxDOT Tex-248-F specification, you may omit most of these questions or simply respond by typing/writing "Tex-248-F." Also, if you are not sure or do not know the exact response, you may just leave it blank!

OT Test Procedure and Specifications

1) What test procedures and specifications are you using in your lab? If you are following Tex-248-F, you can skip several of these questions. However, if you are making modifications to any of the items below (sample prep, loading parameters, etc.), please let us know by completing the sections below.
RESPONSE: Tex-248-F

2) What software type and version do you have?
RESPONSE: ShedWorks 1.3.6

3) Does your OT machine have any extra or improvised features such as external LVDTs, camera, etc.?
RESPONSE: No

4) What calibration protocols do you follow, and what is the frequency of checking/calibrating your equipment?
RESPONSE: The machine is calibrated once a year following manufacturer process.

5) What are you using the OT for? (i.e., routine mix design and screening, verifying designs, testing plant mixes from contractors, forensic investigations, others, etc.)
RESPONSE: In research to evaluate the resistance of the asphalt mixtures to reflective cracking.

OT Sample Preparation

6) What specifications and procedures do you follow when preparing the OT samples (i.e., Tex-248-F)?
RESPONSE: Tex-248-F

7) To what dimensions do you mold the SGC samples prior to cutting (i.e., height of 2.5 or 4.5 in.)? And from one molded SGC sample, how many replicate specimens would you typically cut?
RESPONSE: 4.5 in., one replicate from each SGC sample

8) What is the typical target or range of the air voids final OT test specimen? (i.e., 7±1%)
RESPONSE: 7±0.5%

9) How do you dry your samples after wet cutting (air, fan, or oven dried)? And for how long? If oven dried, what is the drying temperature?
RESPONSE: In front of a fan for a minimum of 24 hr

10) What type (i.e., Devon 2-ton epoxy) and quantity (in ml or grams) of glue do you use for gluing the samples?
RESPONSE: Devon 2-ton epoxy, 2/3 of the tube

11) What is your curing procedure in terms of the curing weight (i.e., 10 lb) and curing time (min 12 hr)?
RESPONSE: 10 lb, min 16 hr

12) On an average, how much time do you typically take from the day of molding the samples up to the day of testing? (i.e., 4, 5, 6 days, etc.)
RESPONSE: On average, 5 days. Depends on the quantity of samples prepared.

13) At what temperature are the samples conditioned after gluing prior to testing? (i.e., room temperature or 77°F?)
RESPONSE: Room temperature (around 68F to 75F)

14) Are there any other modifications you have made to theTex-248-F test setup or test procedures? If so, what are they, and are there any improvements compared to the standard setup?
RESPONSE: None

15) When fastening the sample-plate assembly into the machine, how much torque force (lbf) do you use? (i.e., Tex-248-F specifies 15 lbf)
RESPONSE: 21 lbf

16) What is the opening displacement loading rate that you use (i.e., is it the standard 0.025 in.)?
RESPONSE: 0.025 in. at 77°F and 0.018 in. at 50°F

17) What is the test temperature and the tolerance that you allow?
RESPONSE: Usually the equipment maintains the temperature between temp ±0.2%.

OT Loading Parameters and Test Conditions

18) What rest time do you typically allow after specimen setup and temperature equilibrium prior to start of the actual test?
RESPONSE: 2 hours conditioning and 1 hour after specimen setup for 77°F, and 5 hours conditioning and 1 hour after specimen setup for 55°F

HMA Materials and Test Results

19) What type of mixes do you often test in the OT? (dense-graded, fine-graded, etc. [or Type A, B, C, D, etc., for Texas labs)?
RESPONSE: NDOT dense-graded mixes (T2C-coarse and T3-fine), TEXAS CAM, UTAH SRC

20) What type of results do you typically get?
    a. Range of cycles to failure:
        - Short-term aged mixes (4 hr at 275°F before compaction)
            i. Coarse-graded mixes from the north: no failure after 5000 cycles
            ii. Coarse-graded mixes from the south: 10–100 cycles
            iii. Stress-relief course mixes: no failure
        - Long-term oven-aged mixes (5 days at 185°F for compacted specimens before cutting):
            i. Coarse-graded mixes: 10–100 cycles
            ii. Stress-relief course mixes: 2000–4000 cycles
    b. Range of peak load on first cycle: 500–800 lb at 77°F and 900–1200 lb at 50°F

21) What is the level of repeatability and statistical variability in the test results for the mixes you have tested so far?
    a. Standard deviation: 0.5–120
    b. Coefficient of Variation (COV): 4%–55%

22) In addition to the number of cycles and/or peak load, which other parameters do you recommend to look at when analyzing the OT data and characterizing the fracture crack resistance potential of HMA mixes?
RESPONSE: Air voids, aging, temperature

OT Problems

23) What are the general problems you have experienced with the OT machine?
RESPONSE: None

24) If you have been able to address these problems, how?
RESPONSE: None

25) What general problems, if any, have you experienced with the OT results? And what are your suggestions of how these problems can be addressed or minimized?
RESPONSE: Variability of the test results: need more than three replicates to have acceptable results, especially when testing temperature is 50°F.

OT Improvement

26) What other applications, if any, are you using the OT machine for in your lab?
RESPONSE: None

27) From your experience with the OT, how can it be improved particularly with respect to minimizing variability in the test results?
RESPONSE: None

28) Any other comments regarding the OT operations and applications will be gratefully appreciated.
RESPONSE: None

APPENDIX E. EXAMPLES OF OT TEST RESULTS FROM OTHER STATES—STATE X1

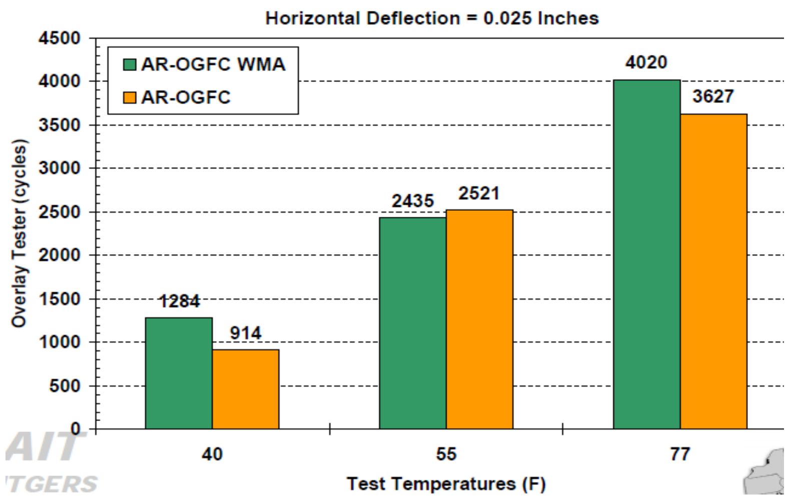


Figure E-1. OT Results @ Different Test Temperatures from State X1.

