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16. Abstract

The focus of many asphalt mixture design procedures over the past 10 years has led to the development of stiffer, drier mixtures. However, these mixes are more difficult to construct and are potentially more prone to reflective cracking. In this research the upgraded overlay tester is introduced and proposed as a simple performance test on reflective cracking. The overlay tester can be run on standard size samples, typically 6 in (150 mm) long by 3 in (75 mm) wide by 1.5 in (38 mm) high. These specimens can be prepared from either field cores or from Superpave Gyratory Compactor (SGC) molded specimens. The test is rapid and repeatable, and poor samples fail in minutes. It characterizes both crack initiation and crack propagation properties of asphalt mixtures. Based on repeatability study results, three replicates are recommended for the overlay tester. Sensitivity studies indicate that the overlay tester provides reasonable test results. Increasing asphalt content will significantly improve the reflective cracking resistance of asphalt mixtures. In a series of tests on Texas mixtures, it was determined that aggregate absorption has a major impact on the performance of specimens in the overlay tester. This topic has not received much attention recently but it obviously needs to be investigated. In the lab these highly absorptive aggregates did not severely impact the rutting performance but they had a major impact on cracking life. The effectiveness of the overlay tester was validated by five case studies in Texas. The overlay tester results all correlated well with the field performance. Furthermore, the overlay tester results have good correlations with beam fatigue test results and low temperature performance of asphalt mixtures in the field. A preliminary framework of asphalt overlay mixture designs and associated criteria have been proposed. Based on the framework, two examples of asphalt overlay mixture designs are presented in this report. This framework and the associated criteria are preliminary and they will need further refinement. Finally, a brand new overlay tester has been manufactured and delivered to TxDOT's central lab at the Cedar Park office. In addition, training for the operation and analysis has been provided.

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OVERLAY TESTER:
A RAPID PERFORMANCE RELATED CRACK RESISTANCE TEST

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TABLE OF CONTENTS

Page

List of Figures ix

List of Tables xii

Chapter 1. Introduction 1

- Background 1
- Objectives 4
- Report Organization 4

Chapter 2. Development of Upgraded Overlay Tester 5

- Introduction 5
- Upgraded Overlay Tester 5
- Data Interpretation 7
- Variability of Upgraded Overlay Testing 9
- Sensitivity of Upgraded Overlay Testing 12
- Overlay Testing Protocol 15
- Summary and Conclusions 18

Chapter 3. Validation of Upgraded Overlay Tester 19

- Introduction 19
- Validation of Upgraded Overlay Tester Using Field Cores with Known Reflective Cracking Performance 19
- Preliminary Pass/Fail Criteria on Reflective Cracking Resistance of Asphalt Mixtures 26
- Comparison Between Overlay Tester and Beam Fatigue Test 26
- Validation of Overlay Tester Using MnRoad Cores 27
- Summary and Conclusions 28

Chapter 4. Application of the Overlay Tester to Evaluate Reflective Cracking Resistance of Typical TxDOT Mixtures 29

- Influence of Asphalt Binder Type on Reflective Cracking Resistance 29
- Influence of Aggregate Properties on Reflective Cracking Resistance 31
- Evaluation of Reflective Cracking Resistance of TxDOT's Mixture 34

Chapter 5. Case Studies: Optimization of Asphalt Overlay Mixture Design Using the Overlay Tester and Hamburg Wheel Tracking Test (HWTT) 39
Introduction 39
A Preliminary Framework for Asphalt Overlay Mixture Design, Considering Both Reflective Cracking and Rutting 39
Case Study 1: US82, Wichita Falls, Texas 41
Case Study 2: CMHB-F Design for the Atlanta District, Texas 42
Chapter 6. Framework of Overlay Tester Based Reflective Cracking Analysis System...............43
Introduction 43
Reflective Cracking Modeling Approach Based on Fracture Mechanics 43
Framework of Reflective Cracking Analysis System 48
Chapter 7. TxDOT's Brand New Overlay Tester and User Manual...51
Overlay Tester Specifications 51
User Manual for New Overlay Tester 57
Chapter 8. Conclusions and Recommendations 71
Conclusions 71
Recommendations 72
References 73

LIST OF FIGURES

Figure **Page**

1. Two Types of Reflective Cracking 2
2. Concept of TTI Overlay Tester 3
3. Upgraded TTI Overlay Tester Equipment, Plate, and Specimen....5
4. Illustration of Tensile Stress Distribution of Asphalt Concrete under 0.015 in (0.38 mm) Opening....6
5. Schematic Diagram of Loading Types 7
6. Typical Overlay Tester Result 9
7. Repeatability of Overlay Testing TxDOT Type D Mixture 10
8. Repeatability of Overlay Testing on TxDOT CMHB-C Mixture....10
9. Relationship between Number of Specimens and Specified Tolerance of Reflective Cracking Life for TxDOT Type D Mixture 12
10. Influence of Temperature on Reflective Cracking Life....13
11. Influence of Opening Displacement on Reflective Cracking Life....13
12. Influence of Asphalt Content on Reflective Cracking Life 14
13. Influence of Air Void (%) on Reflective Cracking Life....15
14. Three Failure Mechanisms....17
15. Specimen with Absorptive Limestone....18
16. Asphalt Overlay Condition of Section 48A502, SPS5 20
17. Overlay Tester Results on Field Cores from SPS5, US175, US84, and SH6....21
18. Reflective Cracking on US175 Remixer Section....22
19. Reflective Cracking on US84 Remixer Section....22
20. Strata and Petromat Section on SH3, Houston District 23
21. Reflective Cracking in Control Section after One Year of Service....24
22. Overlay Tester Results on Field Cores from SH3, SH6, and IH10 24
23. Strata Materials Rut Depth after Asphalt Pavement Analyzer Test (more than 8 mm after 2500 Load Repetitions at 64 ºC and Loading Pressure of 100 psi)....24
24. Reflective Cracking on the Left Lane of SH6 25
25. Field Cores from MnRoad....28
26. Influence of Asphalt Binders on Reflective Cracking Resistance of Asphalt Mixtures....30

LIST OF FIGURES (Continued)

Page

27. Overlay Tester Results on Two CMHB-F Mixture Where the Aggregate Type was the Main Variable 31

28. Crack Surfaces of Broken Specimens 32

29. Limestone Absorptive 33

30. Influence of Absorption of Aggregate on Reflective Cracking Resistance 34

31. Overlay Tester Results on Type C-Granite and ¾ inch SMA-Granite 35

32. OACs of Mixtures 36

33. Gradations of the Mixtures Evaluated 36

34. Influence of Gradation on Reflective Cracking Resistance of Asphalt Mixtures 37

35. Proposed Asphalt Overlay Mixture Design Process 40

36. Non-dimensionalized Bending and Shearing SIF vs. Non-dimensionalized Crack Length 45

37. Interlayer Element (*21*) 46

38. Automatic Crack Propagation Procedure in CAPA (*21*) 46

39. Framework of Reflective Cracking Analysis Systems 49

40. TTI's Existing Overlay Tester 51

41. Sketch of Simple Relaxation Test 53

42. Sketch of Simple Repeated Load Test 53

43. Two Step Test 53

44. Input and Output of Overlay Tester 54

45. Overlay Tester Input: Displacement vs. Time 56

46. TxDOT's Brand New Overlay Tester 57

47. Mounting Jig 58

48. Specimen Plates Mounted on Jig 58

49. Main Control Panel 59

50. Hydraulic Pump On/Off 60

51. Mode Control Switches 60

LIST OF FIGURES (Continued)

Page

52. Position Right Hand Block with Left/Right Switch to Line Up Pins on Test Specimen Assembly 61

53. Insert Pins into Machine Making Sure Cutout on Center Pin is on the Side Facing the Cams 62

54. Tighten Cam until it Locks in Place 62

55. Main Software Screen 63

56. Typical Display during Testing 64

57. Button Help Pop-up Window 65

58. General Help File 66

59. Test Preferences Screen 67

LIST OF TABLES

Page

1. Comparison between Beam Fatigue Test and Overlay Tester 27
2. Three Test Cells of MnRoad: Asphalt Mixture and Cracking Performance 27
3. US281 Asphalt Overlay Mixture Gradation 29
4. Asphalt Binders Used in This Project 30
5. Proposed Preliminary Criteria on Asphalt Overlay Mixtures 41
6. Reflective Cracking Lives and APA Rut Depth after 8000 Strokes 41
7. Test Results on CMHB-F Mixture from Atlanta, Texas 42

CHAPTER 1

INTRODUCTION

BACKGROUND

TxDOT's recent focus on hot-mix asphalt (HMA) design has been to evaluate the rutting potential and moisture susceptibility of new mixes with the Hamburg wheel tracking test (HWTT). However, the Department has paid less attention to crack resistance of the new HMA surfaces. This crack resistance is a concern because to perform well in the field an HMA overlay must have a balance of both good rut and crack resistance properties. Stiffer binders and good stone-to-stone contact may provide improved rut resistance, but they may also reduce the mix flexibility and thus, crack resistance.

Cracks appear in flexible pavements primarily through either fatigue or reflective cracking mechanisms. Classical fatigue cracks are associated with weak areas in the pavement structure where heavy truck loads induce high tensile strains at the bottom of the HMA layer. These strains initiate cracks that eventually propagate to the surface. The classical fatigue property of HMA surface has been under evaluation for over 40 years. Great advances have been made in the equipment and understanding of the fatigue mechanism. However, the fatigue test itself has not been implemented as a design tool primarily because the test procedure is very time consuming. It can take several weeks with expensive repeated load test equipment to obtain a single fatigue curve.

Reflective cracks, on the other hand, are initiated by existing discrete subsurface defects such as joints, cracks, or areas of stripping. The cause of reflective cracking can be either environmental or load associated. The reflective cracking mechanism has received less attention than the classical fatigue studies, although for many TxDOT applications fatigue cracking is not the prime concern. Frequently, reflective cracking is the major performance issue. This issue is particularly a concern when selecting HMA surfaces for rigid pavements, flexible pavements with stabilized bases, or simply when the existing pavement has badly cracked. It is well known that when reflective cracks propagate through the HMA overlay, the infiltration of water can cause rapid deterioration of the underlying pavement structure and foundation. Yet, there is a lack of simple and rapid test equipment and procedure for routine use to characterize the reflective cracking resistance of asphalt mixtures before they are placed on the existing cracked pavements. Furthermore, neither the NCHRP1-37A design guide (*1*) nor NCHRP 9-19 (Superpave Support and Models Management) (*2*) specifically addresses the laboratory test on reflective cracking. Therefore, there is an urgent need to develop practical and rapid test equipment and the associated test protocol for characterizing the reflective cracking resistance of asphalt mixtures. In this project, the researchers developed the upgraded Texas Transportation Institute (TTI) overlay tester to address this problem.

Mechanisms of Reflective Cracking

Shortly after opening to traffic, HMA overlays often exhibit a joint and/or cracking pattern similar to that which existed in the old pavements. This propagation of a joint or crack from the existing pavement into and through a new HMA overlay is known as reflective cracking. Reflective cracking is most common in asphalt overlays placed on rigid pavements, but it also occurs in asphalt overlays on cracked asphalt concrete pavements, and in asphalt pavements with stabilized bases. Two types of reflective cracking, as illustrated in Figure 1, have been reported: traditional single reflective cracking and double reflective cracking. When and which type of reflective cracking occurs depends upon the degree of horizontal joint (or crack) movement and the magnitude of vertical deflections across the joint or crack induced by traffic load and environmental effects. Double reflective cracks reported by Marchand and Goacolou *(3)*, Gaarkeuken, et al. *(4)*, and Zhou and Sun *(5)* are located a few inches on each side of the centerline of the old joint (or crack). Compared to the traditional reflective cracking located directly above the joint (or crack), double reflective cracking is less frequent than the single reflective crack case. Advanced three-dimensional (3-D) finite element analysis results *(5)* indicated that double reflective cracking occurred only at joints (or cracks) with significant vertical movement, such as thin asphalt overlays over existing Portland Cement Concrete (PCC) pavements with poor support. Therefore, in the remainder of this report this discussion will focus on the traditional single reflective cracking.

(a) Traditional Single Reflective Cracking (b) Double Reflective Cracking

Figure 1. Two Types of Reflective Cracking.

Traditional Single Reflective Cracking

For traditional reflective cracking, only one crack is observed at the surface of the asphalt overlay directly above the joint or crack in the existing pavement. This type of reflective cracking is caused mainly by the daily temperature variations, especially in the winter time. Daily temperature variations are the primary factors inducing horizontal movement of the subsurface joint or crack. If the overlay is fully bonded with the underlying pavement, tensile stress is created in the overlay directly above the joint or crack. This induced tensile stress is proportional to the relaxation property of the asphalt mixture and the movement taking place in the joint or crack; that, in turn, is proportional to the slab length (or space between the cracks), temperature variation, and the coefficient of thermal expansion (COTE) of the underlying pavement material. When the induced tensile stress exceeds the tensile strength of the asphalt overlay, a single crack directly on top of the joint or crack will occur. With repeated traffic loading and/or temperature variation cycles, the initiated crack will further propagate until reaching the surface of the asphalt overlay.

These mechanisms of traditional single reflective cracking have been summarized by Rigo (*6*) in the second international conference on "Reflection Cracking in Pavements." That is, it is the opening and closing of the joint or crack caused by the temperature variations that induce the reflective cracking initiation and take part in the initial propagation; then, traffic loadings play the role in the second step of the crack propagation. In fact, these mechanisms have been validated by Jayawickrama and Lytton (*7*), finding that "the number of days to failure due to thermal movements was directly correlated to the observed pavement performance." They will be further validated by the field data in this report.

Therefore, in order to characterize the reflective cracking resistance of asphalt mixtures, it is crucial to simulate the horizontal opening and closing of subsurface joints or cracks. The TTI overlay tester was specially designed to simulate this mechanism.

TTI Overlay Tester

The TTI overlay tester was designed by Germann and Lytton, et al. (*8*) in the late 1970s to simulate the opening and closing of joints or cracks, which are the main driving force inducing reflective crack initiation and propagation. The key parts of the apparatus, as shown in Figure 2, consist of two steel plates, one fixed and the other movable horizontally to simulate the opening and closing of joints or cracks in the old pavements beneath an overlay. There are two overlay testers in TTI: one is a small overlay tester for a specimen size of 15 in (375 mm) long by 3 in (75 mm) wide with variable height; the other is a large overlay tester for larger size specimen of 20 in (500 mm) long by 6 in (150 mm) wide with variable height. Both overlay testers have been successfully used by Pickett and Lytton (*9*), Button and Epps (*10*), Button and Lytton (*11*), and Cleveland, et al. (*12*) to evaluate the effectiveness of geosynthetic materials on retarding reflective cracking. These applications indicate that the overlay testers have the potential to characterize the reflective cracking resistance of asphalt mixtures. The goal of this project was to develop the overlay tester concept into a practical laboratory test for routine pavement design. One limitation of the previous work was that long beam samples were required. These long samples are relatively difficult to fabricate in the laboratory and more difficult to get from the field. To solve these problems, an upgraded TTI overlay tester was developed with the goal of being able to test 6 in (150 mm) diameter samples that could be easily fabricated in the lab using a gyratory compactor or obtained from standard field cores. It was also critical to validate the new test equipment with asphalt mixtures of known performance before full-scale implementation.

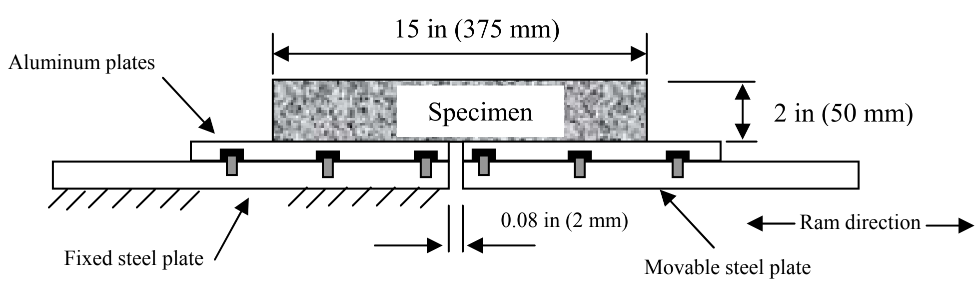


Figure 2. Concept of TTI Overlay Tester.

OBJECTIVES

The overall objectives of this project were to:

- develop and validate the upgraded overlay tester and associated test protocol,
- characterize reflective cracking resistance of TxDOT Type D mixture with different binders and other TxDOT asphalt mixtures,
- design and manufacture a new overlay tester for TxDOT, and
- propose the framework of integrated asphalt overlay mixture and thickness design.

REPORT ORGANIZATION

This report is organized into eight chapters. Chapter 1 focuses on the background information relative to the project. Chapter 2 presents the development of the upgraded overlay tester and associated test protocol. Repeatability and sensitivity of the overlay tester are also presented in this chapter. In Chapter 3 the upgraded overlay tester is validated with the beam fatigue test, and especially with the known performance field cores. Chapter 4 describes overlay testing on both Fort Worth Type D HMA with 10 different binders and all types of TxDOT's typical HMA mixtures. Chapter 5 presents an integrated asphalt overlay mixture design procedure that addresses both rutting and reflective cracking issues. The proposed procedure is demonstrated through two case studies. In Chapter 6 the framework of a reflective cracking analysis system is proposed. The asphalt overlay tester is recommended to characterize the fracture properties of the asphalt mixtures. As a product of this project, a new overlay tester built for TxDOT and the associated user manual are described in Chapter 7. Finally, Chapter 8 presents a summary of conclusions and recommendations from this project.

CHAPTER 2

DEVELOPMENT OF UPGRADED OVERLAY TESTER

INTRODUCTION

This chapter briefly describes the upgraded overlay tester. Then the data interpretation, repeatability, and sensitivity of the overlay tester are discussed. Finally, based on the test results obtained, the researchers propose an overlay testing protocol.

UPGRADED OVERLAY TESTER

The objective of upgrading the TTI overlay tester was to make a more useful tool that can be routinely used by engineers to measure the reflective cracking resistance of asphalt mixtures and evaluate the reflective cracking resistance of field cores. In order to overcome the limitation of previous overlay testers and make the overlay tester easier to operate, the TTI small overlay tester system was upgraded to a fully computer-controlled system. Figure 3 shows the upgraded TTI overlay tester equipment. The main feature of the upgraded TTI overlay tester is the specimen size: 6 in (150 mm) long by 3 in (75 mm) wide with heights from 1.5 in (38 mm) to 2 in (50 mm). This specimen size was determined based on the fact that both 2 in (50 mm) asphalt overlays and 6 in (150 mm) core drills have been used statewide in Texas. For 2 in (50 mm) thick field cores, it is easy to get a 1.5 in (38 mm) high overlay tester specimen after trimming the tack coat layer and underseal. Furthermore, the 3-D finite element program, ABAQUS, was used to analyze the stress distribution of different sizes of specimens. For example, as shown in Figure 4, the main tensile stress of asphalt concrete is limited to the middle 2.5 in (63 mm) part of the specimen. This means that the end effect has little influence on the overlay testing results. Therefore, it is reasonable to use 6 in (150 mm) long specimens in the overlay tester.

Since this size specimen can be readily fabricated from a Superpave Gyratory Compactor (SGC) or cut from field cores, the proposed specimen size makes the overlay tester more practical and easier to use.

In addition, the special programs for one-phase loading and two-phase loading (discussed in chapter 7), have also been built into the upgraded system, and the test data, including time, displacement, and force, can be automatically recorded and saved as an Excel file.

Figure 3. Upgraded TTI Overlay Tester Equipment, Plate, and Specimen.

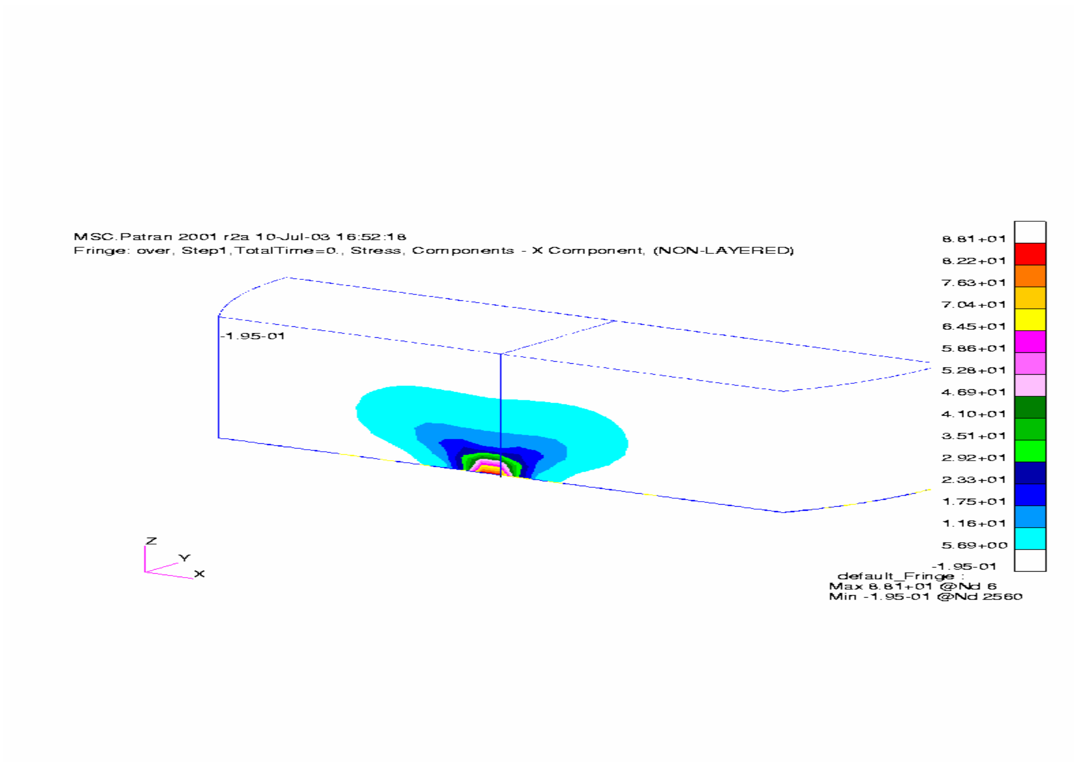


Figure 4. Illustration of Tensile Stress Distribution of Asphalt Concrete under 0.015 in (0.38 mm) Opening.

