Title
Reflective Cracking Study: First-level Report on HVS Testing on Section 587RF - 45 mm RAC-G Overlay

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Reflective Cracking Study: First-level Report on HVS Testing on Section 587RF — 45 mm RAC-G Overlay

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Partnered Pavement Research Program (PPRC) Contract Strategic Plan Element 4.10:
Development of Improved Rehabilitation Designs for Reflective Cracking

PREPARED FOR:

California Department of Transportation
Division of Research and Innovation
Office of Roadway Research

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Abstract:

This report is the third in a series of first-level analysis reports that describe the results of HVS testing on a full-scale experiment being performed at the Richmond Field Station (RFS) to validate Caltrans overlay strategies for the rehabilitation of cracked asphalt concrete. It describes the results of the third HVS reflective cracking testing section, designated 587RF, carried out on a 45 mm half-thickness RAC-G overlay, which was included as a control for performance comparison purposes. The test forms part of Partnered Pavement Research Center Strategic Plan Item 4.10: "Development of Improved Rehabilitation Designs for Reflective Cracking".

HVS trafficking on the section commenced on March 15, 2005 and was completed on October 10, 2005. A total of 2,024,793 load repetitions, equating to 66 million ESALs and a Traffic Index of 15, was applied during this period. A temperature chamber was used to maintain the pavement temperature at 20°C±4°C for the first one million repetitions, then at 15°C±4°C for the remainder of the test. A dual tire (720 kPa pressure) and bidirectional loading with lateral wander configuration was used. Findings and observations based on the data collected during this HVS study include:

- On completion of testing, the surface crack density was 3.6 m/m^2. Cracking on the overlay was predominantly transverse, as was that on the underlying layer. The crack patterns of the two layers did not match exactly; however, the areas of most severe cracking corresponded.
- The average maximum rut depth across the entire test section at the end of the test was 18.2 mm. The rate of rutting was relatively slow during the early part of the experiment, but increased significantly after the 100 kN load change, despite reducing the pavement temperature to 15°C±4°C.
- Both of the failure criterion set for the experiment were reached within 100,000 load repetitions of each other.
- Ratios of final-to-initial elastic deflections show that damage had increased significantly at all depths in the pavement structure by the end of trafficking, with loss of stiffness highest in the area of most severe cracking in the underlying layer.
- Analysis of surface profile and in-depth permanent deformation measurements indicate that most of the permanent deformation occurred in the asphalt-bound surfacing layers (overlay and cracked DGAC) with approximately twice as much damage occurring in the area of most severe cracking in the underlying DGAC layer. Permanent deformation was also recorded in the upper part of the aggregate base in this area. Negligible deformation was recorded in the subgrade.

No recommendations as to the use of the modified binders in overlay mixes are made at this time. These recommendations will be included in the second-level analysis report, which will be prepared and submitted on completion of all HVS and laboratory testing.

Keywords:

Reflective cracking, overlay, modified binder, HVS test, MB Road

Related documents:

UCPRC-RR-2005-03, UCPRC-RR-2006-04, UCPRC-RR-2006-05

Signatures:

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PROJECT OBJECTIVES

The objective of this project is to develop improved rehabilitation designs for reflective cracking for California.

This objective will be met after completion of four tasks identified by the Caltrans/Industry Rubber Asphalt Concrete Task Group (RACTG):

1. Develop improved mechanistic models of reflective cracking in California
2. Calibrate and verify these models using laboratory and HVS testing
3. Evaluate the most effective strategies for reflective cracking
4. Provide recommendations for reflective cracking strategies

This document is one of a series addressing Tasks 2 and 3.

ACKNOWLEDGEMENTS

The University of California Pavement Research Center acknowledges the assistance of the Rubber Pavements Association, Valero Energy Corporation, and Paramount Petroleum which contributed funds and asphalt binders for the construction of the Heavy Vehicle Simulator test track discussed in this study.