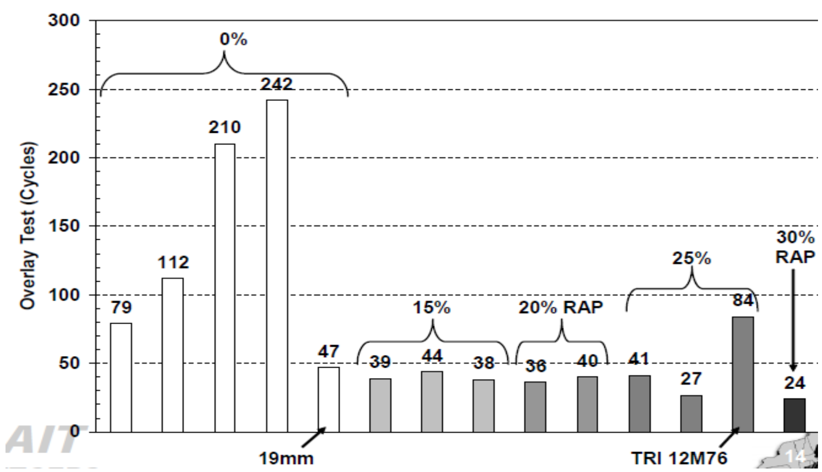


Figure E-2. OT Results for RAP Mixes @77°F (0.025 in) from State X1.

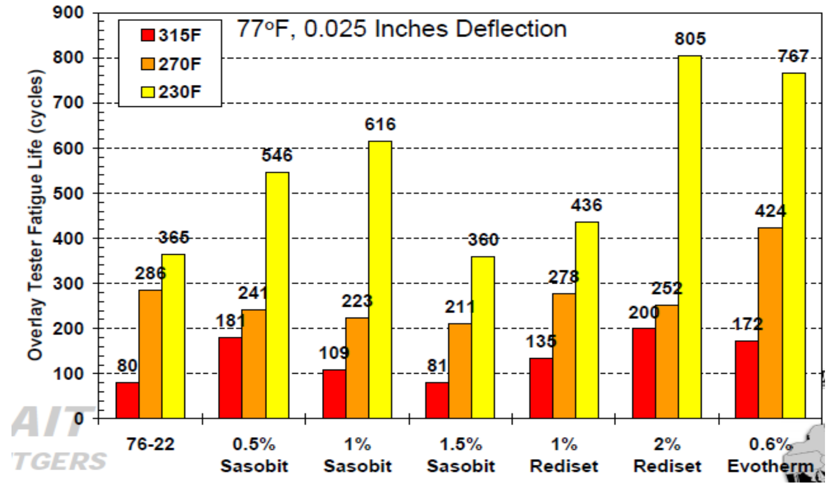


Figure E-3. OT Results for 12.5 mm NMAS Superpave HMA & WMA Mixes @ Different Mixing Temperatures from State X1.

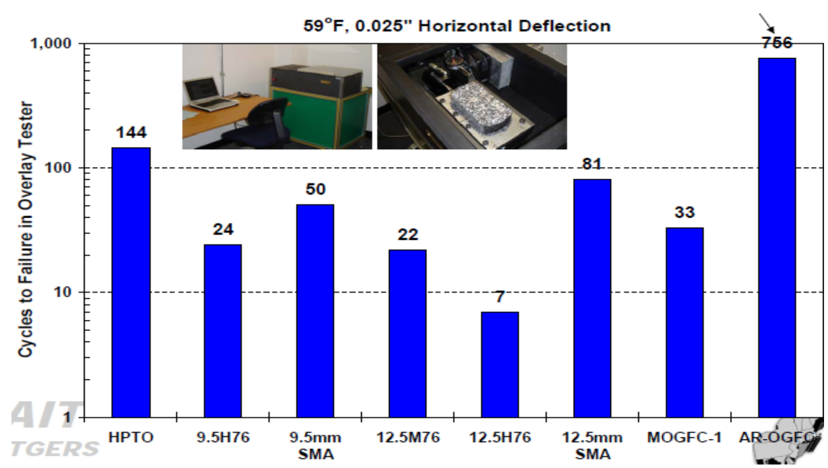


Figure E-4. OT Results for Mixes @59°F (0.025in.) from State X1.

APPENDIX F. EXAMPLES OF OT TEST RESULTS FROM OTHER STATES—STATES X1 AND X2

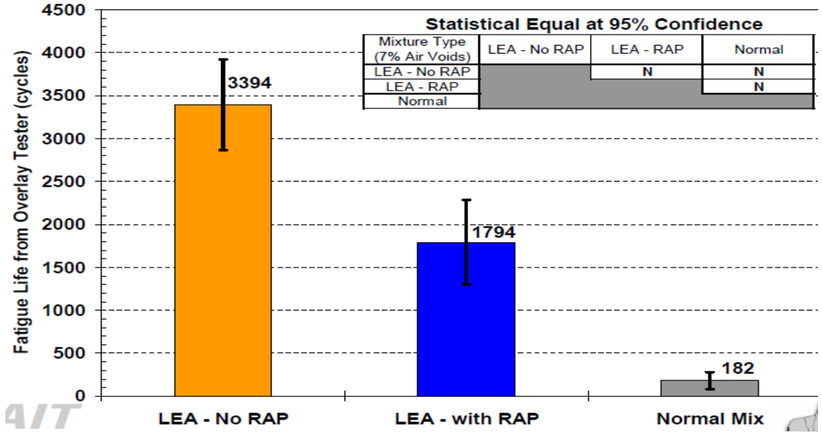


Figure F-1. OT Results for LEA-Warm Mixes @ 77 °F (0.025in.) from State X1.

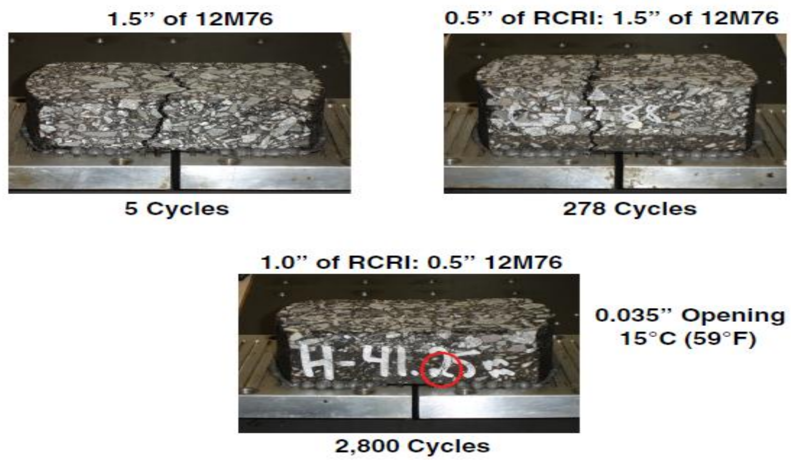


Figure F-2. Evaluating Interlayer Thickness @ 59 °F (0.025in.) from State X1.