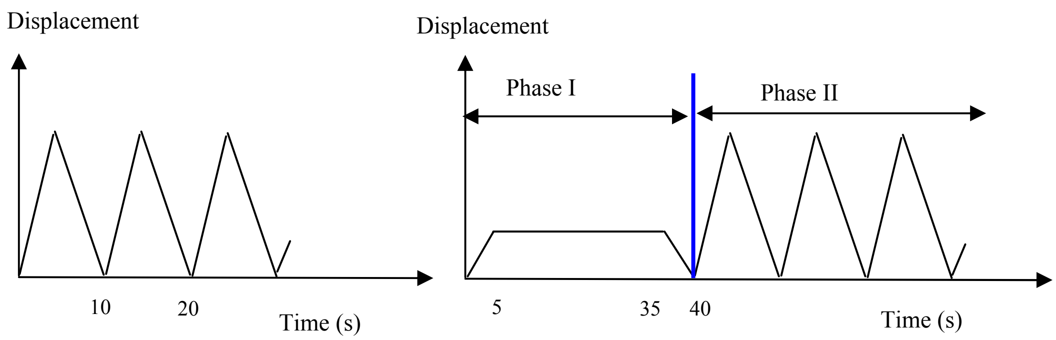
Engineers can conduct the upgraded overlay tester in a controlled displacement mode under the following conditions:

- temperature: 32–77 ºF (0–25 ºC);
- opening displacement: 0–0.08 in (0–2 mm);
- loading rate: 10 sec per cycle–10 min (or more) per cycle; and
- loading type:

    - Procedure A (one-phase loading): this loading is applied in a cyclic triangular waveform with constant maximum displacement, as shown in Figure 5a. The reflective cracking life of the asphalt mixture, as discussed later, can be determined based on the recorded loading data. Fracture properties of the asphalt mixture can also be evaluated in the overlay tester.

    - Procedure B (two-phase loading): this two-phase loading is designed for advanced users. As illustrated in Figure 5b, the first phase is a constant displacement waveform having a ram displacement of 0.007 in (0.18 mm). The overlay tester uses the measured displacement and associated load from 5 to 35 sec to determine a relaxation modulus curve. The second phase is conducted until the specimen fails. The second phase is similar to Procedure A.

Note that the researchers propose Procedure A for routinely evaluating the reflective cracking resistance of the asphalt mixture. Normally, the overlay testing is conducted at room temperature (77 ºF/25 ºC) in a controlled displacement mode until the failure occurs at a loading rate of one cycle per 10 sec with a maximum displacement of 0.025 in (0.64 mm). This amount of horizontal movement is approximately equal to the displacement experienced by PCC pavements undergoing 30 ºF (14 ºC) changes in pavement temperature with a 15 ft (4.5 m) joint or crack spacing. The selected loading rate (0.005 in/s or 0.13 mm/s) does not really represent the field condition, but keep in mind that Procedure A is proposed to be an accelerated crack resistance test. Although it is possible to better simulate the realistic loading rate in the field, realistic simulation will take days to test one specimen. Procedure B was recently recommended by Cleveland, et al. (*12*) for advanced mechanistic analysis. It should be mentioned that Procedure A, due to its simplicity for data analysis, was recommended to pursue in this project by the project director, program coordinator, and other advisors during the project meeting on September 15, 2003.



(5a) (5b)

Figure 5. Schematic Diagram of Loading Types.

DATA INTERPRETATION

The overlay testing data include the time, displacement, and load corresponding to a certain number of loading cycles. In addition, the crack length can be manually measured. Two types of information can be gained from the overlay tester: one is the reflective cracking life of the asphalt mixture under certain test conditions; the other is the fracture parameters of the asphalt mixture. Since it was determined by the project advisory committee to focus on Procedure A in this project, only reflective cracking life of the asphalt mixture is discussed below.

Definition and Determination of Reflective Cracking Life of Asphalt Mixtures

Similar to the traditional beam fatigue test, reflective cracking life of an asphalt mixture is defined as the number of cycles needed to propagate a crack through a specimen under a defined test condition. As determined from this research work, this value is a good indicator of reflective cracking resistance of asphalt mixtures. In the past, the number of cycles to failure was subjectively determined by the operator's visual observation of the crack. The life was defined as the number of cycles until a crack was clearly present on the top of the specimen. There are two disadvantages regarding visual observation of the crack. The first is that the operator(s) has to watch the whole testing period; the other is the subjectivity of the operator(s). Another potential indicator of failure is the energy-based criteria including both the dissipated energy and the pseudo-strain energy concepts. But, these two energy concepts may be not good for the upgraded overlay tester because of the non-uniform load and displacement distribution along the cross section of the asphalt mixture specimen, which makes the energy calculation complex. In addition, the energy calculated based on the measured load and displacement will be affected by the size of each specimen. Current overlay tester specimens are cut from 6 in (150 mm) diameter cores. It is difficult to get the exact same size of specimens. Thus, the energy-based criteria are not recommended at the current time.

In this project we proposed to automate the reflective cracking life determination by analyzing the load and displacement versus the time plot. A typical set of data is presented in Figure 6, showing load and displacement for each opening and closing cycle. From observations of the results from many overlay tests, it is proposed that this plot has three distinct phases, as described below.

- Phase I: Crack initiation and steady propagation

In this phase the load and displacement have similar shapes. As the displacement increases, the load increases too. For the first cycle, the load reaches its maximum value before the displacement arrives at the maximum displacement. This indicates that the crack initiates at the bottom. After the first cycle, the load decreases rapidly as the crack starts to propagate through the specimen. However, both load and displacement reach the maximum values at the same time. In this stage, the cracking is steadily and slowly propagated to the top surface.

- Phase II: Late crack propagation

Phase II is the late stage of crack propagation, which is monitored as a saddle-shaped load. The saddle-shaped load indicates that the crack has partially gone through the whole cross section of the specimen. In fact, the first peak load is associated with the minor adhesion as the specimen gap is closed and the two halves of the specimen bond together. Then, the load rapidly decreases just after breaking the weak adhesion bonds. With the increasing opening displacement, more loading is needed to break the remaining parts of the specimen. Corresponding to the maximum displacement, there is another peak load. With the continuing cyclic loading, the crack will totally break the specimen and the second peak load will disappear. This indicates the onset of Phase III.

- Phase III: Specimen failure

As described above, the crack has propagated completely through the specimen in this phase. The maximum load induced by the minor adhesion occurs well before the maximum displacement.

Based on the above discussion, the reflective cracking life of asphalt mixtures, thus, can be defined by the number of cycles corresponding to the onset of Phase II or Phase III. From the conservative point of view, the onset of Phase II should be used to define the reflective cracking life. To demonstrated, Figure 6 shows the overlay tester result of a specimen. Using the evaluation scheme described above, the reflective cracking life of the specimen was determined to be four cycles (10 sec/cycle).

A wide variety of reflective cracking lives have been determined based on the testing completed to date. Some specimens failed in one or two cycles, whereas others did not fail after 1500 cycles, at which point the test was terminated. As shown in chapter 3, the longer the reflective cracking life of the sample, the better its' reflective cracking performance in the field.

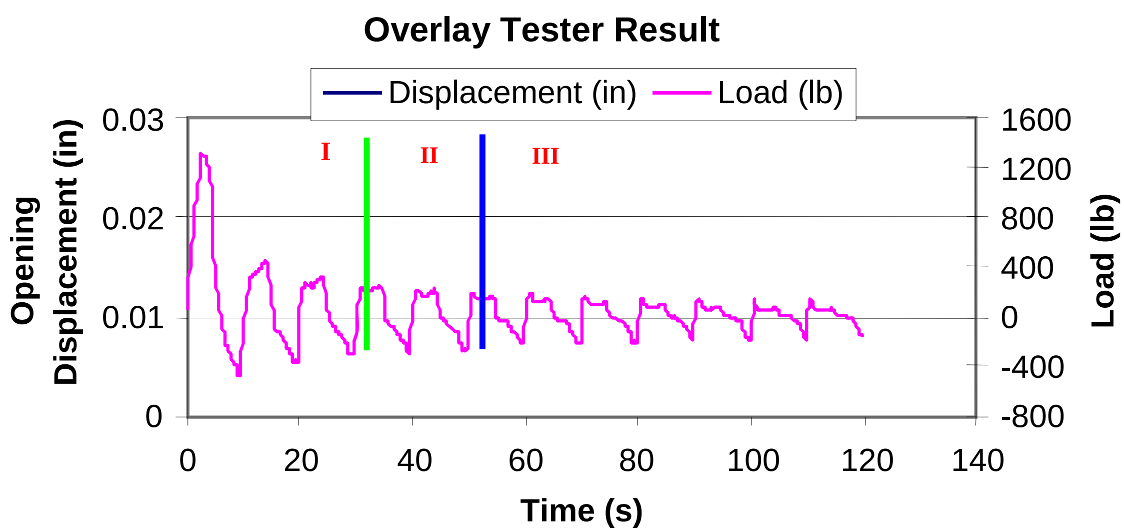


Figure 6. Typical Overlay Tester Result (Each Opening and Closing Cycle is 10 s).

VARIABILITY OF UPGRADED OVERLAY TESTING

The first step in evaluating the overlay tester concept, especially with the recommended small sample size, was to determine the repeatability of the test. As discussed previously, both reflective cracking life and fracture properties of asphalt mixtures could be determined from the overlay testing. However, only the reflective cracking life is discussed herein because it is the primary output of the overlay testing and this value can be easily used by the engineers to design asphalt overlay mixtures.

Overlay Testing Repeatability

In general, the smaller the specimen, the more variable the test results can be. Since the upgraded overlay tester was using a small specimen, there was concern about its repeatability. Thus, two types of TxDOT mixtures, Type D and CMHB-C using PG64-22 asphalt binder, were selected to make six identical specimens (6 in [150 mm] diameter by 2.25 in [57 mm] high) for each mixture. All the specimens were molded using the SGC. Then, the specimens were cut to be 1.5 in (38 mm) high using a double blade saw; after that, 1.5 in (38 mm) was trimmed from each side of the specimens. The air void content of each specimen was controlled within 7±0.5 percent after trimming the specimens, which is similar to the required air void content of the specimens for TxDOT's Hamburg test. Finally, six overlay tester specimens for each mixture were glued to the overlay tester plates. The testing was conducted at room temperature (77 ºF [25 ºC]) and the opening displacement was set to 0.025 in (0.63 mm).

Figure 7 shows the reflective cracking lives of six identical Type D specimens. The average reflective cracking life is 140 cycles. The corresponding standard deviation and coefficient of variation are 11.7 and 8.3 percent, respectively. Generally speaking, the coefficient variation of asphalt mixtures is around 10 to 25 percent. These results clearly indicate that the overlay testing is repeatable.

Figure 8 illustrates overlay testing results on a CMHB-C mixture. This mixture failed very quickly and each of the specimens failed after two cycles. This poor mixture was not representative, and it was excluded from the following repeatability analysis.

The results from Figure 7 will be used in the next section of this report to determine the number of samples to test for a given level of reliability.

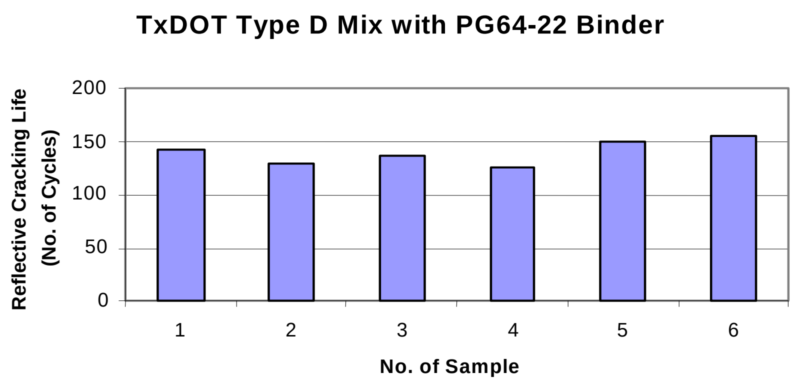


Figure 7. Repeatability of Overlay Testing on TxDOT Type D Mixture.

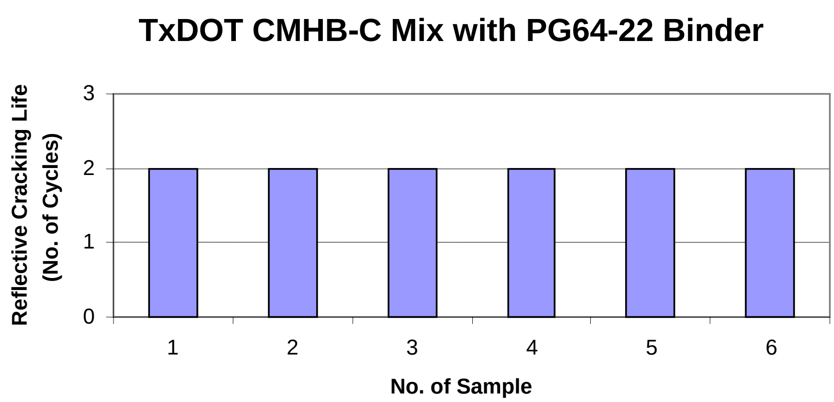


Figure 8. Repeatability of Overlay Testing on TxDOT CMHB-C Mixture.

Number of Specimens

Another important issue for the overlay testing is the number of specimens required to obtain an estimate of the material property within certain tolerances, since variation inevitably occurs from specimen to specimen even in the same material. This is a classic application of confidence intervals in a statistical analysis. For a known population variance, the number of replicates required to achieve the specified levels of tolerance and reliability is defined in the following well-known Equation 1 (*13*):

$$n = \left(\frac{Zs}{\Delta x}\right)^2 \qquad (1)$$

where:

n = number of specimens
Z = two-tailed probability statistic from the standard normal distribution
s = population standard deviation
Δx = specified tolerance value ($= x_{average} * specified$ tolerance$(\%)$)
$x_{average}$ = average value of population

That is, for a Z value of 1.96, the average value of reflective cracking life of *n* specimens will be within $\pm\Delta x$ of the "true" reflective cracking life of asphalt mixtures for 95 percent of the time.

To provide a conservative estimate, only the results from the Type D samples are considered. Figure 9 shows the relationship between the number of specimens and the specified tolerance. It can be seen that the average reflective cracking life of two specimens, for Type D mix, will be within ±12 percent of the "true" reflective cracking life of asphalt mixture with 95 percent reliability.

The recommendation resulting from this analysis is that TxDOT measure three replicates to get an error of less than 10 percent.

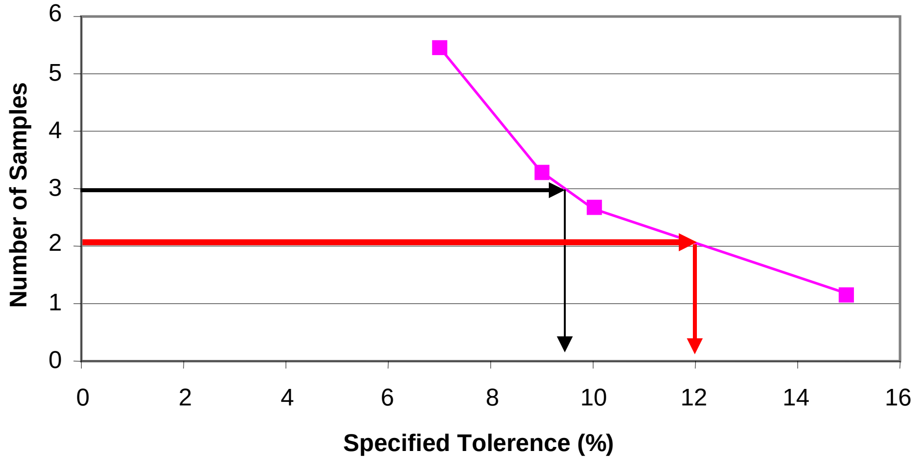


Figure 9. Relationship between Number of Specimens and Specified Tolerance of Reflective Cracking Life for TxDOT Type D Mixture.

SENSITIVITY OF UPGRADED OVERLAY TESTING

In addition to the repeatability, the sensitivity of the upgraded overlay tester to material properties and test conditions were also investigated. The parameters investigated in this project included test temperature, opening displacement, air void, asphalt performance grade, and asphalt content. The TxDOT Type D mixture from US281 in the Fort Worth District wa used here. The optimum asphalt content wa 5.1 percent. It should be noted that only one parameter was variable in this sensitivity test and the others were kept the same. The detailed results are presented as follows.

- Influence of temperature on reflective cracking life

It is well known that the temperature is the major contributor to reflective cracking of asphalt overlays. A PG76-22 SBS modified binder was used to mold six identical specimens with the target air void content of 4 percent. Overlay testing was conducted at two temperatures: 77 ºF (25 ºC) and 50 ºF (10 ºC). The opening displacement was 0.025 in (0.63 mm) for both temperatures. At each temperature, three replicates were used. The averaged reflective cracking life is presented in Figure 10. It is clear that the temperature had significant influence on the reflective cracking life of the asphalt mixture, and the overlay testing is sensitive to the temperature.

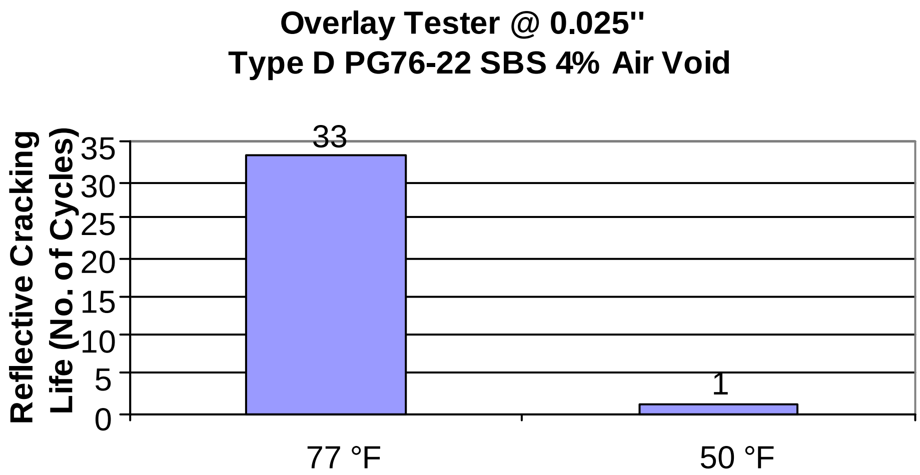


Figure 10. Influence of Temperature on Reflective Cracking Life.

- Influence of opening displacement on reflective cracking life

The temperature variation or opening displacement is another major factor affecting the reflective cracking. Similar to the previous test, a PG76-22 SBS modified binder was used to mold six identical specimens with the target air void content of 4 percent. Overlay testing was conducted at 77 ºF (25 ºC). The opening displacements were 0.025 in (0.63 mm) and 0.035 in (0.89 mm), respectively. At each opening displacement, three replicates were used. The averaged reflective cracking life is presented in Figure 11. Figure 11 indicates that overlay testing results are sensitive to the opening displacement. With increasing opening displacement, the reflective cracking life of asphalt mixtures decreases.

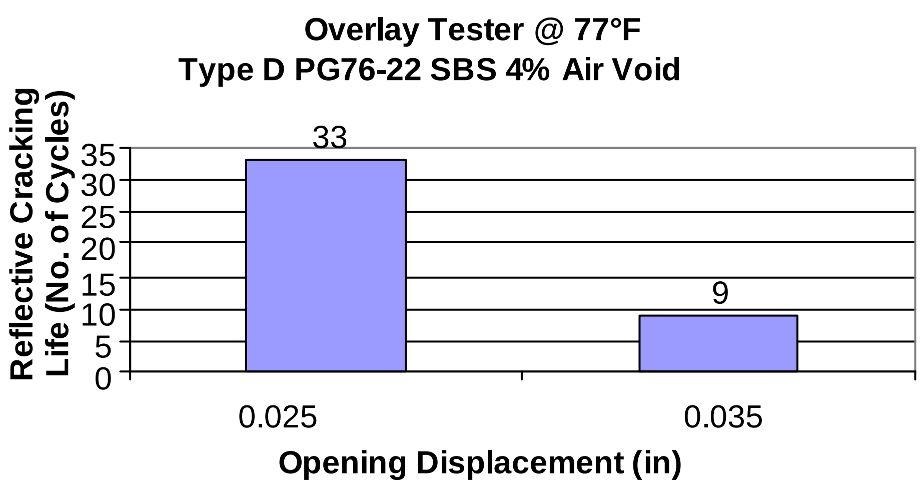


Figure 11. Influence of Opening Displacement on Reflective Cracking Life.

- Influence of asphalt content on reflective cracking life

In this sensitivity study, the influence of variable asphalt content on reflective cracking life was also investigated. The three asphalt contents used were 4.2, 5.1 (optimum), and 6.1 percent, respectively. The overlay testing was conducted at 77 ºF (25 ºC) and 0.025 in (0.63 mm) opening displacement. For each asphalt content, a PG64-22 binder was used to mold three replicate specimens. The averaged reflective cracking life is presented in Figure 12. It can be seen from Figure 12 that with the increasing asphalt content, the reflective cracking life of the asphalt mixture significantly increased. These results are consistent with traditional beam fatigue results.