REFLECTIVE CRACKING STUDY REPORTS

The reports prepared during the reflective cracking study document data from construction, Heavy Vehicle Simulator (HVS) tests, laboratory tests, and subsequent analyses. These include a series of first- and second-level analysis reports and two summary reports. On completion of the study this suite of documents will include:

1. Reflective Cracking Study: Summary of Construction Activities, Phase 1 HVS testing and Overlay Construction (UCPRC-RR-2005-03).
2. Reflective Cracking Study: First-level Report on the HVS Rutting Experiment (UCPRC-RR-2007-06).
3. Reflective Cracking Study: First-level Report on HVS Testing on Section 590RF — 90 mm MB4-G Overlay (UCPRC-RR-2006-04).
4. Reflective Cracking Study: First-level Report on HVS Testing on Section 589RF — 45 mm MB4-G Overlay (UCPRC-RR-2006-05).
5. Reflective Cracking Study: First-level Report on HVS Testing on Section 587RF — 45 mm RAC-G Overlay (UCPRC-RR-2006-06).
6. Reflective Cracking Study: First-level Report on HVS Testing on Section 588RF — 90 mm AR4000-D Overlay (UCPRC-RR-2006-07).
7. Reflective Cracking Study: First-level Report on HVS Testing on Section 586RF — 45 mm MB15-G Overlay (UCPRC-RR-2006-12).
8. Reflective Cracking Study: First-level Report on HVS Testing on Section 591RF — 45 mm MAC15-G Overlay (UCPRC-RR-2007-04).
9. Reflective Cracking Study: HVS Test Section Forensic Report (UCPRC-RR-2007-05).
10. Reflective Cracking Study: First-level Report on Laboratory Fatigue Testing (UCPRC-RR-2006-08).
11. Reflective Cracking Study: First-level Report on Laboratory Shear Testing (UCPRC-RR-2006-11).
12. Reflective Cracking Study: Back Calculation of FWD Data from HVS Test Sections (UCPRC-RR-2007-08).
13. Reflective Cracking Study: Second-level Analysis Report (UCPRC-RR-2007-09).
14. Reflective Cracking Study: Summary Report (UCPRC-SR-2007-01). Detailed summary report.
15. Reflective Cracking Study: Summary Report (UCPRC-SR-2007-03). Four page summary report.

CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m2
VOLUME				
ft^3	cubic feet	0.028	cubic meters	m^3
MASS				
lb	pounds	0.454	kilograms	kg
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	C
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce/square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**Convert From**	**Multiply By**	**Convert To**	**Symbol**
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
VOLUME				
m^3	cubic meters	35.314	cubic feet	ft^3
MASS				
kg	kilograms	2.202	pounds	lb
TEMPERATURE (exact degrees)				
C	Celsius	1.8C+32	Fahrenheit	F
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce/square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

EXECUTIVE SUMMARY

This report is the third in a series of first-level analysis reports that describe the results of HVS testing on a full-scale experiment being performed at the Richmond Field Station (RFS) to validate Caltrans overlay strategies for the rehabilitation of cracked asphalt concrete. It describes the results of the third HVS reflective cracking testing section, designated 587RF, carried out on a 45-mm half-thickness rubberized asphalt concrete gap-graded (RAC-G) overlay, which was included as one of the controls for performance comparison. The testing forms part of Partnered Pavement Research Center Strategic Plan Item 4.10: "Development of Improved Rehabilitation Designs for Reflective Cracking."