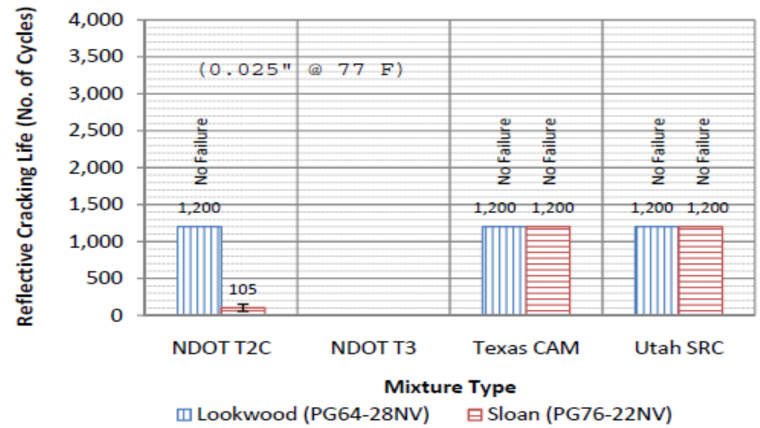


Figure F-3. OT Results for Mixes @ 77 °F (0.025in.) from State X2.

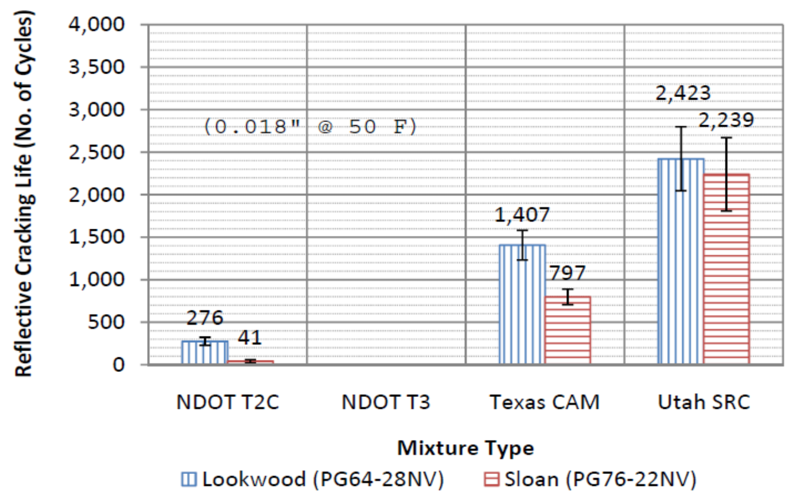


Figure F-4. OT Results for Mixes @ 50 °F (0.018in.) from State X2.

APPENDIX G. MINUTES OF THE FIRST OT USERS' GROUP MEETING

TRB 2011 Jan 25, 2011; 5–7 PM; Room 4340 Wardman Park Tower (Marriot Hotel)

AGENDA

1) To discuss, exchange, and share ideas on the Overlay Tester (OT) and how to further improve it.
2) To discuss the ASTM OT Round Robin and the ASTM Work Group WK26816.

PARTICIPANTS

In total, there were 21 participants representing different institutes, state DOTs, and the industry that included the following: TxDOT, FDOT, TTI (TX), Road Science (OK), UNR (NV), Rutgers (NJ), NCAT (AL), UMASS (MASS), Troxler, Mathy, Gilson, and PBSJ (see Attendance list).

PRESENTATIONS

- **Tom Scullion** (TTI; t-scullion@tamu.edu) made a presentation on the historical background of the OT including the current challenges and ongoing work in Texas.
- **Richard Steger** (Road Science; RSteger@roadsciencellc.com) made a presentation on the upcoming ASTM Round Robin and Draft #4 of the ASTM WK26816 Standard—New Standard Determining the Susceptibility of Bituminous Mixtures to Fatigue or Reflective Cracking Using the OT.
- **Lubinda F. Walubita** (TTI; lfwalubita@tamu.edu) took notes of the meeting deliberations.

SUMMARY OF MEETING DELIBERATIONS

The text below provides a summary of the deliberations and keys issues that were discussed:

ASTM OT Round Robin (ASTM OT-RR)

- Road Science is in the process of fabricating samples from Texas Type D mix (Chico) for shipment to participating labs for Phase I testing. Road Science will provide calibration kit as well as test guidelines to ensure consistency. Phases II and III testing will follow subsequently.
- Richard Steger will create a schedule for shipping the OT Verification Kit for Round Robin participants.
- Gerry Reinke (greinke@mathy.com), with a non-ShedWorks manufactured OT, expressed interest to participate in the ASTM OT-RR program. He will liaise with Richard Steger.
- Nam Tran and Randy West (NCAT) were of the opinion that three labs were sufficient for the intended ruggedness study. Road Science will look into this but intends to proceed as initially planned; the more the number of participating labs, the more the confidence in the results.

ASTM Overlay Test Task Group (WK26816)

- Richard Steger expressed concern at the non-responsiveness of the task group members in the online ASTM collaboration area. He urged participating members to post their comments on the Draft #4 Standard and on any other work in a timely manner so as to expedite the spec developmental process.

- He welcomed new members who are interested in participating in the work group. Anyone interested can contact him through RSteger@roadsciencellc.com or 918-576-3129 (cell) or 918-960-3827 (office).
- Like other ASTM standards that cater to the national level, this ASTM standard will also be more general and not very specific like the Tex-248-F is. For instance, items like specific test temperatures, gap openings, etc., will be left up to the users.
- Road Science will also work with TTI to establish a preliminary in-laboratory precision statement. Lubinda will also liaise with TxDOT (Brett Haggerty and Richard Izzo) on this aspect.