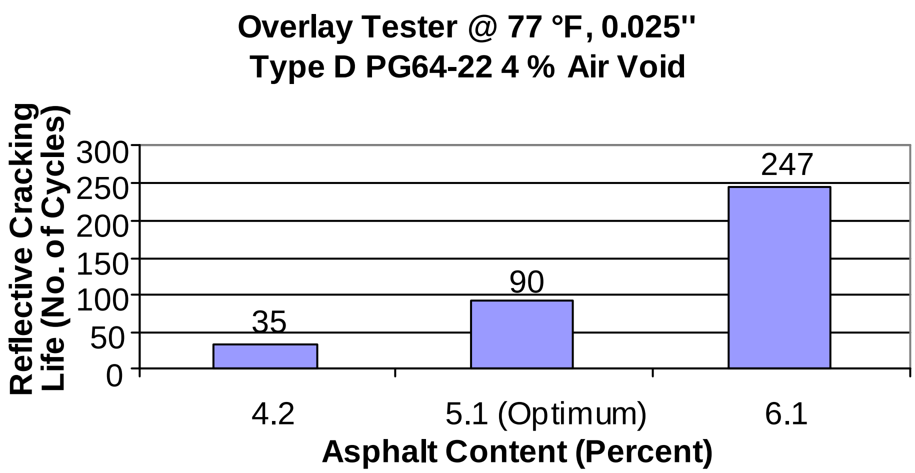


Figure 12. Influence of Asphalt Content on Reflective Cracking Life.

- Influence of asphalt performance grade on reflective cracking life

Comparing Figure 11 with Figure 12, the influence of performance grade (PG) of asphalt binder on reflective cracking life can be easily seen. When increased from a PG of 64 to 76, the reflective cracking life dropped from 90 to 33. This decrease indicates that the stiffer the asphalt binder, the poorer its reflective cracking resistance.

- Influence of air void on reflective cracking life

Figure 13 presents the influence of air void on reflective cracking life. For this case, a high air void content showed better reflective cracking resistance. One possible explanation may be is that reducing air void content made the specimen denser and stronger. It means that the specimen with lower air void content would have higher stiffness, and higher strength as well, which is good to resist rutting. However, thermal reflective cracking simulated by the overlay tester is a different scenario. If temperature dropping is kept constant, the denser mixture with higher modulus will suffer a higher thermal stress. Inversely, although its strength is lower, the thermal stress induced within the specimen with higher air void content will be lower, too. When the thermal stress induced within a specimen is higher than its strength, a crack will occur. Whether or not a specimen with lower air void content is resistant to thermal reflective cracking depends on both its stiffness and strength. Thus, it is difficult to simply make a general conclusion regarding the influence of air void on thermal reflective cracking. It is recommended that the influence of air void content be treated case by case.

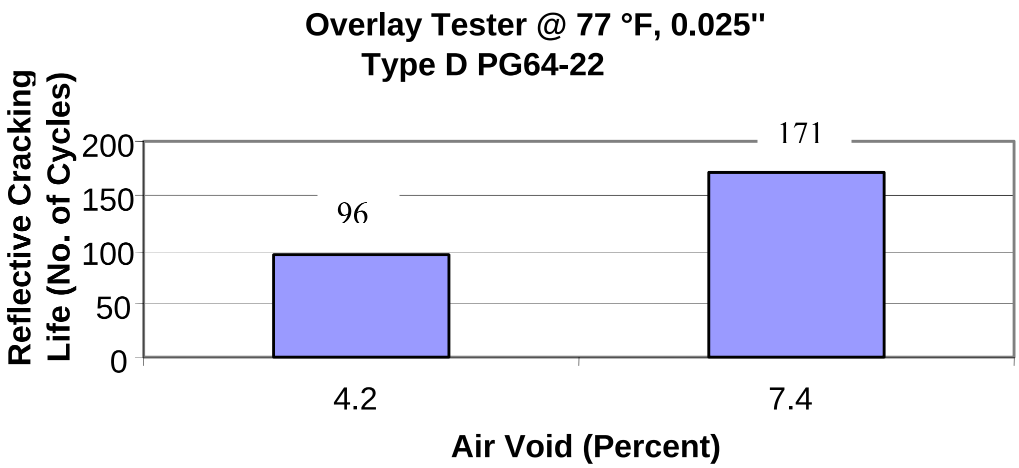


Figure 13. Influence of Air Void (%) on Reflective Cracking Life.

In summary, the overlay tester is sensitive to the test conditions and the properties of the asphalt mixtures themselves. With an increase of the opening displacement and performance grade of the asphalt binder, or a decrease of the temperature, the reflective cracking life of asphalt mixtures will decrease. The influence of air void should be treated case by case. In this project, reducing air void content decreased the reflective cracking resistance of specimens. However, it is important to especially note that increasing the asphalt content and decreasing PG binder grades will significantly improve the reflective cracking resistance of the asphalt mixtures.

OVERLAY TESTING PROTOCOL

The researchers developed an overlay testing protocol based on the repeatability and sensitivity studies and the experience gained from past studies. The following section briefly introduces the main part of the protocol. The detailed protocol has been submitted previously in Report FHWA/TX-04/4467-P1.

- Test specimen

  Size — Perform overlay testing on 6 in (150 mm) long by 3 in (75 mm) wide by 1.5 in (38 mm) high specimens sawed from gyratory compacted mixtures or field cores.

  Gyratory specimens — Prepare 6 in (150 mm) diameter by 2.5 in (63 mm) high specimens to the required air void content of 7±0.5 percent in accordance with Tex-241-F.

  Note — Testing should be performed on test specimens 1.5 in (38 mm) high meeting the specific air void tolerances. The air void content of a gyratory compacted specimen with 2.5 in (63 mm) height and 6 in (150 mm) diameter required to obtain a specified test specimen air void content must be determined by trial and error. Generally, the test specimen air void content is 1.5 to 2.5 percent lower than the air void content of the gyratory specimen when the test specimen is removed from the middle of the 6 in (150 mm) diameter specimen.

Sawing — Cut the specimens to be 1.5 in (38 mm) high using the double blade (or single blade) saw. Then, trim 1.5 in (38 mm) from each side of the specimen.

- Glue the specimen — A cut specimen is epoxied to the horizontal surface plates with half the length of the beam resting on each plate.

- Overlay tester procedure — Although two types of procedures (A and B) have been built into the upgraded overlay tester system, only Procedure A is recommended with the consideration of quick implementation in TxDOT district laboratories. Procedure A was designed for routine use. The repeated loading is applied until failure occurs at a loading rate of one cycle per 10 sec using a cyclic triangular waveform with constant magnitude of 0.025 in (0.63 mm), as shown in Figure 5a.

- Calculations

    - Determine the air void content for each specimen.
    - Determine the reflective cracking life of each specimen (see data interpretation section).
    - (Advanced application only) Determine the fracture mechanics properties: A and n. Detailed methods have been documented in References *(9)* and *(12)*.

- Evaluate the failure plane and absorption — At the conclusion of the test it is important to look at the failure face of the cracked sample. Determine if the crack propagated primarily through the asphalt, or through the interface between asphalt and aggregate, or through the aggregate. In addition to the primary crack failure through the asphalt binder, two secondary modes of cracking can be observed: debonding and aggregate crushing. These three failure planes are shown in Figure 14.

  Furthermore, it was found that the asphalt absorption had considerable negative influence on crack resistance of asphalt mixtures. After cutting or breaking the specimen, report the absorption of the asphalt into the aggregate. Figure 15 shows the absorption of the asphalt into the aggregate.

(a) Crack through Binder

(b) Crack through Interface

(c) Crack through Aggregate

Figure 14. Three Failure Mechanisms.

Figure 15. Specimen with Absorptive Limestone.

SUMMARY AND CONCLUSIONS

This chapter focused on developing the upgraded overlay tester. The new features of the upgraded overlay tester include the 6 in (150 mm) diameter specimen and a fully automated test procedure. These features make the upgraded overlay tester a rapid crack resistance test. Furthermore, the testing results clearly indicate that overlay testing is very repeatable, and three specimens are recommended for asphalt mixture testing. The sensitivity study shows that the overlay testing is sensitive to opening displacement, testing temperature, asphalt performance grade, asphalt content, and air void content. Increasing the asphalt content will substantially improve the cracking resistance of the asphalt mixture. Finally, the overlay tester protocol is recommended. Validation of the overlay tester through field cores and case studies will be presented in the next chapter.

CHAPTER 3

VALIDATION OF UPGRADED OVERLAY TESTER

INTRODUCTION

Validation was another critical step in developing the upgraded overlay tester. In this project, the validation of the upgraded overlay tester was composed of three steps. First, the effectiveness of the overlay tester on characterizing reflective cracking resistance of asphalt mixtures was discussed. Field cores with known reflective cracking performance were used for this validation. Then, the potential application of the overlay tester to evaluate the fatigue cracking resistance of asphalt mixtures was investigated. Finally, cores taken from MnRoad were tested to check the potential of the overlay tester on characterizing the low temperature cracking resistance of asphalt mixtures. These three steps are discussed as follows.

VALIDATION OF UPGRADED OVERLAY TESTER USING FIELD CORES WITH KNOWN REFLECTIVE CRACKING PERFORMANCE

Since 2000, the TTI small overlay tester has been successfully employed to characterize the reflective cracking resistance of different asphalt mixtures with known reflective cracking performance in the field. Reflective cracks quickly appeared in new overlays placed on US175, US84, SH3, SH6, and IH10 throughout the state. Cores taken from these poorly performing pavements were tested in the overlay tester. The results were compared with those of cores from the Special Pavement Studies 5 (SPS5) section on US175 near Dallas. This overlay was placed over a stabilized base and had no reflective cracks after 10 years in service. All of these good and poor performing cores provided a valuable opportunity to validate the TTI overlay tester concept. Furthermore, the asphalt mixtures tested by the overlay tester cover TxDOT Type C mixtures with PG76-22 tire-rubber, Type D with PG64-22, Type D asphalt mixture with 30 percent recycled asphalt concrete, and Type D asphalt mixture with 75 percent recycled asphalt concrete, which are quite representative of those used within the Department. The detailed information is presented as follows.

Case 1: SPS5 Sections on US175

The Long-Term Pavement Performance (LTPP) program was initiated in 1987 by the Strategic Highway Research Program (SHRP). The SPS5 sections in Texas were built on US175 in the Dallas District in 1991 to compare the effectiveness of rehabilitation treatments for thin and thick overlays, constructed with virgin and recycled hot mixtures on milled and non-milled surfaces. The eight test sections representing the combinations of these three features were placed adjacent to each other for comparison.

US175 is a moderately traveled highway with two lanes per direction. The average daily traffic (ADT) for this roadway in 2000 was 29,510 vehicles, about 14 percent of which were trucks. The main problem associated with US175 was cracking. However, the average deflection measured by Falling Weight Deflectometer (FWD) was low at about 5 mils (0.127 mm) at 9000 lbs (40 kN). The deflection level was compatible to those normally observed on

Interstate Highways. Therefore, there was no structural problem with these sections. After 10 years of service, no significant distress was found on the SPS5 sections. Although many transverse cracks were observed on the shoulder, they discontinued at the travel lanes, as shown in Figure 16. The performance for all SPS5 sections has been excellent. It is important to note that the asphalt binder used was AC 5 plus 3 percent SBR Latex.

Several 6 in (150 mm) diameter cores were taken in year 2000 from two sections: the 5 in (125 mm) virgin asphalt overlay and the 30 percent recycled asphalt overlay. The cores were then shipped to TTI for overlay testing. Since the reflective cracking in the existing pavement is the bottom-up type of crack, the bottom layer plays a key role in resisting the reflective cracking. Thus, the bottom layer was tested on the overlay tester. Three cores were cut and trimmed into overlay tester specimens, 6 in (150 mm) long by 3 in (75 mm) wide by 2 in (50 mm) high. In this evaluation, all the tests were performed at 77 ºF (25 ºC) with 0.04 in (1 mm) opening displacement and 10 sec per cycle loading rate.

Figure 16. Asphalt Overlay Condition of Section 48A502, SPS5.

Figure 17 shows the test results with average values from three cores: virgin, recycled, and remixer. It can be seen that the virgin mixture has much better reflective cracking resistance than the recycled mixture. Both the virgin and the recycled mixtures are more resistant to reflective cracking than the remixer process even after 10 years of service.

In addition to the overlay testing, penetration tests were performed on the binders extracted from the two cores. Penetration numbers at 77 ºF (25 ºC) are all above 35 for both SPS5 mixtures.

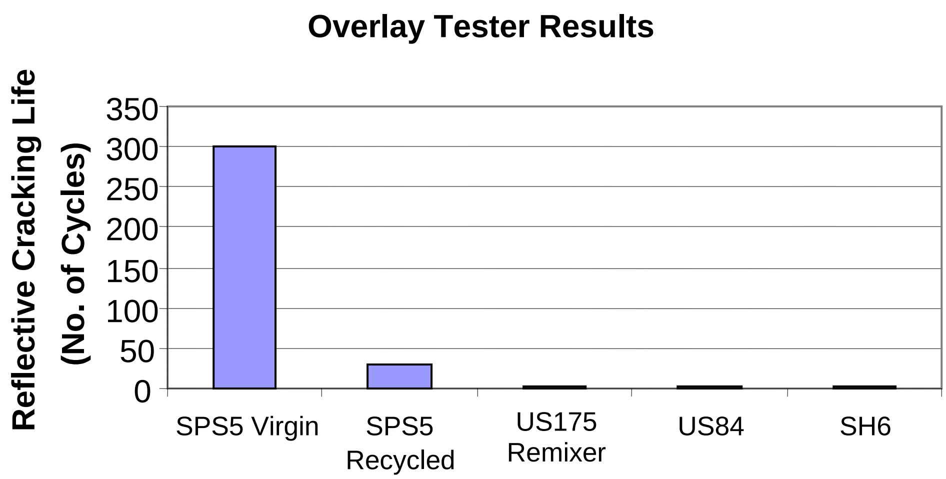


Figure 17. Overlay Tester Results on Field Cores from SPS5, US175, US84, and SH6.

Case 2: US175 and US84 Remixer

The Remixer is a hot-in-place recycling process. In this process, the top 1.5 in (38 mm) of asphalt pavement was initially heated. The Remixer machine milled it, then added and mixed about 25 percent new asphalt mixture with the recycled material. A 1.9 in (48 mm) thick recycled pavement was then compacted with a vibrating steel-wheel and pneumatic rollers. The added asphalt mixture was a standard TxDOT Type C mixture with a PG64-22 binder. In addition, approximately 0.5 percent of polymer-modified emulsified rejuvenator was added to the new mixture.

This Remixer section was on US175 a few miles from the SPS5 section, so both traffic and environmental conditions were the same as those of the SPS5 section. The reflective cracks shown in Figure 18 appeared at the surface less than one month after the Remixer overlay. The same Remixer process was also used on the US84 asphalt overlay project, in the Abilene District, Texas, where severe transverse cracks reflected through the overlay only a few weeks after opening to traffic (Figure 19). This premature reflective cracking clearly indicates that the thermal stress induced by the opening and closing of joints or cracks was the main contributor to the reflective cracking because the cracks were full width and only a low amount of traffic was applied to the section. This observation appears to confirm both the mechanism of reflective cracking discussed above and the significance of the overlay tester to simulate the thermal reflective cracking.

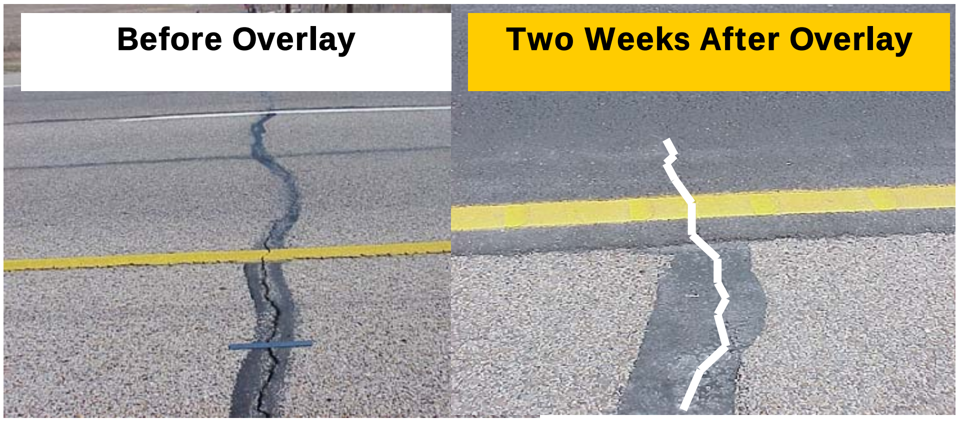


Figure 18. Reflective Cracking on US175 Remixer Section.

Figure 19. Reflective Cracking on US84 Remixer Section.

Cores were taken from both the US175 and US84 Remixer sections in the year 2000. Similarly, three cores each from US175 and US84 were cut, trimmed, and tested by the overlay tester under the same test conditions as that used on the SPS5 cores. The average value of the test results is presented in Figure 17. After two cycles, asphalt mixtures from both the US175 and US84 projects broke. Compared to the recycled and virgin asphalt mixtures from SPS5, the reflective cracking resistances of the US175 and US84 Remixer samples are much poorer. The overlay testing results are consistent with the reflective cracking performance of those materials in the field. These results reveal that the overlay tester can effectively differentiate the mixtures with poor reflective cracking resistance from the ones with good resistance.

In addition to the overlay testing, penetration tests at 77 ºF (25 ºC) were conducted on the extracted asphalt binder from two US175 cores. The penetration was 25. This value is lower than that of the extracted SPS5 binder after 10 years of service. Thus, the hardness of the binder is one contributing factor to the poor field performance.

Case 3: SH3

The original structure of SH3 is an old jointed concrete pavement with several inches of asphalt overlay located in the Galveston area, in the Houston District. The section had extensive reflective cracking. In late 2001, most of the original hot mix was removed. After milling, 1 in (25 mm) of existing hot mix asphalt was left on top of the PCC slab. Three experimental sections were then placed on this highway. The first consisted of a 1 in (25 mm) layer of Strata followed by a 2 in (50 mm) layer of Type C mix with a PG76-22 binder. A second section consisting of a Petromat fabric and the same 2 in (50 mm) surfacing was placed in the lane adjacent to the Strata section. The third section was the control section, which simply received the 2 in (50 mm) Type C surfacing course.

Pavement inspection and sampling were conducted after one year in service. Figures 20 and 21 show the condition of the experimental and control sites. Neither the Strata nor Petromat sections had any reflective cracks after one year, but many reflective cracks were present in the control section. As shown in the figures, the left lane has the Strata and the right lane has the Petromat. After one year in service no cracks were observed in either lane.

Two 6 in (150 mm) diameter cores taken from both the Strata and control sections, respectively, were cut and trimmed to the overlay tester specimen size of 6 in (150 mm) long by 3 in (76 mm) wide by 1.5 in (38 mm) high. Following the test protocol presented in Chapter 2, these specimens were tested at room temperature and a 0.025 in (0.63 mm) opening.

The results obtained for the two mixes used on SH3 are shown in Figure 22. The Type C mixture failed after 30 cycles, whereas the Strata material lasted more than 750 cycles. The test was stopped after 750 cycles, and the Strata material just cracked a little bit. Similar testing was conducted at a reduced temperature of 50 ºF (10 ºC) and the Strata material still performed very well. From the overlay tester results, the Strata material has superior crack retarding properties; however, the lab molded specimens show really poor rutting resistance (Figure 23).

Figure 20. Strata and Petromat Section on SH3, Houston District.

Figure 21. Reflective Cracking in Control Section after One Year of Service.

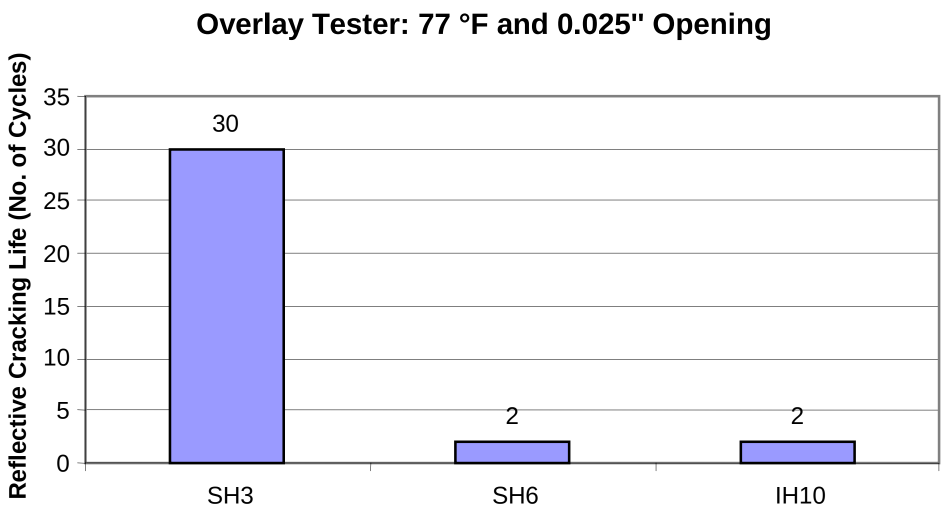


Figure 22. Overlay Tester Results on Field Cores from SH3, SH6, and IH10.

Figure 23. Strata Material Rut Depth after Asphalt Pavement Analyzer Test (more than 8 mm after 2500 Load Repetitions at 64 ºC and Loading Pressure of 100 psi).

Case 4: SH6

SH6 is a moderately traveled highway with two lanes per direction located in the Waco District. The main lanes of the existing pavement consisted of an asphalt overlay over concrete pavement, but the left turn lane was jointed concrete slabs. A level-up TxDOT Type D asphalt mixture with a PG64-22 binder was applied on the main traffic lanes. The 2 in (50 mm) TxDOT Type C asphalt mixture with 4.3 percent PG76-22 tire-rubber binder was then laid down on both main traffic lanes and the left turn lane in October 2002. After a winter season, the reflective cracks shown in Figure 24 were found on the left turn lane. However, there are still no cracks in the main traffic lanes. This observation further confirms the mechanism of reflective cracking, since traffic levels are much lower in the left turn lane than in the main lanes. It was the opening and closing induced by thermal (expansion and contraction) variation that caused the occurrence of reflective cracking.