The objective of this project is to develop improved rehabilitation designs for reflective cracking for California. This objective will be met after completion of the following four tasks:

1. Develop improved mechanistic models of reflective cracking in California
2. Calibrate and verify these models using laboratory and HVS testing
3. Evaluate the most effective strategies for reflective cracking
4. Provide recommendations for reflective cracking strategies

This report is one of a series addressing Tasks 2 and 3. It consists of three main chapters. Chapter 2 provides information on the experiment layout, pavement design, HVS trafficking of the underlying layer, and the test details, including test duration, pavement instrumentation and monitoring methods, loading program, test section failure criteria, and the environmental conditions recorded over the duration of the test. Chapter 3 summarizes the data collected and includes discussion of air and pavement temperatures during testing (measured with thermocouples), elastic deflection (measured on the surface with the Road Surface Deflectometer and at depth with Multi-depth Deflectometers), permanent deformation (measured on the surface with the Laser Profilometer and at depth with Multi-depth Deflectometers), and visual inspections. Chapter 4 provides a summary and lists key findings.

The underlying pavement was designed following standard Caltrans procedures and it incorporates a 410-mm (16.1 in) Class 2 aggregate base on subgrade with a 90-mm (3.5 in) dense-graded asphalt concrete (DGAC) surface. Design thickness was based on a subgrade R-value of 5 and a Traffic Index of 7 (~121,000 equivalent standard axles, or ESALs). This structure was trafficked with the HVS in 2003 to induce fatigue cracking then overlaid with six different treatments to assess their ability to limit reflective cracking. The treatments included:

- Half-thickness (45 mm) MB4 gap-graded overlay (referred to as "45 mm MB4-G" in this report)
- Full-thickness (90 mm) MB4 gap-graded overlay (referred to as "90 mm MB4-G" in this report)

- Half-thickness MB4 gap-graded overlay with minimum 15 percent recycled tire rubber (referred to as "MB15-G" in this report)
- Half-thickness MAC15TR gap-graded overlay with minimum 15 percent recycled tire rubber (referred to as "MAC15-G" in this report)
- Half-thickness rubberized asphalt concrete gap-graded overlay (RAC-G), included as a control for performance comparison purposes (the section discussed in this report)
- Full-thickness (90 mm) AR4000 dense-graded overlay (AR4000-D), included as a control for performance comparison purposes

The thickness for the AR4000-D overlay was determined according to Caltrans Test Method 356. The other overlay thicknesses were either the same or half of the AR4000-D overlay thickness. Details on construction and the first phase of trafficking are provided in an earlier report.

A laboratory fatigue and shear study is being conducted in parallel with HVS testing. Results of these studies will be detailed in separate reports. Comparison of the laboratory and test section performance, including the results of a forensic investigation to be conducted when all testing is complete, will be discussed in a second-level report once all the data from all of the studies has been collected and analyzed.

HVS trafficking on the section commenced on March 15, 2005, and was completed on October 10, 2005. During this period a total of 2,024,793 load repetitions at loads varying between 60 kN (13,500 lb) and 100 kN (22,500 lb) were applied, which equates to approximately 66 million ESALs, using the Caltrans conversion of $(\text{axle load}/18{,}000)^{4.2}$, and to a Traffic Index of 15. A temperature chamber was used to maintain the pavement temperature at 20°C±4°C (68°F±7°F) for the first one million repetitions, then at 15°C±4°C (59°F±7°F) for the remainder of the test. A dual tire (720 kPa [104 psi] pressure) and bidirectional loading with lateral wander was used.

Findings and observations based on the data collected during this HVS study include:

- Cracking was first observed after approximately 1.5 million repetitions. On completion of testing, the surface crack density was 3.6 m/m^2 (1.10 ft/ft^2), considerably lower than the 5.4 m/m^2 (1.65 ft/ft^2) recorded after 377,556 repetitions on the underlying layer during Phase 1 trafficking. The surface crack density reached 2.5 m/m^2 (0.76 ft/ft^2), the failure criterion set for the experiment, after about 1.9 million load repetitions. Cracking on the overlay was predominantly transverse, as was that on the underlying layer. The crack patterns of the two layers did not match exactly; however, the areas of most severe cracking corresponded.