OT Results and Variability

- Tom Scullion pointed out that one major challenge in Texas is the OT severity and variability for some mixes, i.e., the dense- and coarse-graded mixes.
- None of the other participants voiced or reported this issue (variability). Consensus of the participants was that variability should not be an issue, but concern should be whether the mix passes or fails the spec.
- Tom Scullion pointed out that it becomes more problematic when one sample out of three replicates is an outlier, i.e., passes or fails. The participants (Tom Bennert and Elie Hajj) responded that in that case, we should be looking at more replicates (i.e., four or five) instead of just three. Tom Scullion agreed that Lubinda will look into this (more replicates) in the current TxDOT Project 0-6607 but cautioned participants to be aware of the work involved.
- Bearing in mind that repeated crack tests are by their nature variable, Tom Bennert asked German Claros what level of variability was considered acceptable for crack tests by TxDOT. German responded that a COV of 20 percent or less would be considered acceptable. Participants (Tom Bennert, Elie Hajj, Waala Mogawer, and Fujie Zhou) jointly responded that that would not be easily attainable for most mixes, citing examples that even bulk-property tests such as the dynamic modulus had yielded COV values as high as 30 percent.
- Consensus was that variability would be experienced with any repeated load crack tests and should not be compared with monotonic crack tests or compression loading tests. Tom Scullion supplemented this statement with presentation of bending beam, flexural trapezoidal, and diametral fatigue results by Monismith et al. that had COV values as high as 172 percent. Furthermore, the participants emphasized that it should be understand that these are localized failure tests and, as such, variability would always be expected in whatever repeated crack test is considered.
- Tom Bennert highlighted that the OT, unlike most other crack tests, is a rapid test that easily captures the effects of asphalt-binder content and closely relates to crack propagation in the field. This was also echoed by Ellie Hajj, who also stated that the OT is a better discriminator of HMA mixes and can be conducted in a reasonably short time period.
- Tom Bennert also stated that they have been using the OT to simulate anticipated PCC horizontal slab movement by determining the coefficient of thermal expansion of the PCC, the slab length, and an estimate of the daily change in temperature at the bottom of the HMA layer. They (Tom Bennert et al.) successfully applied this in a project for MassHighway to identify reasons for premature reflective cracking on I495.

- Thus far, other states have not seen any double cracking in the OT other than what has been reported by Texas.

OT Test Parameters and Failure Criteria

- NCAT (Nam Tran and Randy West) wanted more clarifications on the test parameters and failure criteria, particularly the origin of the 300 threshold. Texas participants (German Claros, Tom Scullion, and Fujie Zhou) provided some explanations, stating that it was based on a correlation study with field performance conducted about 7 years ago. TTI participants further added that documentation (reports) of this work can be provided if needed.
- NCAT participants also indicated they were unable to reach –5°C with their OT machine and wondered if others had similar experiences. TTI participants responded the OT chamber should be able to reach that range, although such temperatures have never been tried at TTI. None of the other OT users expressed similar problems.

Comparison with Other Crack Tests

On comparison with other crack tests, participants aired the following as some of the OT's advantages:
- Fast, simple, and reasonable test time.
- Practical and reasonable correlation with field performance.
- Sensitive to asphalt-binder changes and can therefore, easily discriminate and screen mixes.

Supply of OT Machines and Accessories

- Troxler will take over from ShedWorks and will inform the OT users when this is formalized.
- ShedWorks will continue to provide technical support to already existing equipment that it supplied.

Ongoing Research Work Related to the OT and Mixes Being Evaluated

- ASTM Round Robin and WK26816 to establish an ASTM OT standard (Road Science).
- TxDOT Project 0-6607: Search for a Fracture Test for HMA Mixes (includes review of Tex-248-F & sensitivity evaluation of OT to improve robustness and repeatability)—by TTI (predominantly on dense-graded mixes).
- Evaluation of RAS, WMA, and RAP mixes (Rutgers).

INFORMATION BEING REQUESTED

For participants with the OT machines, the following information is kindly being requested.

#	Item	RESPONSE
1	What do you use the OT for? (i.e., routine mix design, mix screening, etc.)	
2	Type of mixes being evaluated with the OT?	
3	Type of results or typical numbers being obtained for your mixes?	
4	Any problems experienced with the OT?	

5	Any modifications or changes made to the OT machine or the Tex-248-F?	
6	Any suggestions for further improving the OT, the Tex-248-F spec, and/or the upcoming ASTM OT spec?	
7	Any other issues or comments related to the OT and/or the upcoming ASTM OT Round Robin?	

Attendance List and Participants of the First OT Users' Meeting

#	Name	Institute	Email
1	Ken Brown	Troxler Labs	kgb@troxlerlabs.com
2	Christian Swiers	Troxler Labs	cswiers@troxlerlabs.com
3	Dick Reaves	Troxler Labs	dreaves@troxlerlabs.com
4	Juan Diego Porras	UNR	juandiegoporras@gmail.com
5	German Claros	TxDOT	German.Claros@txdot.gov
6	Tom Scullion	TTI	t-scullion@tamu.edu
7	Fujie Zhou	TTI	f-zhou@tamu.edu
8	Lubinda F. Walubita	TTI	lfwalubita@tamu.edu
9	Jim Bibler	Gilson	jbibler@gilsonco.com
10	Alan Brooker	Fahrner Asphalt	abrooker@fahrnerasphalt.com
11	Richard Steger	Road Science	rsteger@roadsciencellc.com
12	Ed Cortez	UNR	ecortez@unr.edu
13	Elie Hajj	UNR	elieh@unr.edu
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15	Nam Tran	NCAT	nht0002@auburn.edu
16	Gerald Reinke	Mathy Construction	greinke@mathy.com
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24	Stacy Glidden	Mathy Construction	sglidden@mathy.com
25	Imad N. Abdullah	UTEP	emadn@utep.edu
26	Adam Tylor	NCAT	Tayloa3@auburn.edu

Bennert (Rutgers) Comments for OT improvement

#	Item	RESPONSE
1	What do you use the OT for? (i.e., routine mix design, mix screening, etc.)	Mix screening and cracking potential analysis
2	Type of mixes being evaluated with the OT?	Anything made in NJ (Superpave, SMA, OGFC, specialty mixes)
3	Type of results or typical numbers being obtained for your mixes?	Anywhere from one cycle (high RAP mixes) to over 5000 cycles (reflective crack-relief materials)
4	Any problems experienced with the OT?	Response from manufacturer when issues do come up
5	Any modifications or changes made to the OT machine or the Tex-248-F?	None at this time. Looking into lowering test temperature to something more appropriate for NJ conditions.
6	Any suggestions for further improving the OT, the Tex-248-F spec, and/or the upcoming ASTM OT spec?	Perhaps glue jig guide and standard gluing procedure. Right now, it is “eye balled” to the middle of the platens. A centering jig with standard surcharge weight.
7	Any other issues or comments related to the OT and/or the upcoming ASTM OT Round Robin?	