Cores were taken from both the left turn lane and traffic lanes (surface layer only). Following the same procedures as stated previously, the overlay tester was employed to characterize the reflective cracking resistance of these cores. The test results are presented in Figures 17 and 22. After two cycles, the specimens broke. Laboratory testing of these cores indicates that the binder in the failed mixture was prematurely aged. It is suspected that this binder was "burnt" during production.

Figure 24. Reflective Cracking on the Left Lane of SH6.

Case 5: IH10

Interstate Highway 10 is one of the major traffic roads in the Houston District. IH10 is plain concrete pavement with heavy traffic. In order to improve the ride quality and structural adequacy, 4 in (100 mm) of Type C asphalt mixture was laid in two lifts on the existing concrete pavement in 2002. Designers used 4.4 percent PG76-22 S asphalt binder to produce this overlay mixture. After two winters the reflective cracking was observed at the surface of the 4 in (100 mm) asphalt overlay. In order to investigate the reflective cracking, several cores were taken back to TTI. Two cores were used to prepare the overlay tester specimens (6 in [150 mm] long by 3 in [76 mm] wide by 1.5 in [38 mm] high). The overlay tester conditions were 0.025 in (0.64 mm) opening and 77 ºF (25 ºC). The average test result is shown in Figure 22. The specimens failed after two cycles.

In summary, the case studies conducted above clearly show that the overlay tester results are consistent with the field performance, and the poor crack resistant asphalt mixtures can be rapidly differentiated from the good ones. These case studies also confirm the overlay tester as a rapid performance-related tool to evaluate the reflective cracking resistance of asphalt mixtures. Thus, the researchers recommend incorporating the overlay tester into the current asphalt mixture design system to optimize both rutting potential and reflective cracking resistant asphalt mixtures. In addition, it can be seen that the current Type C mixture with PG76-22 binder is not crack resistant. More research should be conducted in designing both rutting and cracking resistant asphalt mixtures using stiff binders.

PRELIMINARY PASS/FAIL CRITERIA ON REFLECTIVE CRACKING RESISTANCE OF ASPHALT MIXTURES

Based on the overlay tester results on the known field performance cores taken from different highways, it can be seen from Figures 16 to 24 that asphalt mixtures performed very well when the reflective cracking life (from the overlay tester) is larger than 300. Thus, the researchers propose the preliminary pass/fail criterion on reflective cracking resistance to be 300 cycles. For the rich bottom layer (if used), the reflective cracking life should be at least 750 cycles.

COMPARISON BETWEEN OVERLAY TESTER AND BEAM FATIGUE TEST

The beam fatigue test results are from TxDOT project 0-4468 "Evaluate the Fatigue Resistance of Rut Resistance Mixes." In project 0-4468, three types of asphalt mixtures were tested under the AASHTO TP8-94 test procedure. These three mixtures were a Type C mixture with 4.6 percent PG64-22 binder and limestone aggregate from the Bryan District, a Superpave D mixture with 5.3 percent PG76-22 binder and crushed gravel from the Yoakum District, and a Superpave C mixture with 5.3 percent PG70-22 binder and igneous aggregate from the Waco District. The target air void content for all the beam specimens was 7 percent. The beam fatigue test consists of applying a repeated constant vertical strain to a beam specimen in flexural tension mode until failure or up to a specified number of load cycles. The test was strain controlled, and the input strain waveform was sinusoidal shaped, applied at a frequency of 10 Hz. Only beam fatigue test results under low strain level (approximately 374 microstrain) are discussed. These beam fatigue tests were conducted at a test temperature of 68±1 °F (20±0.5 °C). The fatigue resistance of these three mixtures can be ranked from the best to poorest as: ¾ in Superpave C with igneous, ½ in Superpave D with gravel, and Bryan Type C (*14*).

Since the control point (or zone) of the beam fatigue test is the middle one-third part, both one-third ends are under low strain and less damage occurs. Thus, it is reasonable to use the beam end part to run the overlay tester and make the qualitative comparison with beam fatigue test results. Two overlay tester specimens were cut from both end parts of the beam. The overlay tester was conducted for all three mixtures under standard testing conditions: 77 ºF and 0.025 in (25 ºC and 0.64 mm) opening. The overlay tester results are presented in Table 1.

It is clear to see that the overlay tester results show the same ranking as those from the beam fatigue test. Thus, the overlay tester can be used to qualitatively evaluate the fatigue cracking resistance of asphalt mixtures.

Table 1. Comparison between Beam Fatigue Test and Overlay Tester.

Asphalt Mixture	**Type C**	**½ in Superpave**	**¾ in Superpave**
Overlay Tester	2	325	>750
Fatigue Resistance	127,000	224,000	443,000

VALIDATION OF OVERLAY TESTER USING MnROAD CORES

In addition to reflective cracking and traditional fatigue cracking, the TTI overlay tester was also used to evaluate the low temperature cracking resistance of asphalt mixtures from MnRoad. Three representative test cells (15, 18, and 20) at MnRoad were selected for evaluation. Table 2 presents the asphalt mixture information and field performance of these three cells. Two 6 in (150 mm) diameter cores from each cell were taken from the mid-lane of the driving lane (6 feet offset), then shipped to TTI for overlay testing.

As noted by Mr. Ben Worel *(15)* of MnRoad these cells were microsurfaced. The micro-surface layer can be seen from the cores taken (Figure 25). Thus, the microsurface layer was trimmed off during preparation of the overlay tester samples. Furthermore, only the top asphalt mixture layer was tested under the overlay tester, although these cores are composed of different layers, because the asphalt mixture layer for the low temperature cracking is critical. The overlay tester was conducted at a temperature of 77 °F (25 °C) with an opening displacement of 0.025 in. The overlay tester results are presented in Table 2. It can be seen that the overlay tester results are consistent with the observed field cracking performance of asphalt mixtures. The results also indicated that both asphalt content (cells 15 and 18) and asphalt binder PG (cells 15, 18, and 20) had influence on crack resistance, which is consistent with the results of the sensitivity study conducted in chapter 2.

Table 2. Three Test Cells of MnRoad: Asphalt Mixture and Cracking Performance.

Test Cell	**Asphalt Type**	**Mix Design (Marshall)**	**Linear Feet of Cracking in Field**	**Overlay Tester Results**
15	PG64-22	75 blow	475	91
18	PG64-22	50 blow	315	153
20	PG58-28	35 blow	100	500

Figure 25. Field Cores from MnRoad.

SUMMARY AND CONCLUSIONS

The above overlay tester results indicate that the upgraded overlay tester can effectively differentiate between the reflective cracking resistance of asphalt mixtures. It also appears feasible to use the small specimens (6 in long by 3 in wide by 1.5 in high [150 mm by 75 mm by 37 mm]) to evaluate the reflective cracking resistance of the asphalt mixtures. It is clear that a relationship exists between reflective cracking resistance of asphalt mixtures and the associated asphalt binders. Stiff binders have poorer reflective cracking resistance than soft binders (Figures 16 to 24). Higher asphalt binder contents plus softer binder will provide the asphalt mixtures with better crack (fatigue, low temperature, and reflective crack) resistance. Furthermore, the overlay tester can also be used to evaluate the fatigue cracking and low temperature cracking resistance of asphalt mixtures.

Based on the overlay tester results from these field cores, the recommended preliminary pass/fail criteria on reflective cracking resistance of asphalt mixtures are as follows:

Rich bottom layer mixtures: reflective cracking life > 750 cycles;

Other layer mixtures: reflective cracking life > 300 cycles

CHAPTER 4

APPLICATION OF THE OVERLAY TESTER TO EVALUATE REFLECTIVE CRACKING RESISTANCE OF TYPICAL TXDOT MIXTURES

As validated in the previous chapter, the upgraded overlay tester can be used to evaluate the reflective cracking resistance of asphalt mixtures over PCC or cracked flexible pavements. In this chapter, reflective cracking resistances of commonly used asphalt overlay mixtures in Texas were evaluated. Those mixtures include Type C, Type D, CMHB-C, CMHB-F, ½ in (12.5 mm) Superpave, and Stone Matrix Asphalt (SMA). It is well known that type and percent of asphalt binder, type of aggregate, and gradation influence the reflective cracking resistance. Thus, all three factors were considered during the experimental design and are discussed as follows.

INFLUENCE OF ASPHALT BINDER TYPE ON REFLECTIVE CRACKING RESISTANCE

A TxDOT Type D mixture from the US281 Erath County asphalt overlay project, southwest of Fort Worth, Texas, was used in this investigation. Since the focus here is on the influence of binder type on reflective cracking resistance, the same aggregate and gradation as that used in the field project were utilized for molding the specimens. The only factor changed was the binder type. The aggregate was limestone with some absorption, and its gradation is listed in Table 3. As listed in Table 4, nine types of asphalt binders were evaluated; these binders represented most of those used in Texas. It should be noted that based on Dynamic Shear Rheometer and Bending Beam Rheometer test results, the last three SBR Latex modified binders are all classified as PG76-22.

This Type D mixture was designed based on 4 percent design air void content with the Texas Gyratory Compactor. The binder used for the design was Koch PG64-22 and the optimum asphalt content was determined to be 5.1 percent. Compared to gradation and aggregate type, the binder itself had minor effect on the optimum asphalt content for the different binders. Thus, the same optimum asphalt content (5.1 percent) was used in the laboratory study for all the binders.

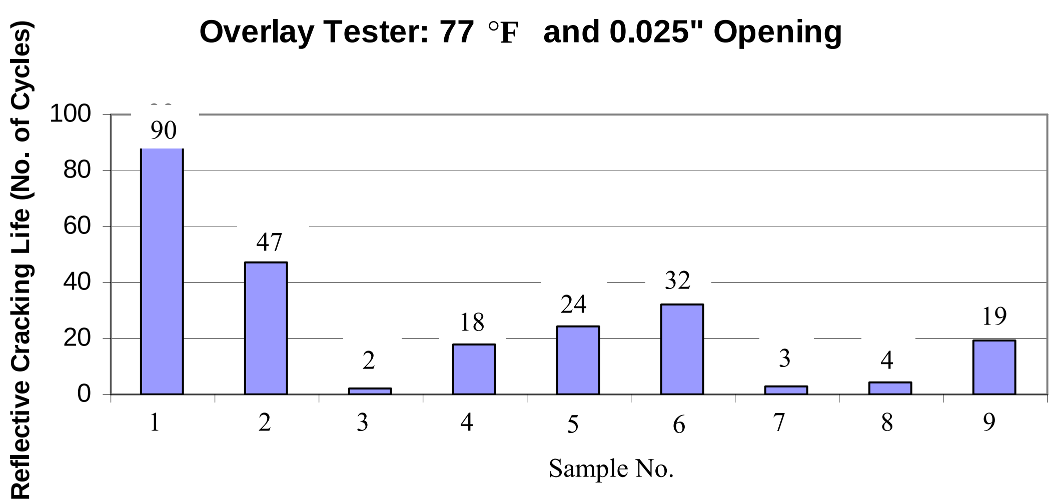
Table 3. US281 Asphalt Overlay Mixture Gradation.

Sieve Size	Contractor's Cumulative Pass (Total % 100)	TxDOT Specs. (%)
½ in (12.5 mm)	100	98-100
3/8 in (9.5 mm)	98.9	85-100
4.75 mm (No. 4)	64.2	50-70
2.0 mm (No. 10)	36.8	32-42
0.425 mm (No. 40)	18.7	11-26
0.180 mm (No. 80)	8.1	4-14
0.075 mm (No. 200)	3.0	1-6

Table 4. Asphalt Binders Used in This Project.

Specimen No.	**1**	**2**	**3**	**4**	**5**
Binder Type	PG64-22	PG70-22	PG76-16 Air Blown	PG76-22 Tire Rubber	PG76-22 Elvaloy
Specimen No.	**6**	**7**	**8**	**9**	
Binder Type	PG76-22 SBS	PG58-22 +4%SBR	PG64-22 +4%SBR	PG64-22 +3%SBR	

Three 6 in (150 mm) diameter by 2.5 in (63 mm) high specimens for each asphalt mixture were fabricated using the SGC. The specimens were then cut and glued to the tester plates. The final air void contents of all the specimens were controlled within 4±0.5 percent. The testing was performed in repeated load form (Procedure A) at 77 °F (25 °C) and with a 0.025 in (0.63 mm) opening displacement. Figure 26 presents the results from this project.



1-PG64-22, 2-PG70-22, 3-PG76-16, 4-PG76-22TR, 5-PG76-22 Elvaloy,
6-PG76-22 SBS, 7-PG58-22+4%SBR, 8-PG64-22+4%SBR, 9-PG64-22+3%SBR

Figure 26. Influences of Asphalt Binders on Reflective Cracking Resistance of Asphalt Mixtures.

It can be seen from Figure 26 that the reflective cracking lives of the asphalt mixtures generally decrease with the increase in performance grade of asphalt binder used at high temperature. For example, the asphalt mixture with the PG64-22 binder performed better than that with the PG70-22 binder, which was better than those with the PG76-16 and all the other PG76-22 binders. In this study, the PG76-16 Air Blown performed the worst. It should be noted that the field cores with the PG64-22 plus 3 percent Latex taken from the US281 project performed differently from the lab molded specimen, although the raw materials were kept the same. One possible reason for this difference may be the compaction methods. The structure (such as aggregate distribution and air void distribution) of specimens molded in the laboratory may be different from that of the asphalt mixtures in the field, since different types of compaction machines were used. More research is needed to investigate how to simulate the field compaction in the lab.

INFLUENCE OF AGGREGATE PROPERTIES ON REFLECTIVE CRACKING RESISTANCE

Compared to asphalt binder, the influence of aggregate on reflective cracking resistance is seldom studied. From preliminary work at TTI, it appears that one property in particular, the aggregate adsorption, has a major impact on cracking life as measured by the overlay tester. One crushed gravel (Hoban Ryolite) and four types of limestone aggregates with variable absorption to asphalt binder were evaluated in this project. The crushed gravel and one of the limestone aggregates were used to make TxDOT's CMHB-F asphalt mixtures for the Odessa and Houston Districts, respectively. These two mixtures had similar gradation, and the asphalt binder used for both mixtures was crumb rubber modified asphalt. Following TxDOT Special Specification Item 3092, the Optimum Asphalt Content (OAC) for these two mixtures was determined to be 7.5 percent and 7.8 percent, respectively.

Three specimens for each CMHB-F mixture were prepared and tested at 77 °F (25 °C) with a 0.025 in (0.63 mm) opening displacement. The results are presented in Figure 27. These two CMHB-F mixtures performed totally different. The CMHB-F with the crushed gravel aggregate failed after 1500 cycles. However, the CMHB-F with the limestone failed after only four cycles. To investigate the reason for this difference, the broken surfaces of the specimens were visually inspected after the overlay test. The crack surfaces of these two CMHB-F mixtures are shown in Figure 28. The crack surface for the limestone (with high absorption of the binder) appears very dry and the asphalt appears to be dull and aged. In contrast, the gravel aggregate (with little absorption of the binder) appears fresh and shining. The aggregate absorption appears to be the main reason for the difference in their performance.

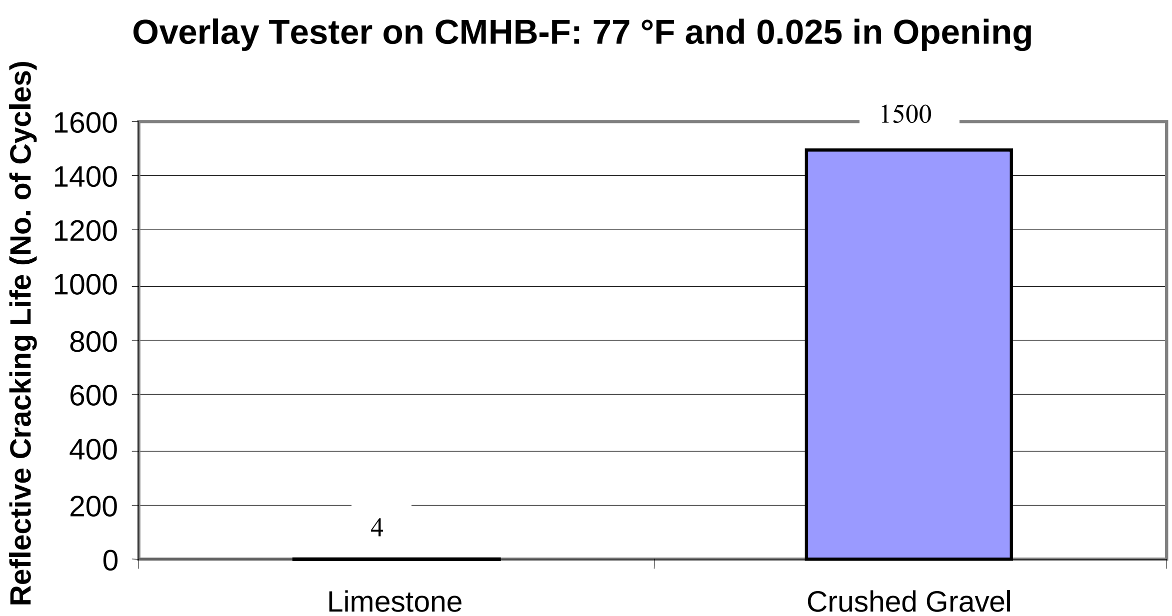
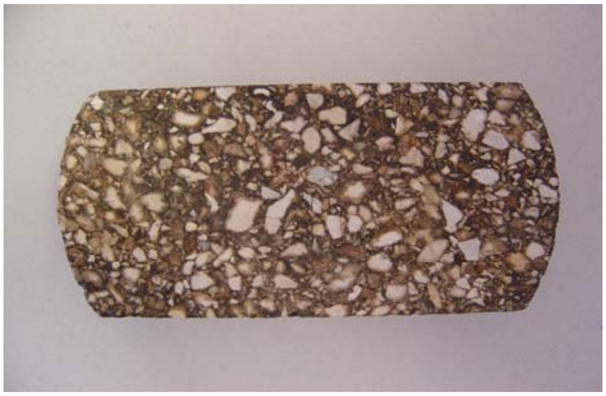


Figure 27. Overlay Tester Results on Two CMHB-F Mixture Where the Aggregate Type was the Main Variable.

Figure 28. Crack Surfaces of Broken Specimens.

To further demonstrate the influence of aggregate absorption, three TxDOT Type D mixtures were evaluated. One was the US281 asphalt mixture discussed previously. The other two Type D mixtures were from the Wichita Falls District, Texas. These three mixtures were made using the same PG64-22 asphalt binder, following the same gradation, but with three different limestone aggregates with variable levels of absorption. The cut surfaces of specimens are shown in Figure 29. It is easy to visually differentiate the level of absorption. The Wichita Falls #1 aggregate was highly absorptive, the #2 aggregate had very little absorption, and the Fort Worth aggregate had intermediate absorption. In the highly absorptive case, the individual aggregates are discolored. The researchers assume that this is selective absorption where the lighter fractions from the asphalt are being drawn into the aggregate. With the better quality aggregates, no discoloration of the aggregates was found. The overlay tester results (Figure 30) clearly differentiate the cracking resistance of these three mixtures.

From these studies it appears that aggregate absorption has significant influence on cracking resistance of asphalt mixtures. The overlay tester is a useful tool to effectively evaluate this influence. It is also interesting to note that all of these mixtures did well in the rut resistance tests.



a. Wichita Falls #1 Limestone: Highly Absorptive.

b. Fort Worth Limestone: Intermediate Absorptive.

c. Wichita Falls #2 Limestone: Little Absorptive.

Figure 29. Limestone Absorptive.

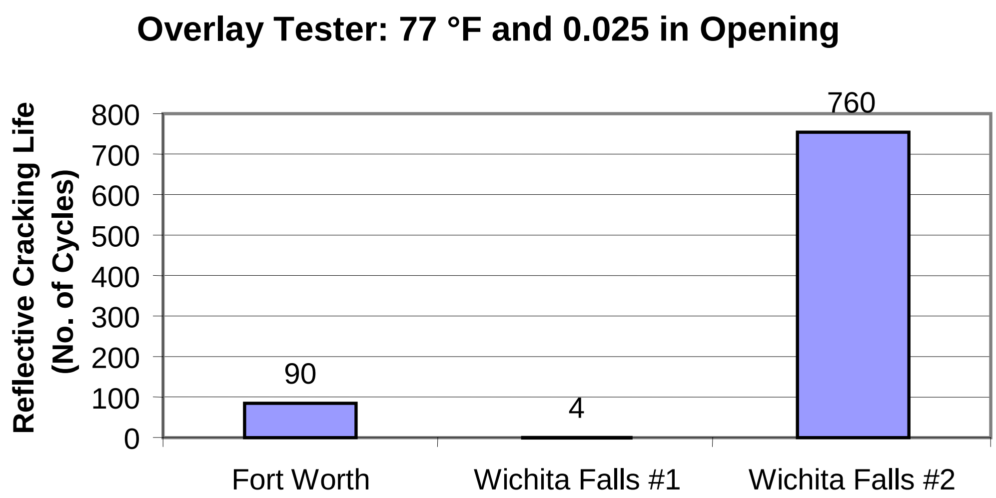


Figure 30. Influence of Absorption of Aggregate on Reflective Cracking Resistance.

EVALUATION OF REFLECTIVE CRACKING RESISTANCE OF TXDOT'S MIXTURE

This evaluation was conducted at two temperatures: 77 °F (25 °C) and 50 °F (10 °C). These tests are discussed as follows.