- The average maximum rut depth across the entire test section at the end of the test was 18.2 mm (0.7 in), which was higher than the failure criterion of 12.5 mm (0.5 in) set for the experiment, reached after approximately 1.8 million repetitions. The maximum rut depth measured on the section was 26.3 mm (1.1 in). The rate of rutting was relatively slow during the early part of the experiment; but increased significantly after the 100 kN (22,500 lb) load change, despite the pavement temperature being reduced to 15°C (59°F).
- Both of the failure criteria set for the experiment were reached within 100,000 load repetitions of each other.
- Ratios of final-to-initial elastic surface deflections under a 60 kN (13,500 kN) wheel load increased by between 3.4 and 5.5 times along the length of the section. The ratios for in-depth deflections show that damage had increased significantly at all depths in the pavement structure by the end of trafficking. The limited data available shows that loss of stiffness in the section was highest in the area of most severe cracking in the underlying layer.
- Analysis of surface profile and in-depth permanent deformation measurements indicate that most of the permanent deformation occurred in the asphalt-bound surfacing layers (overlay and cracked DGAC) with approximately twice as much damage occurring in the area of most severe cracking in the underlying DGAC layer. Permanent deformation was also recorded in the upper part of the aggregate base in this area. Negligible deformation was recorded in the subgrade.

No recommendations as to the use of modified binders in overlay mixes are made at this time. These recommendations will be included in the second-level analysis report, which will be prepared and submitted on completion of all HVS and laboratory testing.

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1. INTRODUCTION

1.1. Objectives

The first-level analysis presented in this report is part of Partnered Pavement Research Center Strategic Plan Element 4.10 (PPRC SPE 4.10) being undertaken for the California Department of Transportation (Caltrans) by the University of California Pavement Research Center (UCPRC). The objective of the study is to evaluate the reflective cracking performance of asphalt binder mixes used in overlays for rehabilitating cracked asphalt concrete pavements in California. The study includes mixes modified with rubber and polymers, and it will develop tests, analysis methods, and design procedures for mitigating reflective cracking in overlays. This work is part of a larger study on modified binder (MB) mixes being carried out under the guidance of the Caltrans Pavement Standards Team (PST) (1), which includes laboratory and accelerated pavement testing using the Heavy Vehicle Simulator (carried out by the UCPRC), and the construction and monitoring of field test sections (carried out by Caltrans).

1.2. Overall Project Organization

This UCPRC project is a comprehensive study, carried out in three phases, involving the following primary elements (**Error! Reference source not found.**):

- Phase 1
  - The construction of a test pavement and subsequent overlays;
  - Six separate Heavy Vehicle Simulator (HVS) tests to crack the pavement structure;
  - Placing of six different overlays on the cracked pavement;
- Phase 2
  - Six HVS tests to assess the susceptibility of the overlays to high-temperature rutting (Phase 2a);
  - Six HVS tests to determine the low-temperature reflective cracking performance of the overlays (Phase 2b);
  - Laboratory shear and fatigue testing of the various hot-mix asphalts (Phase 2c);
  - Falling Weight Deflectometer (FWD) testing of the test pavement before and after construction and before and after each HVS test;
  - Forensic evaluation of each HVS test section;
- Phase 3
  - Performance modeling and simulation of the various mixes using models calibrated with data from the primary elements listed above.

Phase 1

In this phase, a conventional dense-graded asphalt concrete (DGAC) test pavement was constructed at the Richmond Field Station (RFS) in the summer of 2001. The pavement was divided into six cells, and within each cell a section of the pavement was trafficked with the HVS until the pavement failed by either fatigue (2.5 m/m^2 [0.76 ft/ft^2]) or rutting (12.5 mm [0.5 in]). This period of testing began in the summer of 2001 and was concluded in the spring of 2003. In June 2003 each test cell was overlaid with either conventional DGAC or asphalt concrete with modified binders as follows:

- Full-thickness (90 mm) AR4000-D dense graded asphalt concrete overlay, included as a control for performance comparison purposes (AR-4000 is approximately equivalent to a PG64-16 performance grade binder);
- Full-thickness (90 mm) MB4-G gap-graded overlay;
- Half-thickness (45 mm) rubberized asphalt concrete gap-graded overlay (RAC-G), included as a control for performance comparison purposes;
- Half-thickness (45 mm) MB4-G gap-graded overlay;
- Half-thickness (45 mm) MB4-G gap-graded overlay with minimum 15 percent recycled tire rubber (MB15-G), and
- Half-thickness (45 mm) MAC15-G gap-graded overlay with minimum 15 percent recycled tire rubber.