UMASS Comments for OT Improvement

#	Item	RESPONSE
1	What do you use the OT for? (i.e., routine mix design, mix screening, etc.)	Performance test to evaluate the cracking susceptibility or reflective cracking susceptibility of new mixtures
2	Type of mixes being evaluated with the OT?	Superpave, Superpave with PMA, Asphalt Rubber Gap Graded, mixtures with high RAP and RAS contents, warm mix asphalt (WMA)
3	Type of results or typical numbers being obtained for your mixes?	The results vary based on the mixture. Number of cycles to failure (93 percent drop in load) ranges from 3 to 1200 cycles (maximum number of cycles is 1200 per the Tex-248-F specification). All testing conducted at 15ºC (59ºF).
4	Any problems experienced with the OT?	High variability between specimen replicates. Occasional shear failure of the glue affixing specimens to test plates during the testing of very stiff mixtures (specifically those containing RAP and RAS or high-density mixtures). Hydraulic pump must be turned on and the software control mode must be selected prior to mounting the specimen in the OT. Changes from “displacement” to “load” control in the software have resulted in specimens being sheared in half. Turning on the hydraulic pump with the specimen mounted has resulted in specimens being cracked.
5	Any modifications or changes made to the OT machine or the Tex-248-F?	None
6	Any suggestions for further improving the OT, the Tex-248-F spec, and/or the upcoming ASTM OT spec?	A more thorough and standardized specimen-mounting procedure may help improve some of the variability noted in the test. Specifically, more information of the type of epoxy (brand name, set time, strength, etc.) and amount of epoxy on each plate could be provided for the purposes of standardization. Testing different types (quick set vs. long set or different strength) epoxy may also prove beneficial.
7	Any other issues or comments related to the OT and/or the upcoming ASTM OT Round Robin?	It would be beneficial to provide a rationale or determine a justification for the maximum opening displacement (MOD) value, speed of triangular waveform for gap opening/closing, and test temperature (regional values?) being utilized during testing. Specimen fabrication to 115 mm results in 2/3 of specimens being discarded after being cut. Could the height requirement be reduced to still permit cutting but cut down on wasted material?

APPENDIX H: OT TEST RESULTS FROM SENSITIVITY EVALUATION

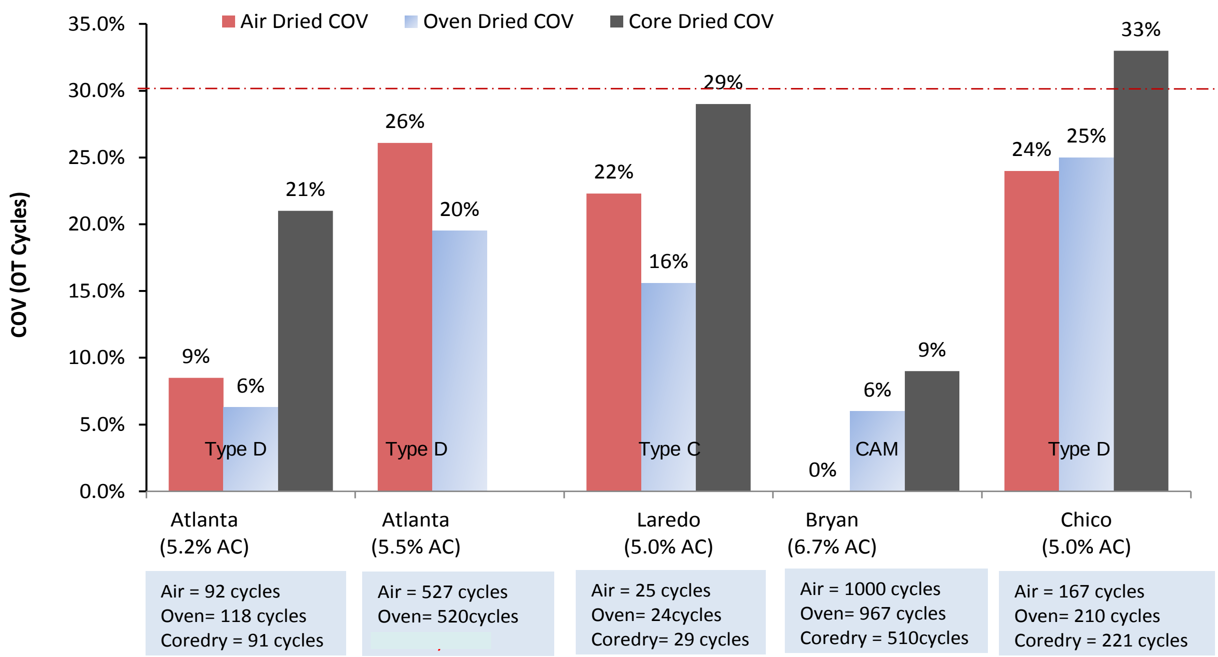


Figure H-1. Comparison of Air (77°F), Oven (104°F), and Core Dryer Drying Methods.

APPENDIX I. SELECTION OF THE OT MONOTONIC TEST LOADING PARAMETERS

Five different loading rates were tried ranging from 0.05 inch/minute to 0.15 inch/minute. The resulting load-displacement response curves are shown in Figure H-1.