Overlay Tester at 77 °F (25 °C)

Most of the TxDOT mixtures have been tested and reported previously. Here the focus will be on two mixtures: Type C mix from the Dallas District and ¾ in (19 mm) SMA from the Tyler District. Both mixtures used a PG76-22 binder and granite aggregates, and their OACs are 4.4 (Type C) and 6.1 (SMA) percent. In addition, 0.2 percent fibers were added in the SMA mixture. Their air voids after cutting were 6.3 (Type C) and 5.9 (SMA). Three samples for each mixture were tested at 77 °F (25 °C) with a 0.025 in (0.63 mm) opening. Figure 31 presents the test results. It should be noted that a Type C mixture from the Bryan District failed after only two cycles. That mixture was made of absorptive limestone aggregate, PG64-22 binder, and 4.6 percent AC. Lower PG and higher asphalt content should perform better. However, it had much poorer crack resistance than the Type C mixture with granite. Also, the SMA with 6.1 percent asphalt content had much better reflective cracking resistance than that of the Type C with granite. These results further indicate the importance of aggregate and asphalt content.

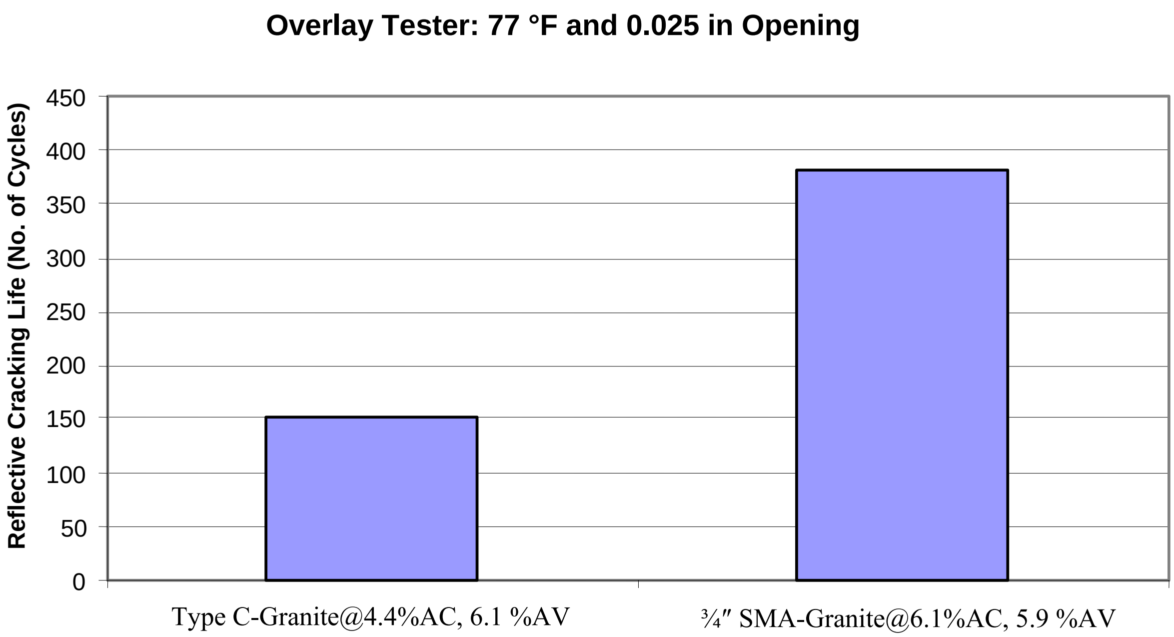


Figure 31. Overlay Tester Results on Type C-Granite and ¾ inch SMA-Granite.

Overlay Tester at 50 °F (10 °C)

Four typical TxDOT overlay mixtures were evaluated: Type C, CMHB-C, ½ in (12.5 mm) Superpave, and CMHB-F mixtures. The OAC for each mixture is presented in Figure 32. It should be noted that the OACs for the Type C, CMHB-C, and CMHB-F were determined based on TxDOT's mixture design procedure (Texas Gyratory Compactor and 4 percent air void content for Type C and CMHB-C, 3 percent air void content for CMHB-F), and the ½ in (2.5 mm) Superpave was designed based on the Superpave volumetric design method (100 gyrations and 4 percent air void content). Three overlay tester specimens were prepared for each mixture with a 4±0.5 percent target air void content of specimen after cutting. All these specimens were made by the SGC using the same PG64-22 asphalt binder and the same crushed gravel aggregates but with variable gradations. Figure 33 illustrates the gradations.

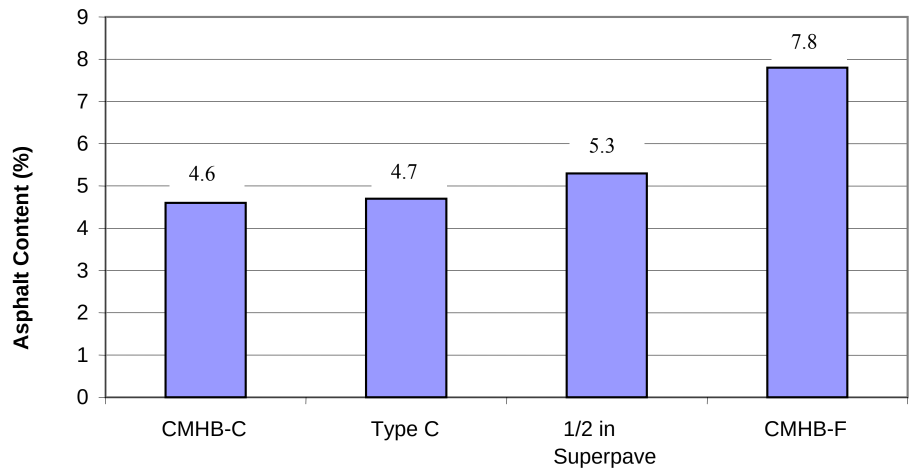


Figure 32. OACs of Mixtures.

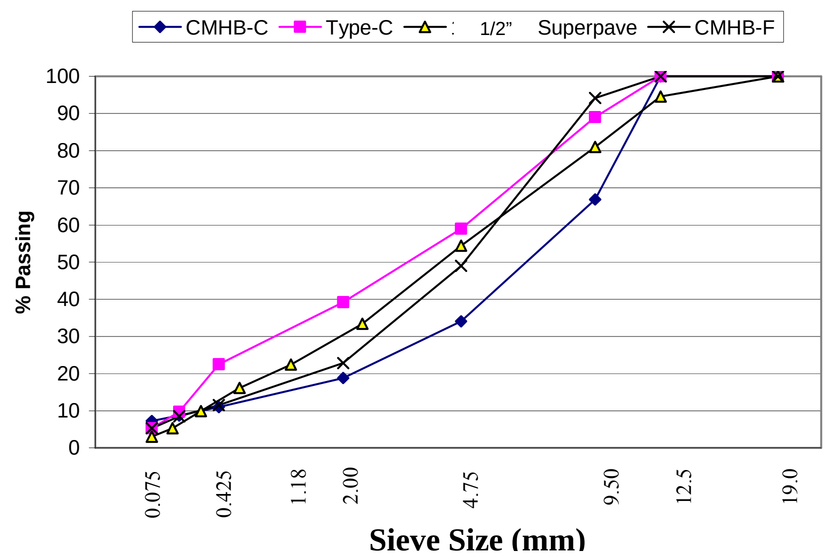


Figure 33. Gradations of the Mixtures Evaluated.

For this comparative testing, more severe test conditions were used. The overlay tester was performed at 50 °F (10 °C) and a 0.018 in (0.45 mm) opening displacement, and test results are shown in Figure 34. These results demonstrate the significance of asphalt content on the cracking resistance. The finer mixtures with higher asphalt contents clearly show better reflective cracking resistance.

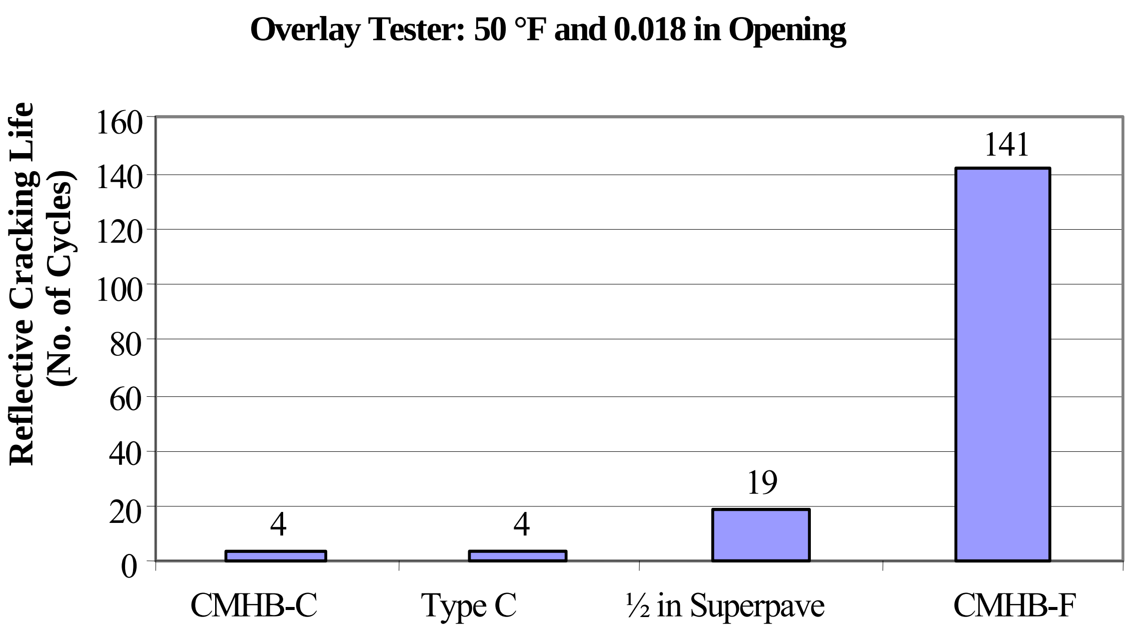


Figure 34. Influence of Gradation on Reflective Cracking Resistance of Asphalt Mixtures.

In summary, based on the results presented in this section, it can be seen that the aggregate type and especially the aggregate absorption have significant influence on the reflective cracking resistance of the asphalt mixtures. In addition, the aggregate gradation affects the OAC and further leads to different reflective cracking resistance. The higher the asphalt content, the better the reflective cracking resistance of the asphalt mixture. Additional research studies are needed to further investigate the influence of aggregates on reflective cracking performance of asphalt overlay mixtures.

CHAPTER 5

CASE STUDIES: OPTIMIZATION OF ASPHALT OVERLAY MIXTURE DESIGN USING THE OVERLAY TESTER AND HAMBURG WHEEL TRACKING TEST (HWTT)

INTRODUCTION

On a pilot basis the overlay tester has also been successfully used to select the design asphalt content for two overlay mixtures in Texas. The overlay tester was integrated into an asphalt overlay mixture design procedure to balance both rutting and reflective cracking requirements. In this chapter, a preliminary framework for an asphalt overlay mixture design procedure is presented. Then, two case studies are presented to demonstrate the procedure.

A PRELIMINARY FRAMEWORK FOR ASPHALT OVERLAY MIXTURE DESIGN, CONSIDERING BOTH REFLECTIVE CRACKING AND RUTTING

As mentioned initially, to perform well in the field the asphalt overlay mixture must be both rut and reflective cracking resistant. Thus, both rutting and reflective cracking must be considered during the mixture design. In practice the overlay can be either a single lift (typically 2 in [50 mm]) or composed of two lifts with a level up layer and then a wearing surface.

For the top wearing surface layer, rutting plus moisture damage are the main concerns, which have been successfully addressed in Texas by using the HWTT. Compared to rutting, reflective cracking is a secondary concern, but it still is a concern. The overlay tester is recommended for this issue. Thus, both the overlay tester and the HWTT are recommended for designing the top asphalt overlay mixtures.

For the bottom asphalt (level up) layer, the reflective cracking issue becomes the main concern. The potential rutting caused by construction traffic and early traffic (before paving the next layer) is a secondary issue. The Asphalt Pavement Analyzer (APA) is temporarily used to address this problem, since there was no HWTT criterion on it. In summary, the researchers propose a preliminary framework of asphalt overlay mixture design shown in Figure 35 to balance both rutting and reflective cracking issues.

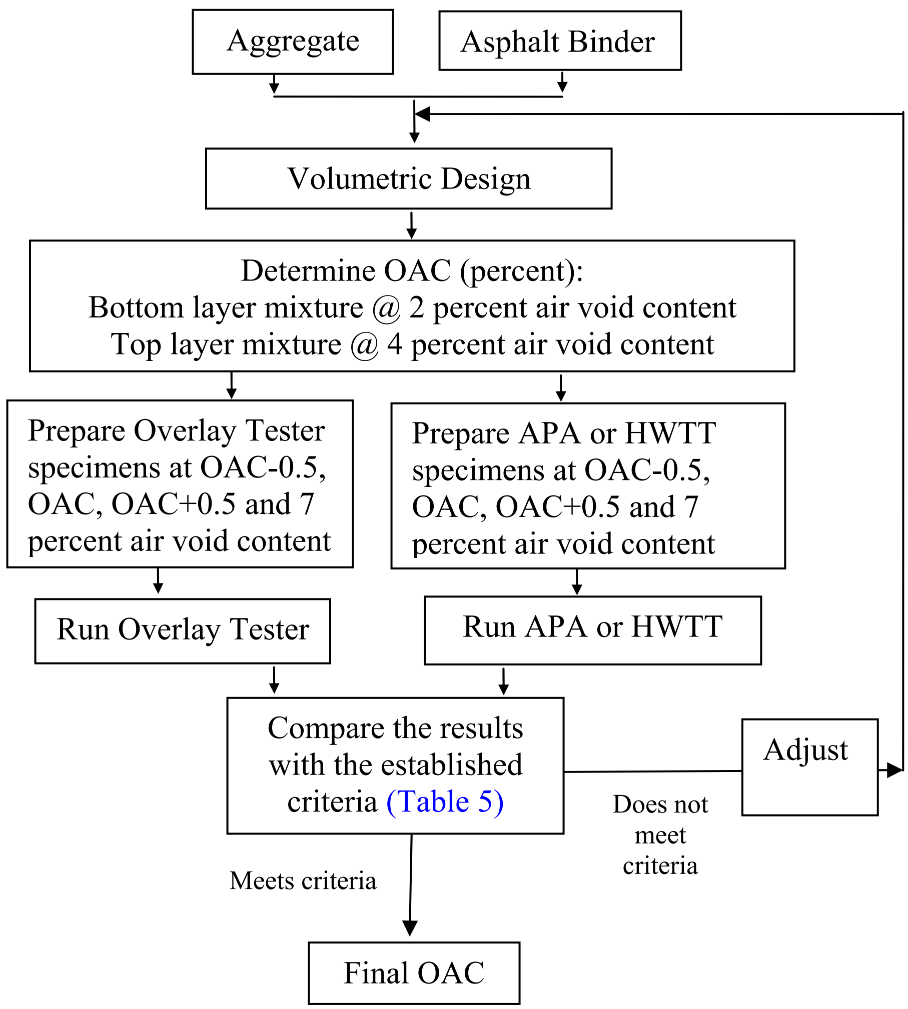


Figure 35. Proposed Asphalt Overlay Mixture Design Process.

As the different layers in the overlay have different critical issues, it is appropriate to set different criteria for each. Based on the substantial overlay tester results, TxDOT's specification on the HWTT (*16*), and the APA criteria (*17*) by others, the preliminary criteria for the overlay tester, the HWTT, and the APA are presented in Table 5. It should be noted that the APA criteria, with consideration of the hot weather in Texas, was reduced from the original 8 mm (*17*) to 6 mm (Table 5). Several asphalt overlay projects have successfully used the proposed framework to design both rutting and reflective cracking resistant asphalt overlay mixtures. These field projects make it possible to further refine this framework and associated criteria in the future. Two examples are presented in the following sections to demonstrate the asphalt overlay mixture design process, although both cases do not follow the exact process proposed. It should be noted that the mix designs were provided by the TxDOT Wichita Falls and Atlanta District Labs rather than TTI.

Table 5. Proposed Preliminary Criteria on Asphalt Overlay Mixtures.

Tests	Indicator	Bottom Layer	Top Layer
Overlay Tester @ 77 °F (25 °C) and 0.025 in Opening	Reflective Cracking Life	750 cycles, min.	300 cycles, min.
APA @ 64 °C, 100 psi	Rut Depth @ 8000 Strokes	6 mm, max.	N/A
HWTT @ 50 °C	Rut Depth (RD)	N/A	PG64-22, RD@10,000<12.5 mm PG70-22, RD@15,000<12.5 mm PG76-22, RD@20,000<12.5 mm

CASE STUDY 1: US82, WICHITA FALLS, TEXAS

US82 is a non-reinforced jointed concrete pavement (JCP) located in the Wichita Falls District, Texas. This highway was built in 1957. The majority of this JCP has been performing well. Over these years, full depth repairs were made at selected locations to improve the roadway condition. However, the Area Engineer was planning to place an HMA overlay on top of the existing JCP, which was going to be the first major rehabilitation since the JCP was built. The proposed rehabilitation strategy was to place 1.5 in (38 mm) Porous Friction Course (PFC), over a 3 in (75 mm) SMA and with a 1.5 in (38 mm) Type D mixture directly on top of the concrete. In this case, only the lower 1.5 in (38 mm) Type D mixture was tested, although other layer mixtures were important to resist reflective cracking as well.

Following the proposed framework, the bottom layer asphalt mixture was designed based on TxDOT's standard Type D mixture design procedure. The aggregates were limestone with very low absorption and a PG64-22 asphalt binder was selected. Using TxDOT procedures, this mix was designed based on a target air void content of 3 percent. The OAC was found to be 5.1 percent. In addition, a mixture with 5.4 percent asphalt content (0.3 percent more than the OAC) was also evaluated. Three specimens (6 in [150 mm] diameter by 2.5 in [63 mm] high) for the overlay tester and six APA specimens (6 in [150 mm] diameter by 3 in [75 mm high]) were molded at 5.1 percent and 5.4 percent asphalt content, respectively. All these specimens were made at 7 percent air void content using the SGC. The average air void content of the overlay tester specimens after cutting was 5.5 percent.

The overlay tester was conducted at 77 °F (25 °C) and a 0.025 in (0.63 mm) opening displacement; the APA was run under the pressure of 690 kPa and at 150 °F (64 °C). The average test results are listed in Table 6. It can be seen that the mixture with either asphalt content passes the proposed criteria (Table 5). Since this mixture is the bottom layer, 5.4 percent asphalt content was recommended to get more cracking resistance without loss of rutting resistance.

Table 6. Reflective Cracking Lives and APA Rut Depth after 8000 Strokes.

Asphalt Content	Reflective Cracking Life	Rut Depth @ 8000
5.1 percent	760	3.4 mm
5.4 percent	902	5.2 mm

CASE STUDY 2: CMHB-F DESIGN FOR THE ATLANTA DISTRICT, TEXAS

The CMHB-F mixture is to be used as a wearing surface mixture, and a PG76-22 binder was chosen to minimize the potential rutting. The aggregates selected for this mixture were a combination of 66 percent crushed gravel, 16 percent limestone, and 18 percent igneous screenings. The OAC was 6.0 percent based on TxDOT's Specification Item 3146. The design air void content for the CMHB-F was 3 percent. Six specimens with 6 in (150 mm) diameter by 2.5 in (63 mm) high (three for the overlay tester and three for the HWTT) were made using the SGC with the target air void content of 7 percent, which is the median air void content anticipated in the field.

The overlay tester was conducted at 77 °F (25 °C) and a 0.025 in (0.63 mm) opening displacement, and the HWTT was performed at 144 °F (50 °C) following TxDOT's standard test method. The test results are listed in Table 7. It is apparent that this CMHB-F mixture passed the surface mixture criteria. Thus, the final asphalt content was determined to be 6.0 percent.

Table 7. Test Results on CMHB-F Mixture from Atlanta, Texas.

Overlay Tester (No. of Cycles)	HWTT@20,000 Passes
325 (>300)	9.6 mm (<12.5 mm)

In summary, the researchers proposed a framework for the asphalt overlay mixture design procedure that addresses both rutting and reflective cracking concerns. This procedure should be used when designing overlays for cracked asphalt or concrete pavements. In this framework, the overlay tester is recommended to characterize the potential reflective cracking, and the HWTT test and APA are recommended to control the rutting problems of the top layer and/or bottom layer mixtures, respectively. Preliminary criteria for each test are proposed and, to be acceptable, the proposed mixture must pass both tests. To demonstrate the procedure, one bottom layer mixture and one surface layer mixture were successfully designed with the proposed design procedure and associated criteria. This preliminary design procedure and associated criteria will be refined based on the performance data of these asphalt overlay projects.

CHAPTER 6

FRAMEWORK OF OVERLAY TESTER BASED REFLECTIVE CRACKING ANALYSIS SYSTEM

INTRODUCTION

As noted previously, reflective cracking is one of the primary forms of distress in HMA overlays of flexible and rigid pavements. The basic mechanism causing reflective cracking is strain concentration in the overlay due to movement in the existing pavements in the vicinity of joints and cracks. This movement may be induced by bending or shear action resulting from traffic loads or daily and seasonal temperature changes. In fact, any reflective cracking is caused by the combination of these three mechanisms: bending, shearing, and thermal stresses. Every pass of a traffic load will induce two shearing plus one bending effect on the HMA overlay. Also, these bending and shear stresses are affected by the daily temperature. Thus, the combination of all three mechanisms is crucial to successfully modeling reflective cracking. In addition, crack initiation and propagation is influenced by the existing pavement structure and conditions, reflective cracking countermeasures (e.g., reinforcing, interlayer), HMA mixture properties, specifically, the degree of load transfer at joints and cracks, and others. Therefore, all three mechanisms plus these influence factors must be addressed in the proposed framework of the reflective cracking analysis system.

REFLECTIVE CRACKING MODELING APPROACH BASED ON FRACTURE MECHANICS

Since Majidzadeh, et al. (*18*) 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. Different from continuum mechanics, the fracture mechanics approach focuses on crack propagation. The occurrence of reflective cracking is a crack propagation process caused by a combination of the three modes of loading:

- Mode I loading (opening mode, K_I) results from loads that are applied normally to the crack plane (thermal and traffic loading).
- Mode II loading (sliding mode, K_{II}) results from in-plane shear loading, which leads to crack faces sliding against each other normal to the leading edge of the crack (traffic loading).
- Mode III loading (tearing mode, K_{III}) results from out-of-plane shear loading, which causes sliding of the crack faces parallel to the crack leading edge. Compared to Modes I and II, Mode III is rare and is often neglected for simplicity.