The conventional overlay was designed using the current (2003) Caltrans overlay design process. The various modified overlays were either full (90 mm) or half thickness (45 mm). Mixes were designed by Caltrans. The overlays were constructed in one day.

Phase 2

Phase 2 included high-temperature rutting and low-temperature reflective cracking testing with the HVS as well as laboratory shear and fatigue testing. The rutting tests were started and completed in the fall of 2003. For these tests, the HVS was placed above a section of the underlying pavement that had not been trafficked during Phase 1. A reflective cracking test was next conducted on each overlay from the winter of 2003-2004 to the summer of 2007. For these tests, the HVS was positioned precisely on top of the sections of failed pavement from the Phase 1 HVS tests to investigate the extent and rate of crack propagation through the overlay.

In conjunction with Phase 2 HVS testing, a full suite of laboratory testing, including shear and fatigue testing, was carried out on field-mixed, field-compacted, field-mixed, laboratory-compacted, and laboratory-mixed, laboratory-compacted specimens.

Phase 3

Phase 3 entailed a second-level analysis carried out on completion of HVS and laboratory testing (the focus of this report). This included extensive analysis and characterization of the mix fatigue and mix shear data, backcalculation of the FWD data, performance modeling of each HVS test, and a detailed series of pavement simulations carried out using the combined data.

An overview of the project timeline is shown in Figure 1.1.

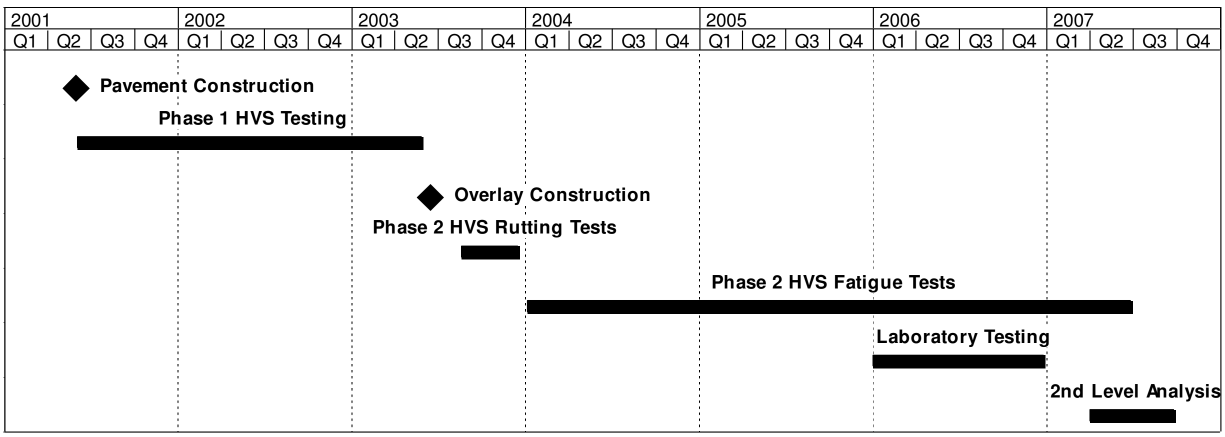

Figure 1.1: Timeline for the Reflective Cracking Study.