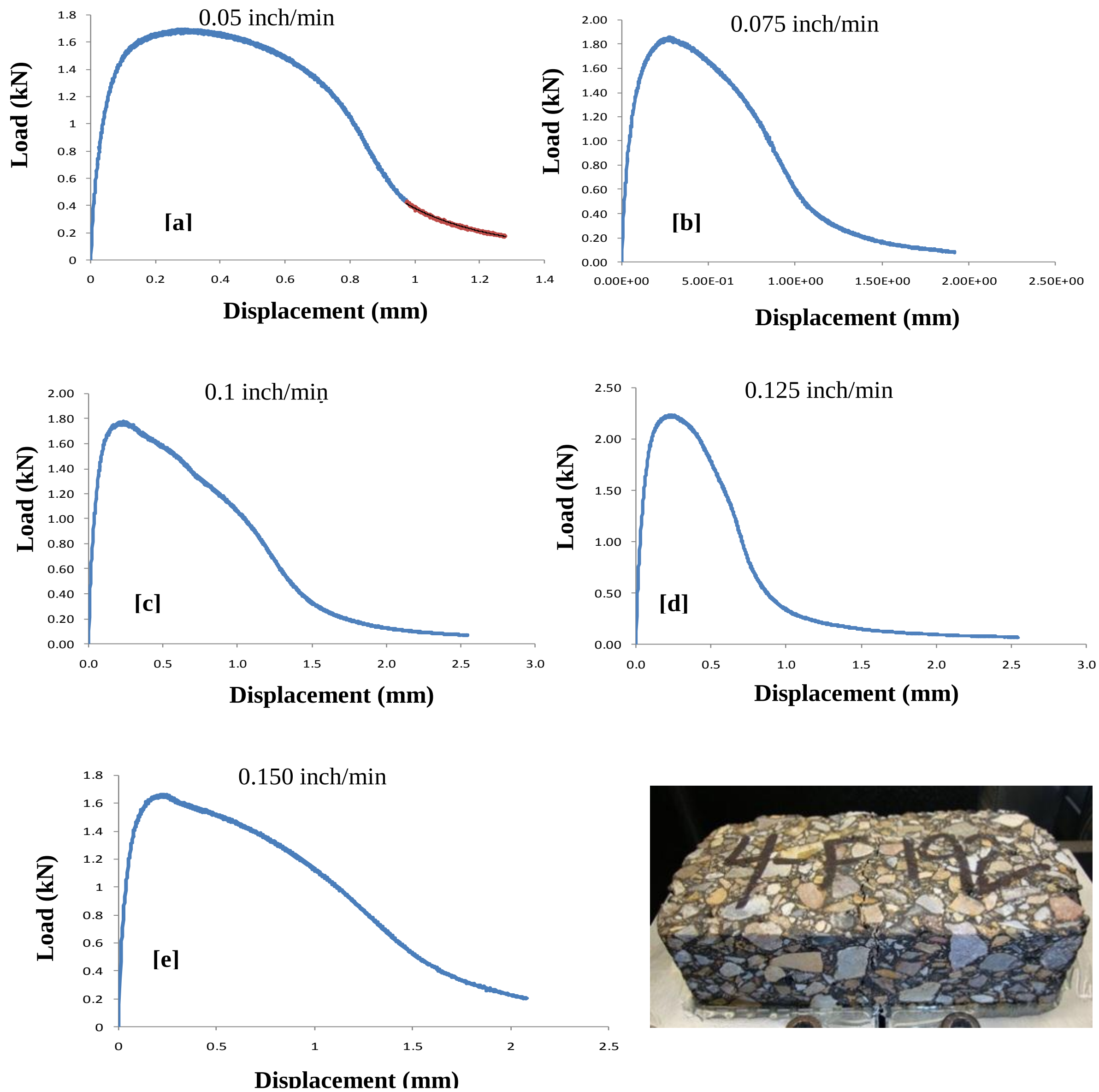


Figure I-1: OT Monotonic Testing - Trial Loading Rates.

As evident in Figure I-1, 0.125 inch/minute yielded the best load-displacement response with marginal tail extension and, therefore, deemed to be the most suitable for using in the monotonic OT test setup. It was also determined that this loading rate was sufficient enough to capture the necessary data and at the same time not too fast to cause premature failure of the specimen.

APPENDIX J. PROPOSED MODIFICATIONS TO THE OT SPECIFICATION

Test Procedure for

Overlay Test

TxDOT Designation: Tex-248-F

Texas Department of Transportation

1. **SCOPE**

1.1 This test method determines the susceptibility of bituminous mixtures to fatigue or reflective cracking. This test method measures the number of cycles to failure.

1.2 The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

2. **APPARATUS**

2.1 Overlay Tester—an electro-hydraulic system that applies repeated direct tension loads to specimens. The machine features two blocks, one is fixed and the other slides horizontally. The device automatically measures and records load, displacement, and temperature every 0.1 sec.

The sliding block applies tension in a cyclic triangular waveform to a constant maximum displacement of 0.06 cm (0.025 in.). The sliding block reaches the maximum displacement and then returns to its initial position in 10 sec (one cycle).

Additionally, the device includes:

- A temperature-controlled chamber.
- A linear variable differential transducer to measure the displacement of the block.
- An electronic load cell to measure the load resulting from the displacement.
- Aluminum or steel base plates with associated screws to restrict shifting of the specimen during testing.
- A mounting jig including a straightedge bar to align the two base plates for specimen preparation.

Refer to manufacturer for equipment range and accuracy for LVDT and load cell.

2.2 Cutting Template—Refer to Figure 1.

Note: Not required with Shedworks double-blade saw.

2.3 3/8-in. Socket Drive Handle with a 3-in. (7.6 cm) extension. Screw driver and wrench with torque capacity of 15 lbf.

3. MATERIALS

3.1 Two-part epoxy with a minimum 24 hr tensile strength of 4.1 MPa (600 psi) and 24 hr shear strength of 13.8 MPa (2000 psi) in accordance with Tex-614-J.

Note: Devcon 2-ton epoxy has proved to be satisfactory in meeting the above requirements, with about16±0.5 g (16±0.5 ml or two-third) per sample.

3.2 4.5 kg (10 lb) weight.

Note: The weight should not overlap the edge of the specimen. The recommended weight size is shown in Figure 2.

3.3 1/4-in. width adhesive tape.

Note: DG2501M CHIARTPAK 1/4 in. graphic tape is recommended.

3.4 Spatula and disposal petri-dish to mix the glue.

3.5 Paint or permanent marker.

4. SPECIMENS

4.1 Laboratory Molded Specimens—Prepare specimens according to Tex-205-F and Tex-241-F. Specimen diameter must be 150 mm (6 in.), and specimen height must be 115 ±5 mm (4.5 ±0.2 in.).

Note: Mixtures modified with warm mix asphalt additives or processes must be oven cured at 275°F for 4 hours ±5 minutes before molding.

Note: It is recommended that the specimens be tested within 5 days from the day of molding. In addition, once testing has started, similar replicates should preferably be completed within 48 hrs. Otherwise, the time period from the day of molding to the day of testing each specimen should be recorded and reported as part of the results.

4.1.1 Density of the trimmed test specimen must be 93 ±1%.

Note: Experience has shown that molded laboratory specimens with 91 ±1% density usually result in trimmed test specimens that meet the 93 ±1% density requirement. Additionally, lab experience has also shown that improved repeatability will low variability in the test results is obtained if the density tolerance is ±0.5%, i.e., 93±0.5%. This is a guide and depends on experience and knowledge of the specific materials.

Note: Mixture weights for specimens prepared in the laboratory typically vary between 4500 and 4700 g to achieve density. Mixture weights for specimens prepared in the laboratory vary with different aggregate sources and with different mix types.

4.2 Core Specimens—Specimen diameter must be 150 ±2 mm (6 ±0.1 in.), and specimen height must be a minimum of 38 mm (1.5 in.). There is not a specific density requirement for core specimens.

5. PROCEDURE

5.1 Sample Preparation:

5.1.1 Use four or **five** cylindrically molded specimens according to Section 4.

Note: Roadway cores may be tested for informational purposes only.