The fact that the mechanisms of reflective cracking (bending, shear, and thermal) can be exactly modeled by fracture Modes I and II makes the fracture mechanics approach the best option for modeling reflective cracking.

The generally accepted crack propagation law was proposed by Paris and Erdogan (*19*) in the form of Equation 2. It has successfully been applied to asphalt concrete by many researchers, for the analysis of experimental test and prediction reflective cracking and low temperature cracking.

$$\frac{dc}{dN} = A * (\Delta K)^n \tag{2}$$

where:

c = crack length
N = number of loading cycles
A, n = fracture properties of asphalt mixture determined by the experimental test
ΔK = stress intensity factor (SIF) amplitude, depending on the geometry of the pavement structure, fracture mode, and crack length

The number of load cycles N_f needed to propagate a crack through the asphalt overlay thickness of h can be estimated by numerical integration in the form of Equation 3.

$$N_f = \int_0^h \frac{dc}{A(\Delta K)^n} \tag{3}$$

It is apparent that the SIF, material fracture properties (A and n), and interlayer properties (if used) must be known in order to design the asphalt overlay thickness and/or predict the reflective cracking performance of an asphalt overlay. The methods to determine the SIF and fracture properties, and the reflective crack propagation models are discussed in detail below.

Determination of SIF

Since there is a singularity at the crack tip in the stress field, a finite element (FE) program is needed to compute the SIF. Two special SIF computation programs have already been developed for crack propagation. CRACKTIP was developed for thermal cracking by Lytton et al. at the Texas Transportation Institute in 1976. CRACKTIP is a two-dimensional (2-D) FE program that models a single vertical crack in the asphalt concrete layer via a crack tip element *(20)*. This program has been successfully used to develop the SIF model and predict the cracking propagation. Figure 36 shows the SIF of bending (SIF_b) and SIF of shearing (SIF_s) versus crack length relationship. It is interesting to note that there is a "neutral axis" where bending stresses no longer cause crack propagation. Its' location depends on the level of load transfer and moduli of pavement layers. This neutral axis must be considered in order to accurately predict the reflective cracking.

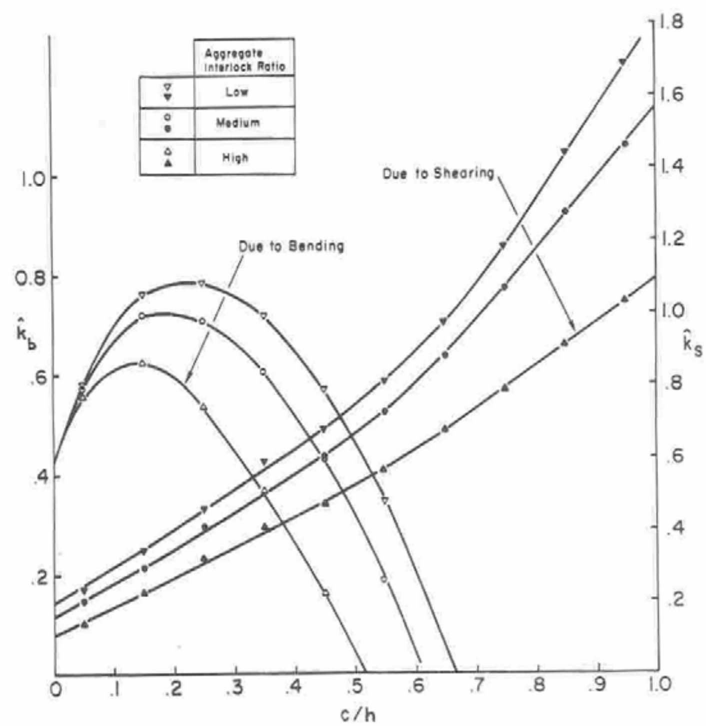


Figure 36. Non-dimensionalized Bending and Shearing SIF vs. Non-dimensionalized Crack Length.

Another powerful SIF program named CAPA (Computer Aided Pavement Analysis) was developed by Delft University of Technology in the early 1990s. The CAPA program was initially developed for reflective cracking analysis. It uses a quarter point triangular singular element to produce the stress singularity at the crack tip. The CAPA program has some special features that were created to specifically address the reflective cracking issue. All of these features make CAPA the best program for reflective cracking analysis and prediction.

- Reflective cracking propagation can be simulated either in 2-D or in 3-D.
- Special elements have been developed for the interlayer products. For example, a bar element (Figure 37) was developed for the reinforcement grid.
- An interface element (Figure 37) was developed to simulate the crack interface or the interface between the overlay layer and the existing pavement (or between the reinforcement product and the surrounding asphalt concrete).
- A powerful remeshing technique shown in Figure 38 was incorporated into the CAPA program to completely, automatically simulate crack propagation.

The CAPA program is the most powerful existing program to analyze the reflective cracking in HMA overlays.

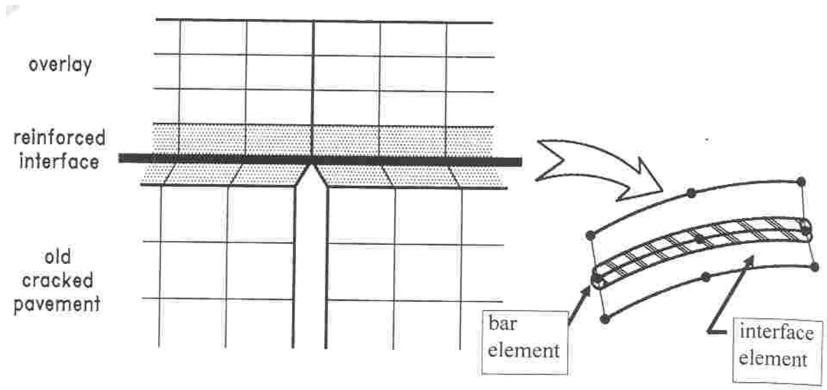


Figure 37. Interlayer Element (*21*).

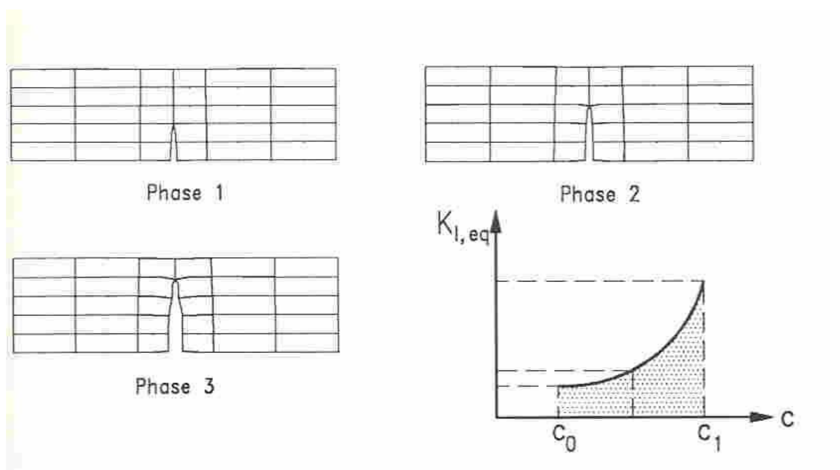


Figure 38. Automatic Crack Propagation Procedure in CAPA (*21*).

Material Properties: A, n, and Overlay Tester

Equation 3 shows two material properties, A and n, which are the fracture properties and which were the subject of much of the testing and analysis in the SHRP A-005 project, the results of which are found in the SHRP A-357 report (*22*) and in several technical papers and presentations since then. The SHRP report shows that these two properties 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. It has also led to the method of estimating the fracture properties that is incorporated in the Texas DOT FPS-19 reflective cracking design check feature and in the Windows-based reflective cracking design program that was developed by TTI for the Florida DOT. This method estimates the viscosity of the bitumen and its temperature dependence from its performance grade, making use of the data that are presented in the A-357 report. It then uses the volumetric composition of the mixture to estimate the stiffness of the mix and its dependence on both loading time and temperature. Given that information, the empirical methods for estimating the A and n are then used. It has been determined from experience with the working programs mentioned above and others that have been developed for commercial use that these fracture property estimates are realistic and give reliable predictions.

If it is desirable to generate the fracture properties from laboratory tests, the overlay tester that was developed at TTI can be used for this purpose. This apparatus was used by Cleveland in his work on TxDOT Project 0-1777 to measure the A and n values directly. The method of using the overlay tester to directly measure the A and n properties and examples of typical data are described in the 2003 TRB paper by Cleveland, et al. (*12*).

Reflective Cracking Propagation Model

The crack propagation calculated from Equation 3 is repeated until the crack either stops growing for bending stress, or reaches the surface of the overlay for thermal tensile stress and/or shear stress. In this way the number of days for a crack to propagate in bending, shear, or thermal mode is calculated separately. Then, the three modes of reflective cracking are combined to predict the actual number of days for a reflective crack to appear at the surface of the overlay. Based on research experience on modeling reflective cracking in the past two decades, TTI has found that the thermal stress is the main contributor to the occurrence of reflective cracking, followed by the shear mode, then by the bending mode. Therefore, TTI used the following combined Equation 4 to predict the reflective cracking propagation.

$$N_f = N_{T1}\left(\alpha_1 - \alpha_2 * \frac{N_{T1}}{N_b} - \alpha_3 * \frac{N_{T1}}{N_{s1}}\right) + N_{T2}\left(\alpha_4 - \alpha_5 * \frac{N_{T2}}{N_{s2}}\right) \quad (4)$$

where:

- N_f = actual number of days for a reflective crack to reach the surface of the overlay.
- N_{T1}, N_{T2} = number of days for thermal reflective cracking to reach the neutral axis (N_{T1}) and the additional number of days for thermal reflective cracking to break through the overlay (N_{T2}).
- N_b = number of days for bending reflective cracking to reach the neutral axis. The "neutral axis" is the point where bending stresses no longer cause crack propagation. Its location depends on the level of load transfer and moduli of pavement layers.
- N_{s1}, N_{s2} = number of days for shearing reflective cracking to reach the neutral axis (N_{s1}) and from there to break through the overlay (N_{s2}).
- $\alpha_1 \ldots \alpha_5$ = calibration factors.

Reflective Cracking Amount and Severity Model

The crack propagation "depth" is related to the total amount of cracking that reaches the overlay surface by way of a crack "depth" distribution function. The idea is that material variability along the length of the pavement section will result in different crack propagation "depth," even for the same exposure conditions. The crack "depth" distribution governs how much cracking is observed in a particular section that has a specific crack "depth" computed on the basis of average material properties. One available reflective cracking amount model was developed by Jayawickrama and Lytton *(7)* and is shown in Equation 5.

$$g = e^{-\left(\frac{\rho}{N}\right)^{\beta}} \quad (5)$$

where:

g = damage rating of the pavement, ranging from 0 to 1
N = number of load repetitions (or days)
ρ, β = calibration coefficients

FRAMEWORK OF REFLECTIVE CRACKING ANALYSIS SYSTEM

The mixed traffic loading, daily (or hourly) temperature variation, other influencing factors (e.g., load transfer), and interlayer materials will be fully taken into account. Also, it is recommended that the same hierarchical input approach as that used in the Mechanistic-Empirical Pavement Design Guide (MEPDG) developed under NCHRP 1-37A be adopted for material properties input and non-destructive testing (NDT) evaluation of existing pavements (see Figure 39).

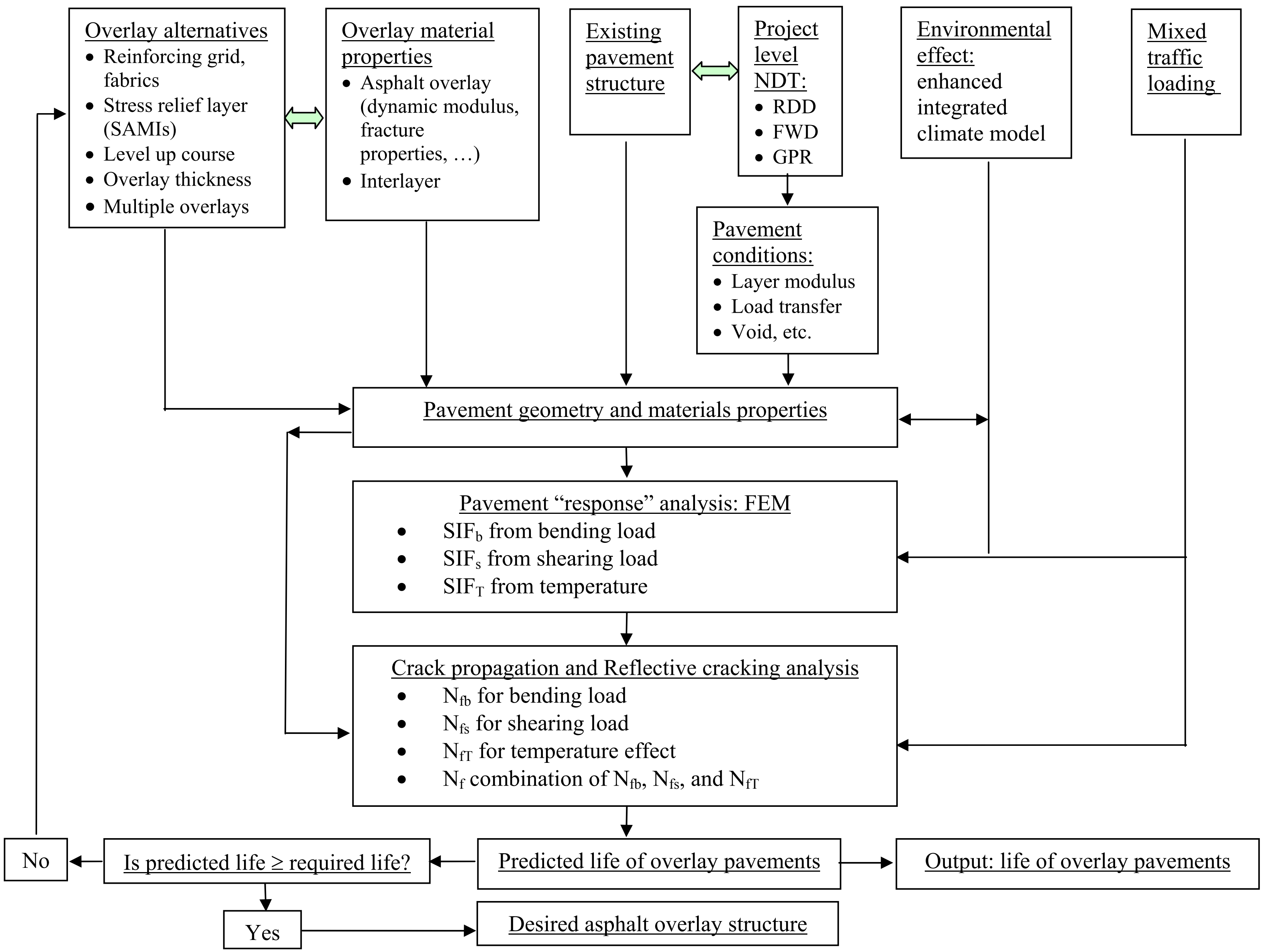


Figure 39. Framework of Reflective Cracking Analysis Systems.

CHAPTER 7

TXDOT'S BRAND NEW OVERLAY TESTER AND USER MANUAL

This chapter consists of two parts: overlay tester specifications for manufacturing the new overlay tester and the overlay tester user manual. They are presented as follows.

OVERLAY TESTER SPECIFICATIONS

The overlay tester is a repeated load tension test on beam samples of hot-mix asphalt to judge their ability to resist reflective cracking. A photograph of TTI's existing system is shown in Figure 40 for reference.

Figure 40. TTI's Existing Overlay Tester.

One base plate is fixed and the other is cycled a small displacement. Both load and displacement as a function of time are recorded. The growth of the crack as observed on the sides or top of the sample is also manually recorded at the end of each load cycle.

With this project, it was proposed to build a new overlay tester system with a self-contained bench top unit. The tester would be a computer controlled and regular electric power driven system, and all data acquisition would be automated as specified below.

Performance Specifications

1. <u>Sample Size and Plate</u>

Beam samples of HMA concrete with the following min/max sizes in inches:

	Length	Width	Height
Small	6	3	1.5
Large	15	3	3

The same plates are to be used for all sample sizes, and six identical sets will be required. Grooves are cut in the size of 1/16 in deep by 1/8 in wide in the plates at each ¼ in interval. Generally, these plates should be made of hardened or plated steel, or anodized high strength aluminum. Softer materials will require more frequent replacement. Materials that have linear elastic modulus properties and hardness properties lower than that of 6061-T6 aluminum shall not be used.

2. Plate Opening

The maximum opening displacement and accuracy requirement are closely related to the selection of Linear Variable Differential Transformers (LVDTs). In order to assist the bidder's selection, the maximum opening at each test temperature must be determined. Based on the research team's experience, the required maximum openings are as follows:

77 °F (25 °C)	Max opening 0.08 in (2.0 mm)
32 °F (0 °C)	Max opening 0.005 in (0.125 mm)

The plate opening displacement for each type of test should be variable, and can be programmed by the user. LVDTs will be mounted on either side to measure the displacement during the test. Amplification and signal conditioning will be used to obtain a resolution down to 0.00005 in or better.

3. Load Cell

An electronic load cell having the capability to test the specified samples will be required. It is anticipated that a 5000 lb (25 kN) cell will be required. A calibration system will be required to demonstrate load cell accuracy of 0.25 percent of full scale.

A calibration sample should be provided with the system. This will be a high strength plastic sample mounted on a loading plate. This sample will be used to periodically calibrate both the load cell and measuring system.

4. Measuring System

The tester will be computer controlled and all data collection will be automated. The manufacturer will supply all hardware and software to run the following test sequences. All tests will be displacement controlled.

a) Simple Relaxation Test

For the relaxation test shown in Figure 41, T_{cl} and T_{cul} represent the load and unload time, respectively, and range from 3 to 60 sec. T_c (time of constant displacement) ranges from 20 to 1000 sec.

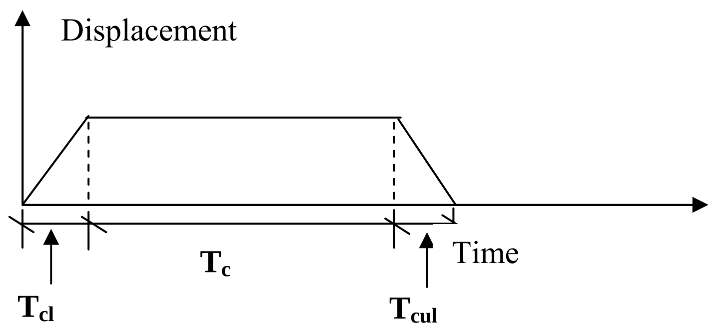


Figure 41. Sketch of Simple Relaxation Test.

b) Simple Repeated Load Test

The load is applied in the form of repeated linear loading and unloading, as sketched in Figure 42.

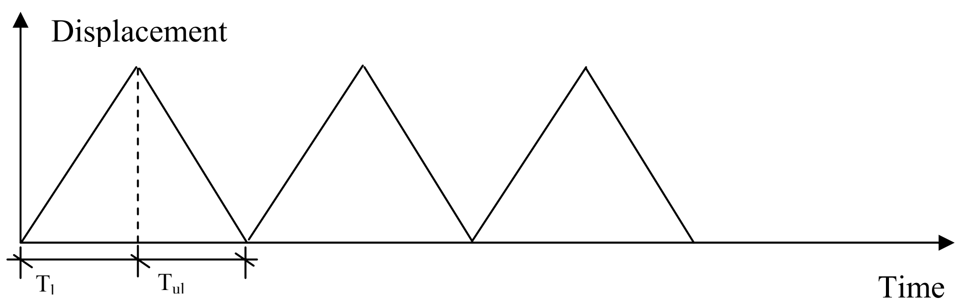


Figure 42. Sketch of Simple Repeated Load Test.

T_l and T_{ul} are the loading and unloading times. These times will always be equal with a range from 3 to 60 (or more) sec.

c) Two Step Test

This test is the same as the simple repeated load test but with a relaxation test performed in the first cycle, as shown in Figure 43.

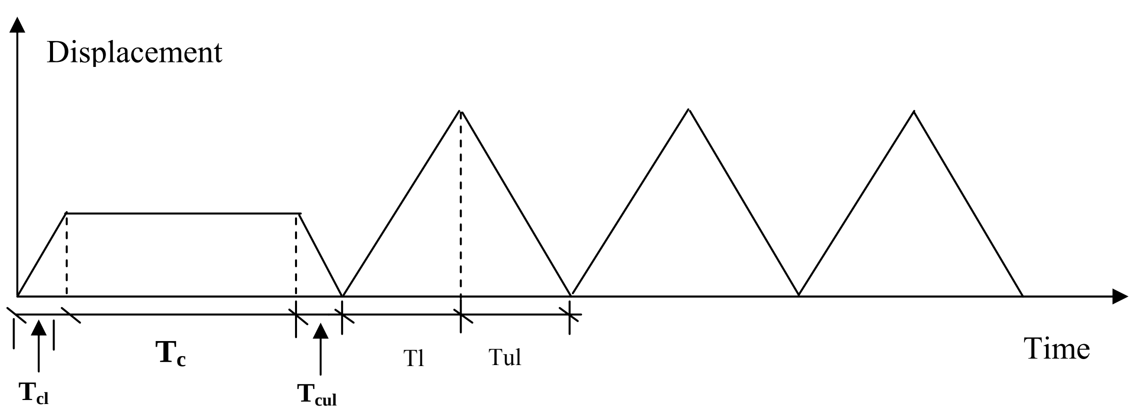


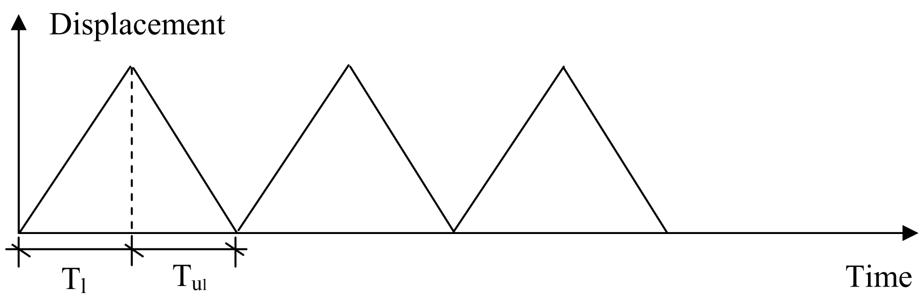
Figure 43. Two Steps Test.