Reports

The reports prepared during the reflective cracking study document data from construction, HVS tests, laboratory tests, and subsequent analyses. These include a series of first- and second-level analysis reports and two summary reports. On completion of the study this suite of documents will include:

- One first-level report covering the initial pavement construction, the six initial HVS tests, and the overlay construction (Phase 1);
- One first-level report covering the six Phase 2 rutting tests (but offering no detailed explanations or conclusions on the performance of the pavements);
- Six first-level reports, each of which covers a single Phase 2 reflective cracking test (containing summaries and trends of the measured environmental conditions, pavement responses, and pavement performance but offering no detailed explanations or conclusions on the performance of the pavement);
- One first-level report covering laboratory shear testing;
- One first-level report covering laboratory fatigue testing;
- One report summarizing the HVS test section forensic investigation;
- One report summarizing the backcalculation analysis of deflection tests,

- One second-level analysis report detailing the characterization of shear and fatigue data, pavement modeling analysis, comparisons of the various overlays, and simulations using various scenarios (Phase 3), and
- One four-page summary report capturing the conclusions and one longer, more detailed summary report that covers the findings and conclusions from the research conducted by the UCPRC.

1.3. Structure and Content of This Report

This report presents the results of the HVS test on the half-thickness (45 mm) Rubberized Asphalt Concrete gap-graded overlay (referred to as "RAC-G" in this report), designated Section 587RF, with preliminary analyses relative to observed performance and is organized as follows:

- Chapter 2 contains a description of the test program including experiment layout, loading sequence, instrumentation, and data collection.
- Chapter 3 presents a summary and discussion of the data collected during the test.
- Chapter 4 contains a summary of the results together with conclusions and observations.

1.4. Measurement Units

Metric units have always been used in the design and layout of HVS test tracks, and for all the measurements, data storage, analysis, and reporting at the eight HVS facilities worldwide (as well as all other international accelerated pavement testing facilities). Continued use of the metric system facilitates consistency in analysis, reporting, and data sharing.

In this report, metric and English units are provided in the Executive Summary, Chapters 1 and 2, and the Conclusion. In keeping with convention, only metric units are used in Chapter 3. A conversion table is provided on Page iv at the beginning of this report.

2. TEST DETAILS

2.1. Experiment Layout

Six overlays, each with a rutting test section and a reflective cracking test section, were constructed as part of the second phase of the study as follows:

1. Sections 580RF and 586RF: Half-thickness (45 mm) MB4 gap-graded overlay with minimum 15 percent recycled tire rubber (referred to as "MB15-G" in this report);
2. Sections 581RF and 587RF: Half-thickness (45 mm) rubberized asphalt concrete gap-graded (RAC-G) overlay;
3. Sections 582RF and 588RF: Full-thickness (90 mm) AR4000 dense-graded asphalt concrete overlay (designed using CTM356 and referred to as "AR4000-D" in this report);
4. Sections 583RF and 589RF: Half-thickness (45 mm) MB4 gap-graded overlay (referred to as "45 mm MB4-G" in this report);
5. Sections 584RF and 590RF: Full-thickness (90 mm) MB4 gap-graded overlay (referred to as "90 mm MB4-G" in this report), and
6. Sections 585RF and 591RF: Half-thickness (45 mm) MAC15TR gap-graded overlay with minimum 15 percent recycled tire rubber (referred to as "MAC15-G" in this report).

These sections and the corresponding Phase 1 fatigue test sections are shown in Figure 2.1. Prior to the Phase 2 reflective cracking testing, a rutting study was carried out whereby HVS loading at high temperature was applied adjacent to the reflective cracking experiments to evaluate the rutting behavior of the overlay mixes. The rutting study will be discussed in a separate report.

2.2. Test Section Layout

The test section layout for Section 591RF is shown in Figure 2.2. Station numbers refer to fixed points on the test section and are used for measurements and as a reference for discussing performance.