5.2 Trimming of Cylindrical Specimen:

5.2.1 Refer to the sawing device manufacturer's instructions for trimming specimens.

5.2.1.1 Place the cutting template on the top surface of the laboratory-molded specimen or roadway core. Trace the location of the first two cuts by drawing lines using paint or a permanent marker along both sides of the cutting template. Keep track of the top and bottom of the sample. Always glue the bottom of the sample to the base plates.

Note: If the cutting procedure gives one slightly rougher surface, cut the sample so that the rougher surface is at the top of the sample.

5.2.1.2 Trim the specimen ends by cutting the specimen perpendicular to the top surface following the traced lines. If the sample size is out of tolerance, discard it.

5.2.1.3 Trim off the top and bottom of the specimen to produce a sample with a height of 38 ±0.5 mm (1.5 ±0.02 in.). Discard the top and bottom parts of the specimen.

---

6. REFER TO FIGURE 3.

5.2.2 Measure the relative density of the trimmed specimen in accordance with Tex-207-F. Density for trimmed laboratory-molded specimen must be 93 ±1%. Discard and prepare a new specimen if it does not meet the density requirement. Density for trimmed core specimens is for informational purposes only.

5.2.3 Oven dry the trimmed specimen at a maximum temperature of 40 ±3°C (104 ±5°F) to constant weight. The minimum oven drying time should be 12 hours and should not exceed 24 hours. Discard all samples that are in the oven more than 24 hours.

---

7. CONSTANT WEIGHT IS THE WEIGHT AT WHICH FURTHER OVEN DRYING DOES NOT ALTER THE WEIGHT BY MORE THAN 0.05% IN A 2-HR INTERVAL.

5.3 Mounting Trimmed Specimen to Base Plates:

5.3.1 Use the straightedge bar to align the base plates. Mount and secure the base plates to the mounting jig. Cut a piece of adhesive tape approximately 102 mm (4.0 in.) in length. Center and place piece of tape over the gap between the base plates.

5.3.2 Prepare 16.0 ±0.5 g (16±0.5 ml or two-third) of epoxy following manufacturer's instructions.

5.3.3 Cover the majority of both base plates with the epoxy including the tape. Glue the trimmed specimen to the base plates.

Note: Wipe any dirt or dust of the bottom of the specimen prior to gluing. Glue the sample for the base plates.

Place a 4.5 kg (10 lb) weight on top of the glued specimen to ensure full contact of the trimmed specimen to the base plates. Allow the epoxy to cure for the time recommended by the manufacturer. Remove the weight from the specimen after the epoxy has cured.

Note: Experience has shown that a minimum of 8 hours curing time for Devcon 2-ton epoxy provides enough bonding strength.

Note: The whole gluing process must be completed within the glue working time recommended by the manufacturer.

5.4 Place the test sample assembly in the Overlay Tester's 25°C (77°F) temperature chamber for a minimum of 1 hour before testing.

5.5 Starting Testing Device:

5.5.1 Turn on the Overlay Tester. Turn on the computer and wait at least 1 minute to establish communication with the Overlay Tester. Start the Overlay Test software.

5.5.2 Turn on the hydraulic pump using the Overlay Test software. If required, turn the machine to displacement mode.

5.6 Mounting Specimen Assembly to Testing Device:

5.6.1 Enter the required test information (operator name, specimen dimension, specimen density, test conditions, etc.) into the Overlay Test software for the specimen to be tested. Mount the specimen assembly onto the machine according to the manufacturer's instructions and the following procedural steps.

5.6.2 Clean the bottom of the base plates and the top of the testing machine blocks before placing the specimen assembly into the blocks. If all four surfaces are not clean, damage may occur to the machine, the specimen, or the base plates when tightening the base plates.

- Ensure that the machine is in displacement mode and position the machine's moving plate far away from the fixed plate to allow the specimen assembly to drop in.

- Put the specimen assembly in the machine with one of the dowel pins aligned in the sleeve in the fixed plate.

- Put the machine in load mode. The moving plate will now start drifting toward the fixed plate. When the moving plate has drifted into position, the specimen assembly plate will drop into place and the screws can then be installed.

- Leave the machine in load mode. Apply 15 lb/in of torque for each screw in a similar pattern for all replicates specimens when fastening the base plates to the machine.

5.7 Testing Specimen:

5.7.1 Wait for a minimum of 10 min for specimen relaxation and then perform testing at a constant temperature of 25 ±0.5°C (77 ±1°F).

Note: Ensure temperature of trimmed test specimen is 25 ±0.5°C (77 ±1°F).

5.7.2 Start the test by enabling the start button in the program. Perform testing until a 93 percent reduction or more of the maximum load measured from the first opening cycle occurs. If 93 percent is not reached, run the test to 1000 cycles. At the end of the test, visually count the number of cracks (zero, single, or more) at the top of the specimen when the test is completed; see Figure 4.
Note: Zero cracks on the surface indicate a failure in the glue; these tests should be discarded. More than one crack is unusual but normally results in a higher number of cycles to failure than the typical single crack case.

5.73 Remove specimen assembly.

8. **NOTE: ENSURE MACHINE IS IN LOAD MODE BEFORE REMOVING SPECIMEN ASSEMBLY.**

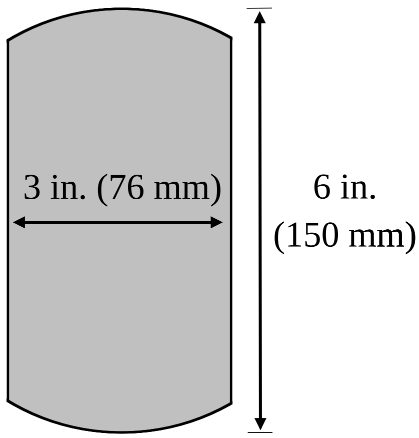


Figure J-1. Cutting Template.