For the stress relax test, T_{cl} and T_{cul} representing the load and unload time, respectively, range from 3 to 60 sec. T_c (time of constant displacement) ranges from 20 to 1000 sec. After the single relax test the repeated load test will be run.

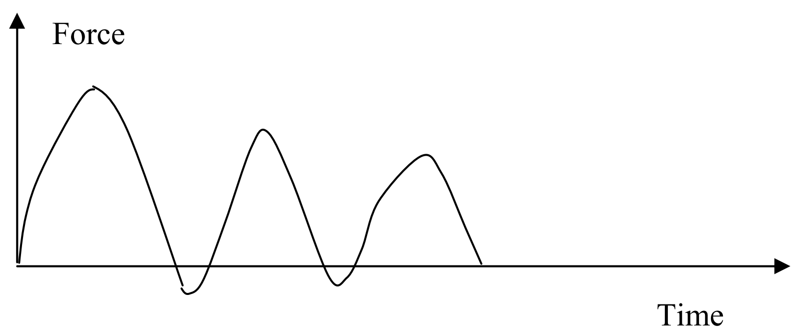
In all tests the maximum number of load/unload cycles, T_{cl}, T_{cul}, T_l, and T_{ul} should be variable, and can be programmed by the user.

5. <u>Data Recording System</u>

a) In the stress relax and repeated load tests the following will be stored in a user defined file:
Time, Cycle Number, Load, Displacement 1, Displacement 2 (if two LVDTs are used). The minimum rate of data collection is at 0.1 sec intervals.
b) Visually display a graph showing load versus time or cycle number. Provide a visual display of the displacement measured on each LVDT as sketched in Figure 44.



Input: Displacement versus Time



Output: Force versus Displacement

Figure 44. Input and Output of Overlay Tester.

c) Two stage test: In the creep part of the test, store a file with the following information: time, load, and displacement. Recording interval every 0.1 sec. Once the stress relax test is complete, the data collection and reporting sequence will be as in 5a) and 5b) above.

6. Linearity of System

All tests will be run in the displacement control mode. To demonstrate the linearity of the loading system the overlay tester will have to pass the following tests:

a) Define the following opening size and loading time on a real sample at 77 °F (25 °C). Opening size of 0.03 inch and T_l of 5 sec. Run the test and record displacements at 0.05 sec intervals (100 in test sequence). This is shown as follows.

Time (sec)	% Time (Ti)	%Displacement (Ci)	Displacement (Mi)
0	0	0	0
0.05	1	C1	M1
0.10	2	C2	M2
.	.	.	.
.	.	.	.
.	.	.	.
5	100	C100	M100

Where Mi is the displacement measured after each time interval, and Ci is Mi/0.03*100%. The unit should pass the following requirement.

C100 should be between 98 and 102.
Absolute value of $|Ti - Ci|$ should be less than 2 for any data set.

b) Repeat the test at a temperature of 50 °F (10 °C) and a specified opening of 0.015 in. Requirements on C100 and Ti – Ci are identical to the above (herein Ci is defined as Mi/0.015*100%).

7. Repeatability of Opening Displacement

To demonstrate the repeatability of displacement, the overlay tester is required to pass the following tests:

a) Define the following opening displacement, loading and unloading time, and load cycles on a real sample at 77 °F (25 °C).
Opening Displacement: 0.04 in
Loading and unloading time of each cycle: 5 sec
Loading cycles: 100
Run the test and record the displacement at 5 sec intervals (200 in test sequence).
Make the following table.

Time (sec)	Displacement (in)	Time (sec)	Displacement (in)
5	D_{max1}	10	D_{min1}
15	D_{max2}	20	D_{min2}
25	D_{max3}	30	D_{min3}
.	.	.	.
.	.	.	.
.	.	.	.
995	D_{max100}	1000	D_{min100}

This is further illustrated in Figure 45.

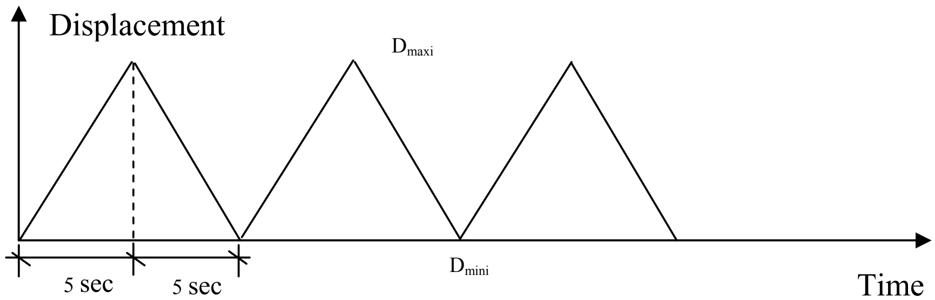


Figure 45. Overlay Tester Input: Displacement vs. Time.

Where D_{maxi} is the maximum displacement measured in each cycle, and D_{mini} is the minimum displacement at the end of each cycle. The overlay tester should pass the following requirement.

$$0.98 \le (D_{maxi}/0.04) < 1.02$$
$$D_{mini} < 0.0002$$

b) Repeat the test at a temperature of 50 °F (10 °C) and a specified opening of 0.02 in. Requirements on D_{maxi} and D_{mini} are as follows:

$$0.98 \le (D_{maxi}/0.02) < 1.02$$
$$D_{mini} < 0.0001$$

8. <u>Smoothness of Track</u>

It should be demonstrated that the primary displacements are in the horizontal direction so that the sample is in tension. The maximum movement of the sample in the vertical direction will be less than 3 percent of the crack opening. A flat target on the sample is required.

The brand new overlay tester, manufactured based on the above specification, is shown in Figure 46.

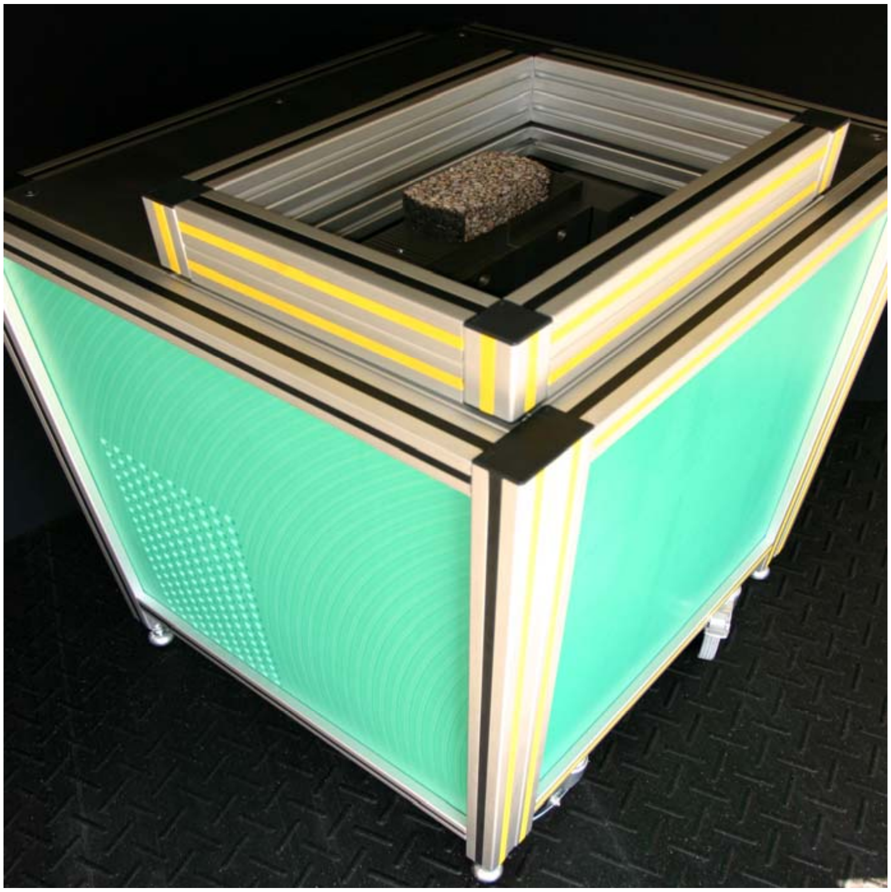


Figure 46. TxDOT's Brand New Overlay Tester.

USER MANUAL FOR NEW OVERLAY TESTER

Operation of the machine is straightforward. In normal operations, it is only necessary to use the positioning switches and a single software interface screen since all operations during a test are automatic. Clean the machine at least daily during use. The test is normally performed in displacement control.

Specimen Preparation and Installation

Generally, a specimen is fabricated from a field core or a lab compacted specimen. If a round core is used, it is usually cut from a 6 in (150 mm) core to be 1.5 in (38 mm) high by 3 in (75 mm) wide by 6 in (150 mm) long. Other beam lengths and configurations may be used, depending on the mounting plates used. The plates are mounted on a specimen mounting jig (Figure 47) and the specimen is then glued to the plates (Figure 48). Epoxy is usually used as an adhesive. Beams should be preconditioned to the temperature at which they will be tested.

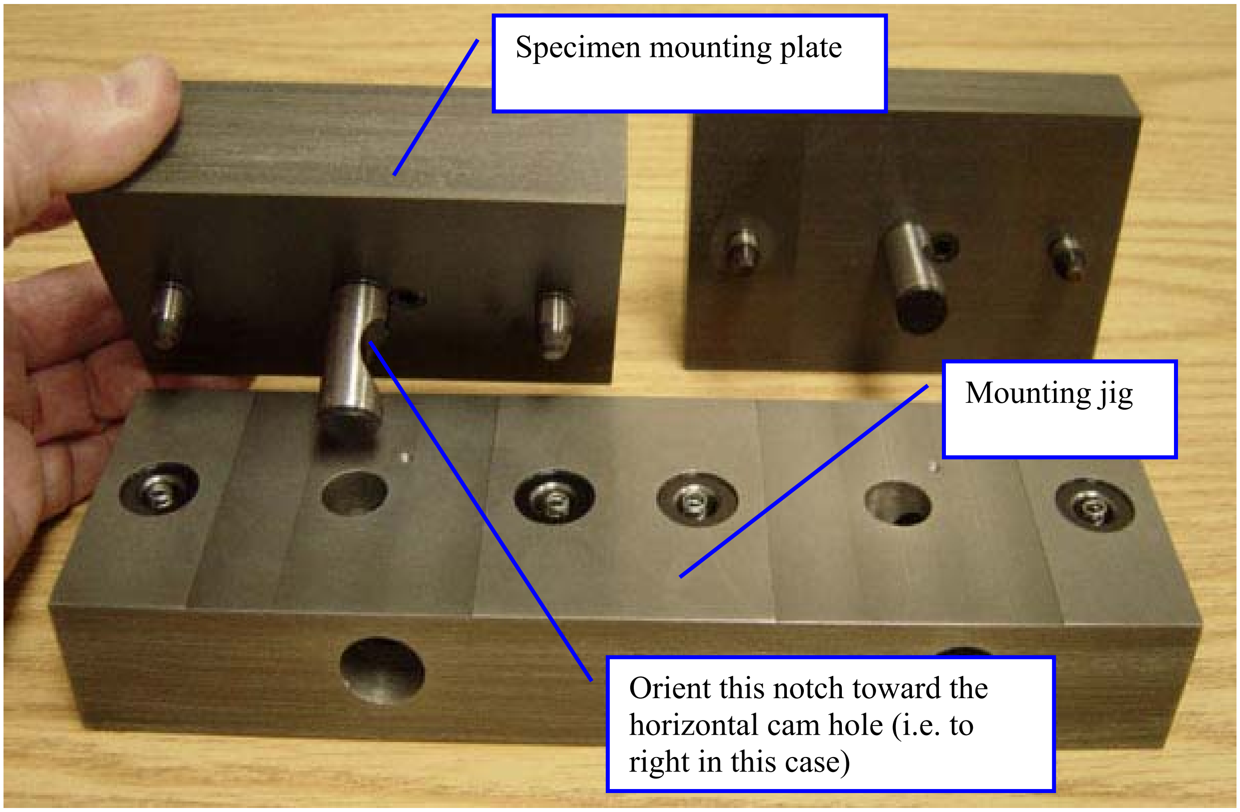


Figure 47. Mounting Jig.

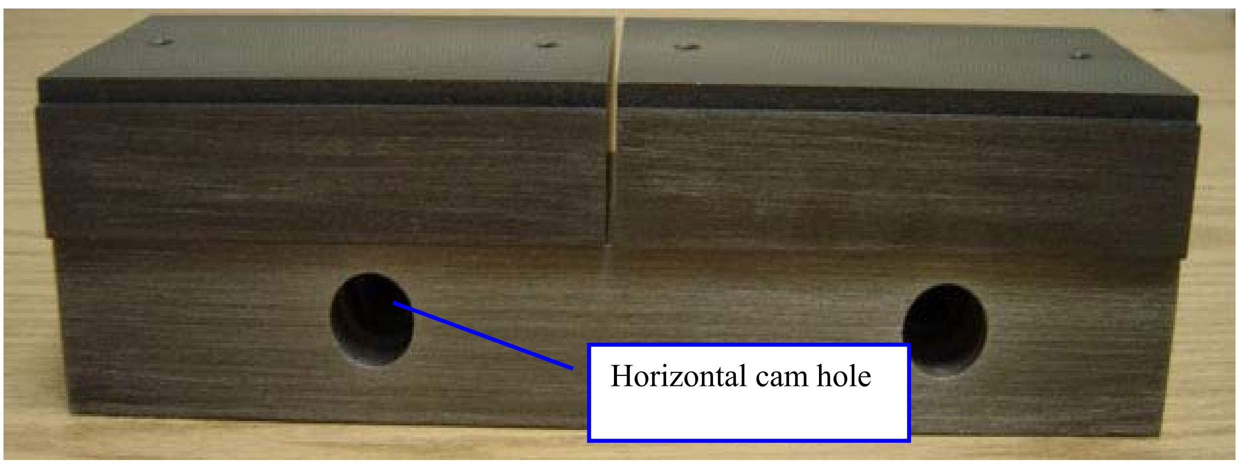


Figure 48. Specimen Plates Mounted on Jig.

Startup and Test Specimen Assembly Installation

1. The Emergency Stop switch must be in the released position (partially rotating the switch allows it to pop out to the released position if it has been previously pushed in). Turn the Master Switch on (Figure 49). The refrigeration system will start when this switch is turned on. Use the arrow keys below to LED screen to set the temperature controller to the desired temperature and wait until it stabilizes.

Figure 49. Main Control Panel.

2. After the main switch has been turned on, turn on the computer and after a period of at least one minute, start the overlay test software. Once the software is loaded, turn on the hydraulic pump through the software (Figure 50). In order to mount the specimen assembly onto the machine, it may be necessary to adjust the position of the testing machine blocks. This can be done with the Load/Stroke and Left/Right switches (Figure 51). Although the Stroke mode can be used for this purpose, it is recommended that the Load mode be used because inadvertent loads applied during mounting of the specimen will be automatically minimized by the control system if it is in load control. Use the Left/Right switch to move the right hand testing block on the machine in the desired direction to line up the pins on the specimen mounting plates. Although the software automatically switches the system to displacement control for the test, it is recommended that operators get in the habit of repositioning the switch back to displacement control before closing the lid of the machine.

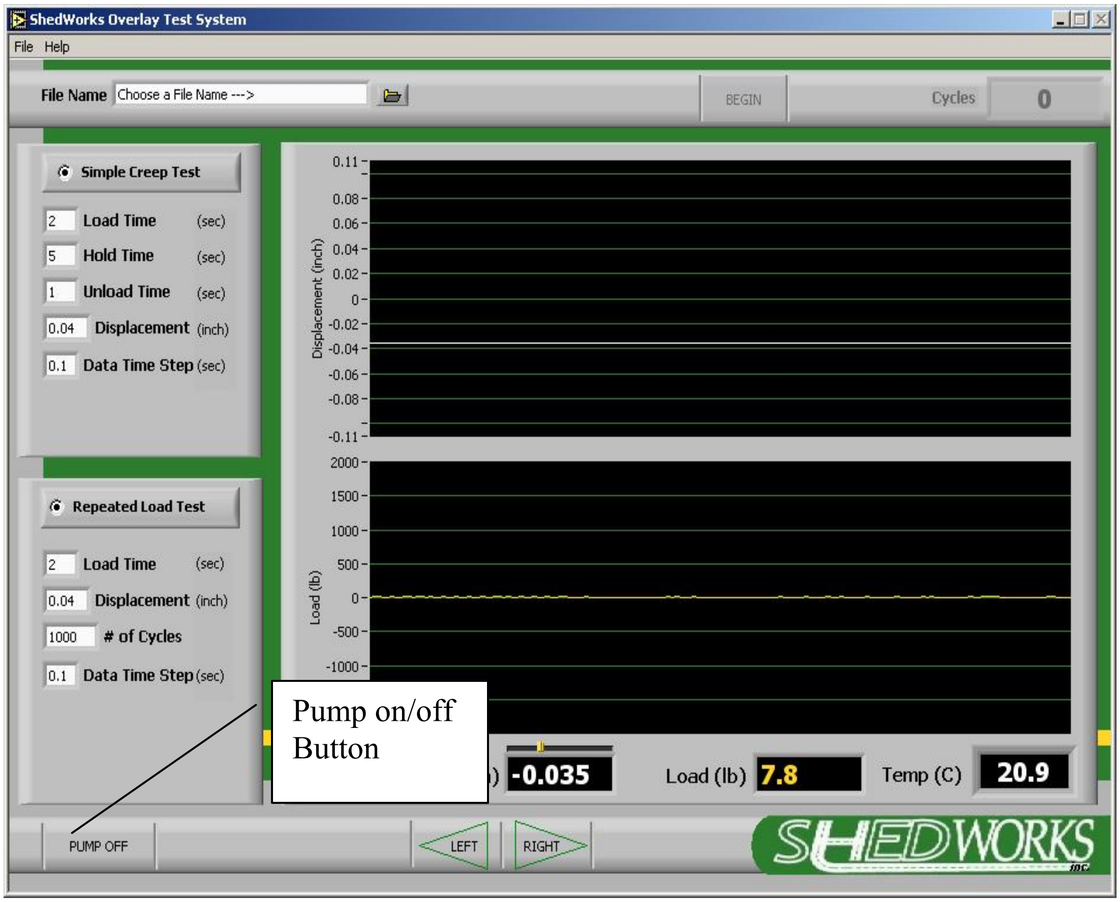


Figure 50. Hydraulic Pump On/Off.

Figure 51. Mode Control Switches.

3. As shown in Figures 52 to 54, once the pins are aligned, place the test specimen assembly in the machine and tighten the locking cams. The cams will tighten after approximately ¼ to ½ turn. There is one cam on the fixed part of the testing machine and one on the moving part. A 3/8 in socket drive handle with a 3 in extension is provided to lock and unlock the specimen plates.

> NOTE: Make sure that both the bottom of the specimen plates and the top of the testing machine are clean before you place the test specimen assembly into the testing device. If all four surfaces are not clean, damage may occur to the machine or the plates when the plates are tightened with the cams. These four surfaces are hard anodized aluminum that protects against corrosion and minor abrasion, but it will not protect against impact and gouging type damage. Do not use extreme force to push the test specimen assembly down onto the machine (e.g., never use a hammer to force the pins into the holes on the blocks). The assembly should slide into place with minimal force if it is properly aligned.

Figure 52. Position Right Hand Block with Left/Right Switch to Line Up Pins on Test Specimen Assembly.

Figure 53. Insert Pins into Machine Making Sure Cutout on Center Pin is on the Side Facing the Cams (Cutout Facing to Right).

Figure 54. Tighten Cam until it Locks in Place.

Basic Software Operation

4. Select the desired test(s), enter the desired control parameters, specify a file name, and begin the test. Active buttons have dark lettering. The Begin button is not active until a file name is specified. The Pump button toggles the hydraulic pump on and off. The radio buttons on the Simple Relaxation test and Repeated Load (displacement) test (Figure 55) are independent so that either one or both of these tests can be specified. When the Begin button is pushed, the selected test or tests will automatically be performed in sequence.

> NOTE: It is not necessary to manually position the actuator so that the displacement reading is zero before the test. The software automatically corrects for an initial displacement reading that is not zero.