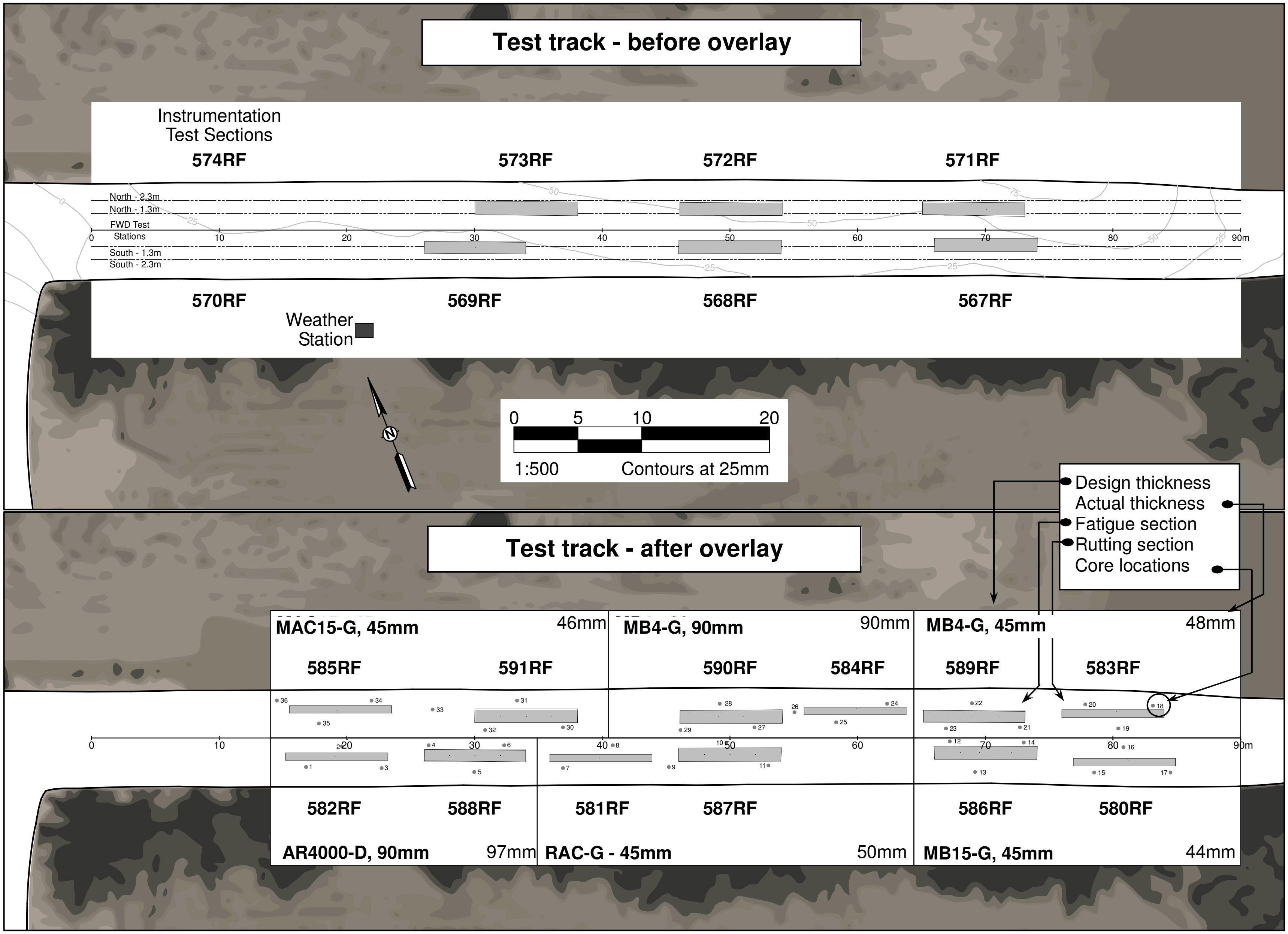

Figure 2.1: Layout of Reflective Cracking Study project.