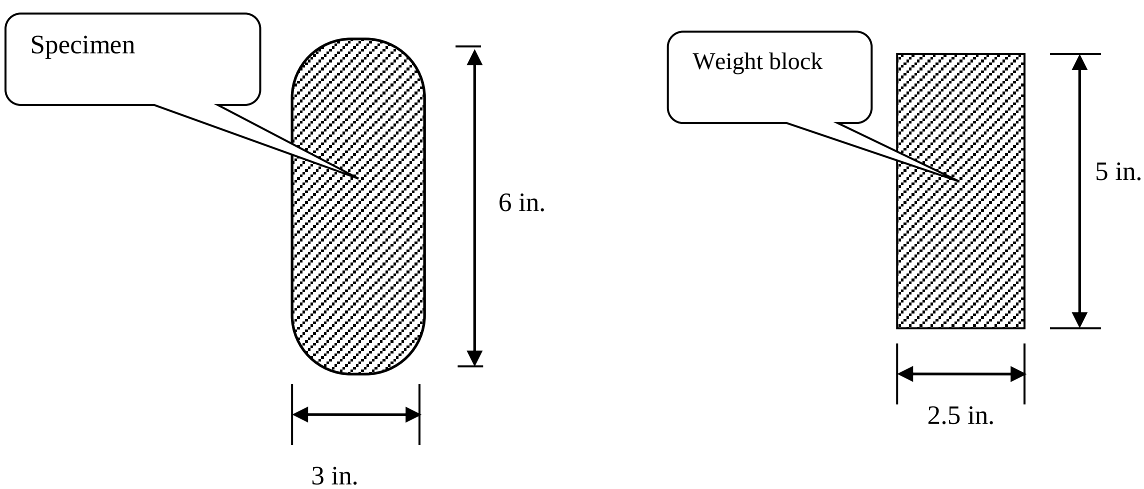
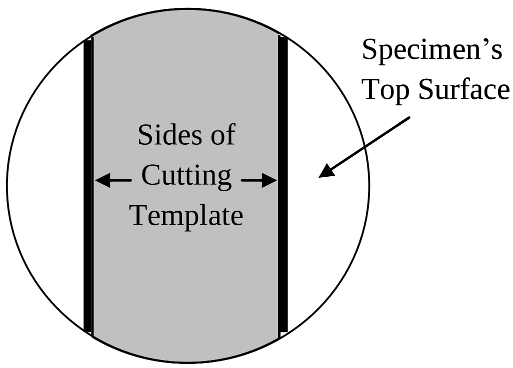
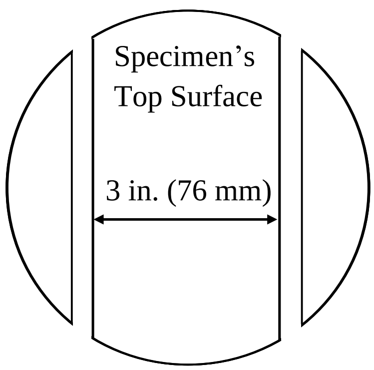


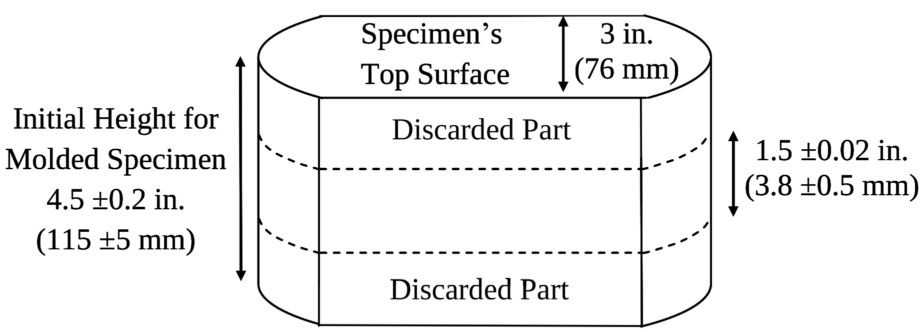
Figure J-2. Weight Block Sketch.



Tracing lines using cutting template



Trimming specimen's ends

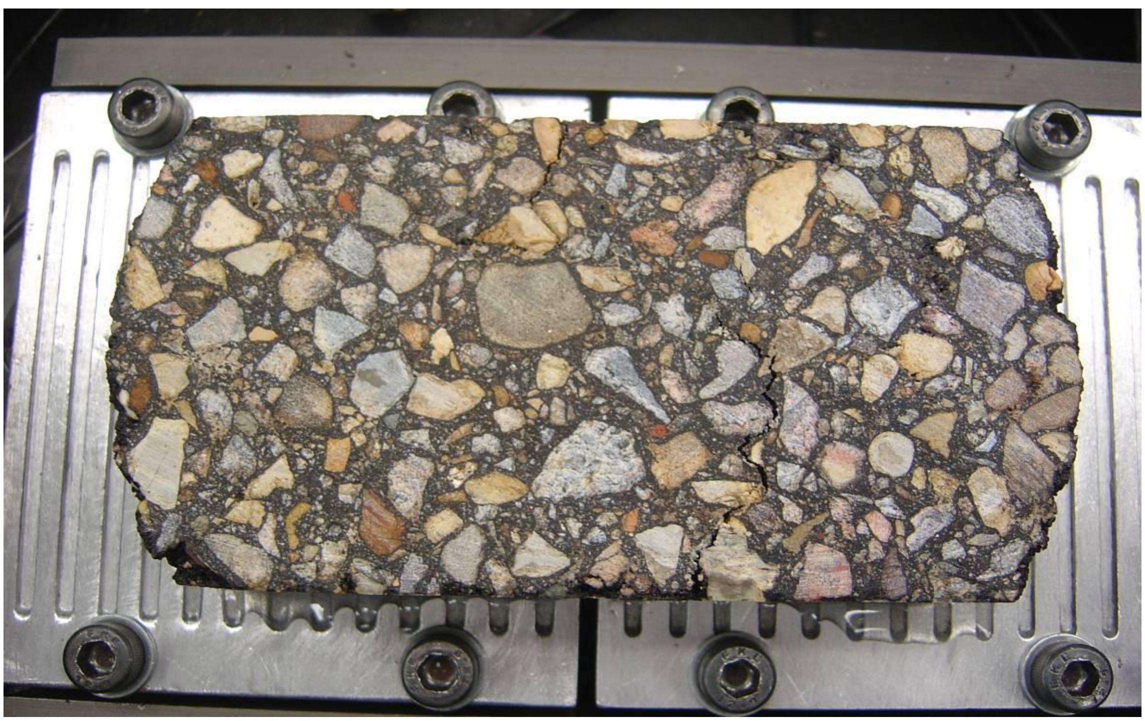


Trimming specimen to required height

Figure J-3. Trimming of Cylindrical Specimen.

(NB: This figure maybe revised once the proposed modifications are approved.)

Single crack



Double cracks

Figure J-4. Single Crack and Double Cracks.

9. REPORT

6.1 Report the following for each specimen:

- Trimmed specimen density.
- Starting load.
- Final load.
- Percent decline in load.
- Number of cycles to failure.
- Number of observed cracks: zero, single, or more.
- Temperature.

6.2 Report the best three specimens out of the five or four tested based on the best OT cycles COV consideration, i.e., the best three with the lowest COV.

10. ARCHIVED VERSIONS

7.1 Archived versions are available.