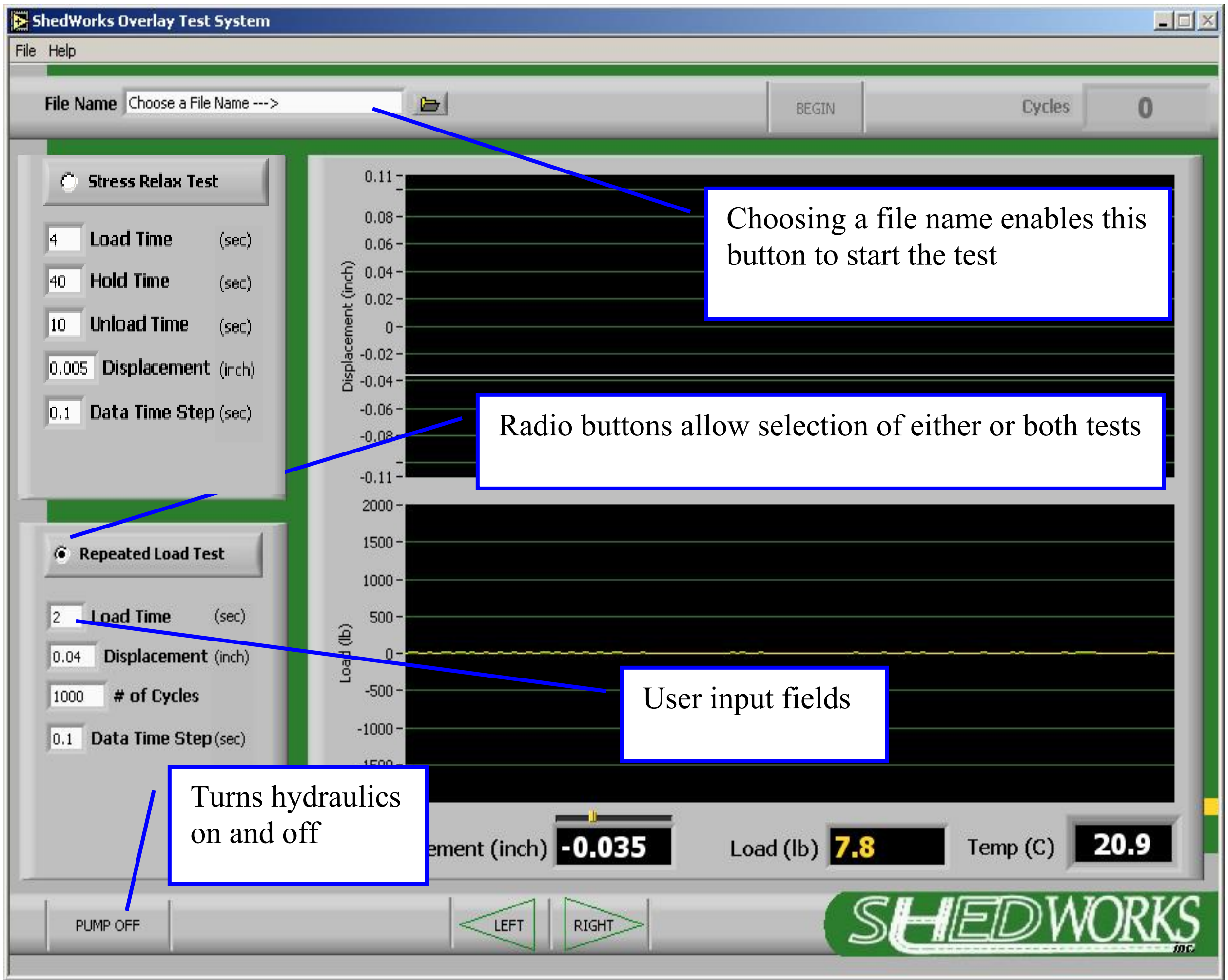


Figure 55. Main Software Screen.

5. During the test, time history plots of displacement and load are presented. In addition, digital indicators are shown and completed number of cycles is presented for the repeated load portion of the test. This is a displacement (i.e., stroke) controlled test. Therefore, the feedback control should show the desired waveform on the displacement plot. The load is a response signal in this case and is merely recording what is happening to the load during the process of applying the displacement. In this example (Figure 56), the specimen is very weak because it has already been partially failed in previous tests. Although the displacement is being moved only in the tension direction relative to the initial position, the load shows both compression and tension readings. Generally, the compressive load readings are indicators of time dependence and/or damage to the specimen because the position (not the load) is being forced back to zero during each cycle.

Figure 56. Typical Display during Testing.

6. After the file is saved and closed at the end of the test, open the lid, switch to Load mode and reposition with the Left/Right switch if necessary to remove the specimen assembly and insert a new one. If the specimen broke during the test, it will not be necessary to adjust the position of the block with the Left/Right switch since each half of the assembly can be removed independently. However, it will likely be necessary to reposition the block to insert a new specimen assembly.

Software Details

The software is very simple to operate. However, there are features available that require some expertise to correctly utilize, and there are some features that are not often used in the normal course of testing.

There are two forms of help files available in the software: a context sensitive button help (Figure 57) and a general help file (Figure 58). When in the button help mode, passing the cursor over a particular area of the screen will pop up a short help window discussion of the item. The general help file contains basic information about the test and machine operation.

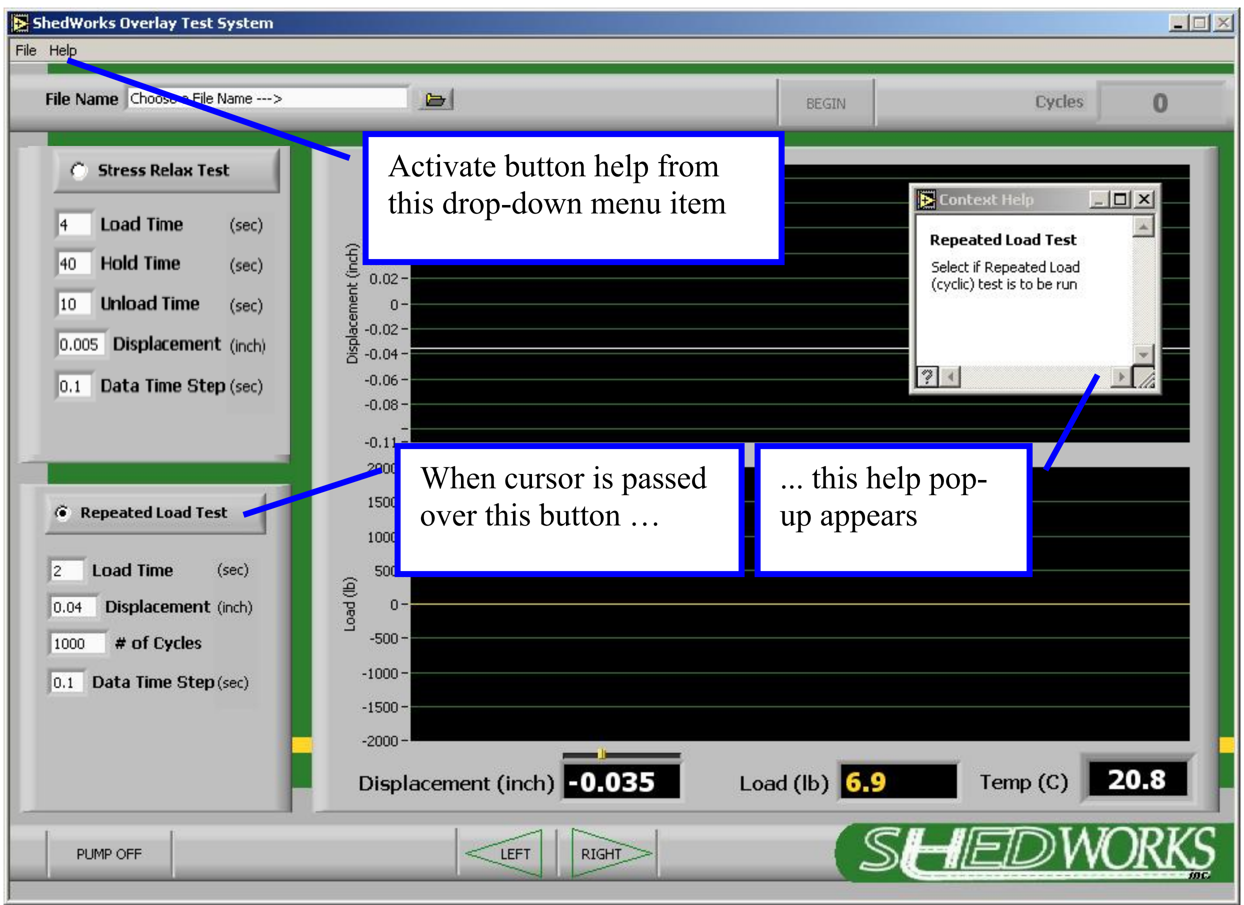


Figure 57. Button Help Pop-up Window.

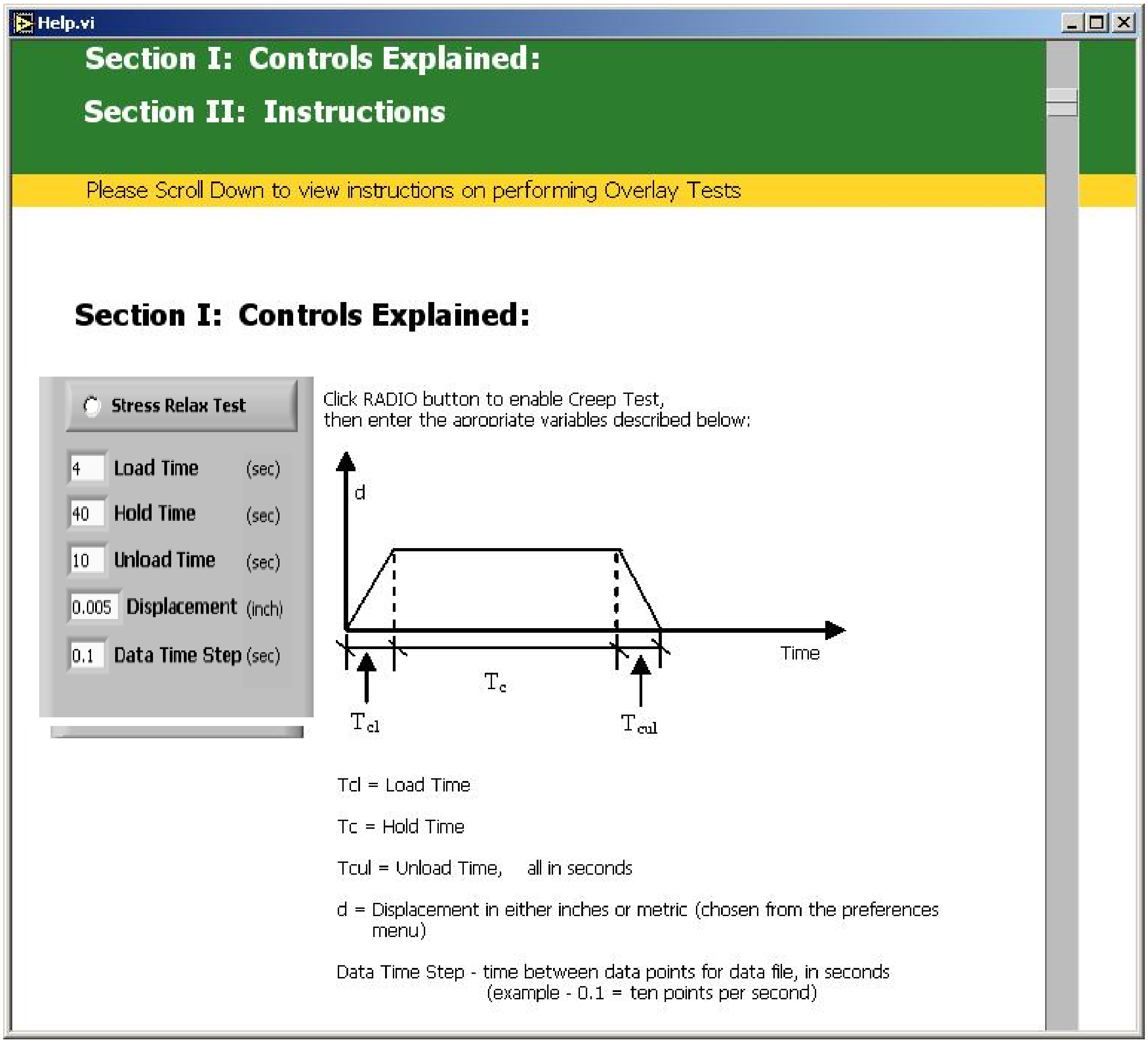


Figure 58. General Help File.

This testing machine is a feedback controlled testing machine. This means that the machine continually looks at the difference between what the operator has told it to do and what it is actually doing, and immediately tries to correct any difference to reduce it to zero. It does this by looking at the transducer used for controlling the machine at a high sampling rate that is hardware-dependent (i.e., in the kHz range – note: this feedback loop closure rate is not controllable by the user, only the data acquisition rate for data collection and storage can be changed by the user in the data time step field on the software test screen). The standard test here is displacement controlled, so it is looking at an LVDT mounted to the back of the two main machine blocks.

What happens when a difference between command and actual is detected is controlled by adjustable parameters in the software called PID settings (Figure 59). PID (proportional, integral, and derivative) setting determination is often more of an art than a science. Typically, the basic settings are found by trial and error, but there are systems that automatically adjust these values during testing. The PID settings affect how the machine responds and, therefore, are dependent on the material properties of the specimen being tested. Fortunately, there are two things that make PID setting a manageable task. The first is that the values do not need to be perfect to achieve acceptable machine control performance, and the second is that most of the effect on control comes from only one of the numbers, P. In this system, with no specimen in the machine, usually P=20 is a reasonable value. However, when running a good asphalt mix in the machine, P=80 seems to give good performance.

The PID settings for the LVDT and the Load Cell are located in the Test Preferences screen that can be found in the drop-down menu. U.S. or metric units can also be selected in this screen. If column headings are not desired in the output data file, they may be deleted here. A criterion for automatically stopping the test can be specified in terms of load drop. As the material is damaged in displacement control, the load will drop. The magnitude of the drop can be used to automatically stop the test before complete failure by checking the radio button and entering a value in percent.

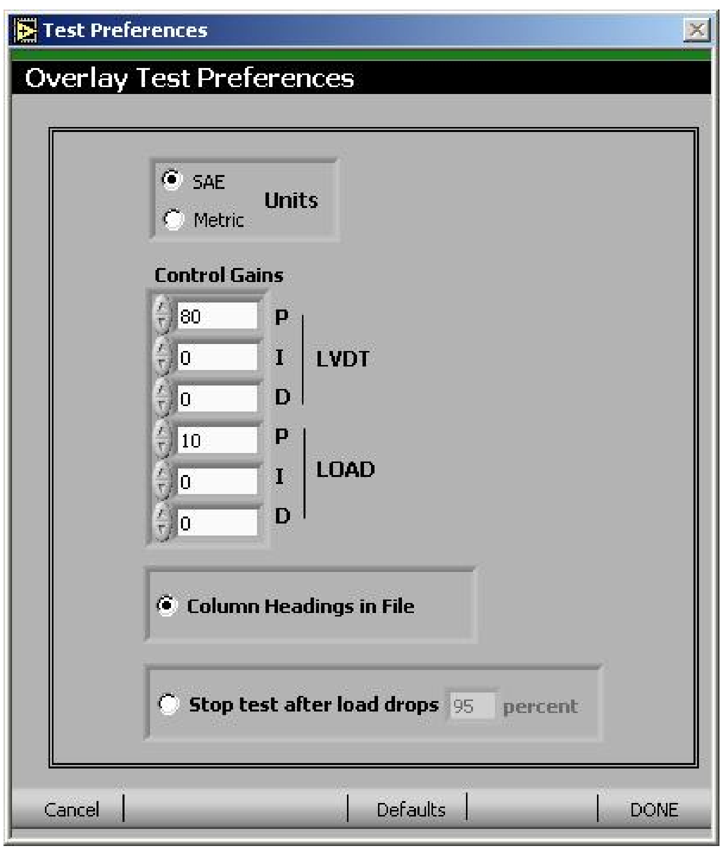


Figure 59. Test Preferences Screen.

Emergency Operations

In the event of an emergency, the primary method of terminating machine operation is by pressing the red Emergency Stop mushroom button located on the control panel. Pushing the switch disconnects power to the machine from the supply line (however, power is still present inside the machine).

If the power upstream of the entry box needs to be disconnected, unplug the machine or disconnect the circuit at the building's service panel (e.g., building's circuit breaker or fuse panel).

Maintenance and Adjustments

Most of the machine is low maintenance. Some components are not corrosion proof, and running at cold temperature in high humidity areas often creates condensation on the parts. Of particular interest are the linear bearings and shafts. Inspect these items frequently.

Maintenance

- Check the grease on the main bearings and shafts daily. Apply new grease if necessary.
- Check hydraulic oil level at least every 6 months. Refill with hydraulic oil as needed (ISO 46 or other readily available hydraulic oil).
- Replace the hydraulic oil filter at least once every 3 years in normal lab operations. In dirty environments or very high production labs, inspect and change the filter more often as warranted.

Recommended lubrication products are available from the manufacturer, or locally through auto parts stores, retail stores, and industrial supply houses.

- For general oiling, use LPS-2.
- For cleaning metal parts, use WD-40 if long term lubrication is not necessary. However, if you use WD-40 to clean the linear shafts, make sure you then clean the WD-40 off the shafts before applying grease.
- To clean parts that need to be clean but not oily, use something like rubbing alcohol.
- For greasing of the main bearings and shafts, use Slick One Grease.
- For cleaning the clear polycarbonate window, use Meguiar's Mirror Glaze plastic cleaner and plastic polish. Do not use any other cleaning products on the polycarbonate.
- For general cleaning of the aluminum and opaque plastic paneling, you can use a number of cleaning products such as Windex. The green panels are Ultra-High Molecular Weight (UHMW) and are very durable and impact resistant. This is the same material often used to line truck beds for hauling rock. Some dents and scratches in the UHMW will inevitably occur, but the material should take punishment better than many other materials. Virtually nothing will stick very well to it.

Adjustments

NOTE: All fasteners on the machine, with the exception of some of the frame mounting screws (flanged nuts, frame screws, wheels, and leveling feet), are U.S. customary hardware.

The leveling feet can be used to level and stabilize the machine after it is moved into place in the laboratory.

Hydraulic pressure may be adjusted at the valve inside the lower part of the machine. Contact the manufacturer if adjustment is desired. PID adjustments to alter machine performance may be accomplished through the software as previously discussed.

The LVDT on the rear of the machine may be adjusted to alter the reading at rest. This should not be necessary, but is possible by loosening the small (1-72) lock nut and turning the small all thread in the desired direction while watching the digital display on the software. Calibration and zero offset requires access to the signal conditioners inside the lower portion of the machine. Contact the manufacturer for assistance.

Temperature set point adjustment is performed by simply pressing the up or down arrow on the temperature controller until the desired set point is reached. Although the controller is also a PID control system, it should not be necessary to access the programming features of the controller under normal operations. The feedback to the controller is a small Resistance Temperature Device (RTD) element located in the right hand portion of the environmental chamber in the return air flow.

Trouble-Shooting

- System grinds/chatters:
  Change PID settings; usually decreasing P will stop valve noise and rough shaped waveforms.
- Rounded waveform not reaching requested peaks:
  If the requested waveform is not supposed to be rounded, but is actually coming out that way, it will often be the case that it is not reaching the requested peak value either. Increasing P will usually solve this problem.

Specifications

Approximate dimensions: 33 in W x 30 in D x 44 in H
Electrical power required: 110VAC, single phase

Warranty

Warranty: Except for expendable components such as oil filters, and except for corrosion, normal wear and tear, and unauthorized Purchaser modification, all parts and labor are warranted to be free from defects for a period of 12 months from date of sale. Liability is limited to refund, repair, or replacement at the Manufacturer’s option.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The focus of many asphalt mixture design procedures over the past 10 years has been to primarily address rutting concerns. This focus has led to the development of stiffer, drier mixtures. However, these mixes are more difficult to construct and are potentially more prone to reflective cracking. In this research the upgraded overlay tester is introduced and proposed as a simple performance test for reflective cracking. A procedure is proposed to use both rutting and cracking criteria when designing overlays for cracked pavements. In addition, as one of the products of this project, a brand new overlay tester has been manufactured for TxDOT. Based on the results presented, the following conclusions are offered:

- The overlay tester can be run on standard size samples, typically 6 in (150 mm) long by 3 in (75 mm) wide by 1.5 in (38 mm) high. These specimens can be prepared from either field cores or from SGC molded specimens.
- The test is rapid, and poor samples fail in minutes. It characterizes both crack initiation and crack propagation properties of asphalt mixtures.
- The overlay tester is repeatable. Based on repeatability study results, three replicates are recommended for the overlay tester.
- Sensitivity studies indicate that the overlay tester provides reasonable test results. Raising the asphalt performance grade, increasing the opening displacement, and decreasing the testing temperature will lead to shortened reflective cracking life. However, increasing asphalt content will significantly improve the reflective cracking resistance of asphalt mixtures.
- In a series of tests on Texas mixtures it was determined that aggregate absorption has a major impact on the performance of specimens in the overlay tester. This topic has not received much attention recently but it obviously needs to be investigated. In the lab these highly absorptive aggregates did not severely impact the rutting performance, but they had a major impact on cracking life.
- The effectiveness of the overlay tester was validated by five case studies in Texas. The overlay tester results all correlated well with the field performance. Furthermore, the overlay tester results have good correlations with beam fatigue test results and low temperature performance of asphalt mixture in the field.
- A preliminary framework of asphalt overlay mixtures design and associated criteria have been proposed. The overlay tester is recommended to characterize the potential reflective cracking, and the HWTT and the APA are recommended to control the rutting problems of the top layer mixture and bottom layer mixture, respectively. Based on the framework, two examples of asphalt overlay mixtures design are presented in this report. This framework and the associated criteria are preliminary and they will need further refinement.
- A brand new overlay tester has been manufactured and delivered to TxDOT's central lab at the Cedar Park, Texas, office.
- User training for the overlay tester operation and corresponding data analysis has been provided.

RECOMMENDATIONS

- The upgraded overlay tester is a practical device that can be incorporated into mixture design systems to complement the current systems, which often focus on minimizing rutting potential. In many instances it is necessary to optimize both cracking resistance and rutting potential to obtain adequate long-term pavement performance.
- The influence of aggregate properties, such as asphalt absorption by aggregate, aggregate texture and angularity, on the asphalt overlay performance, especially the reflective cracking, should be further investigated.
- Future research studies should be directed at optimizing both rutting and cracking potential of asphalt layers. The criteria for each will vary based on the existing structure, traffic level, and performance requirements.

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