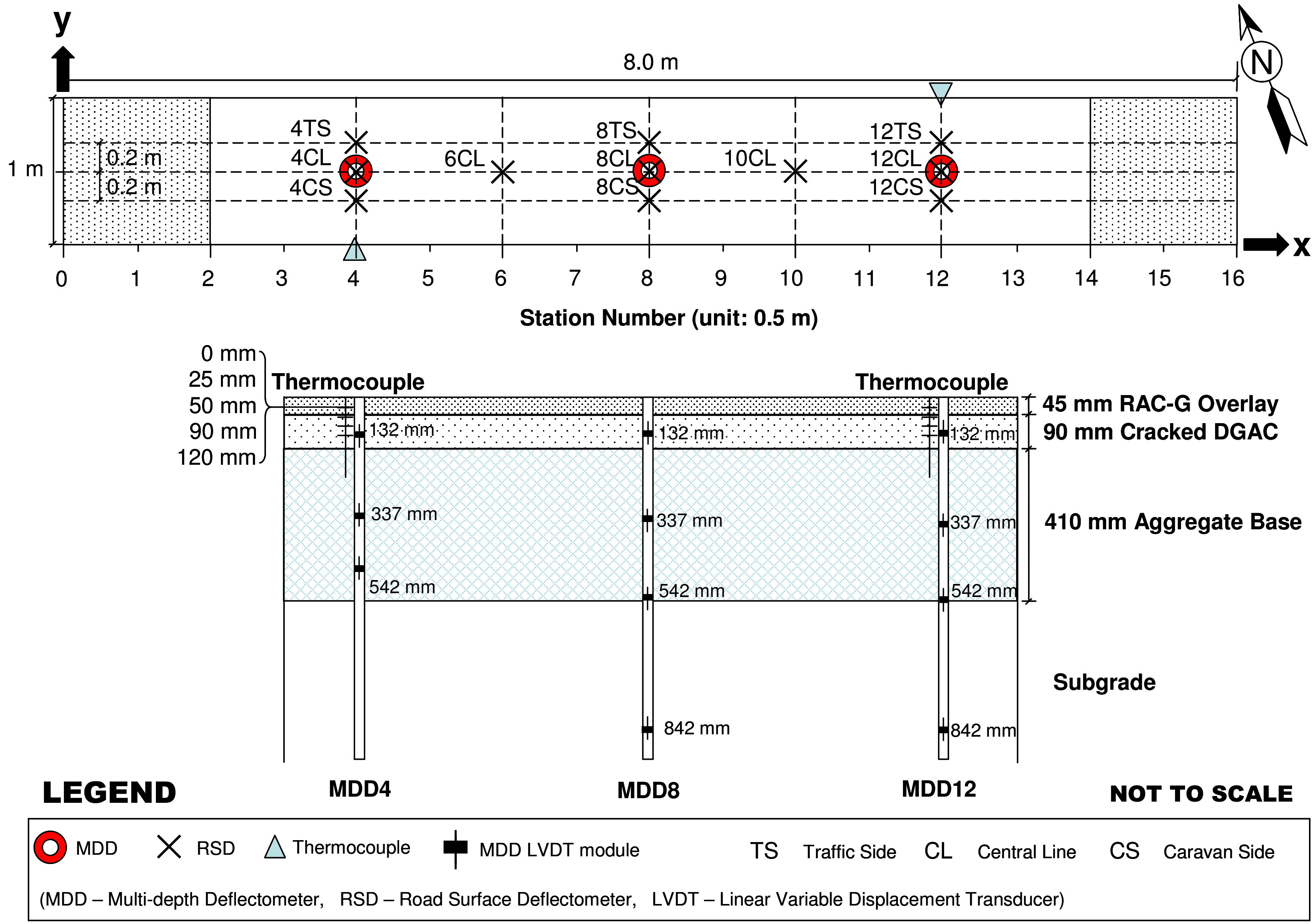

Figure 2.2: Section 587RF layout and location of instruments.

2.2.1 Pavement Instrumentation and Monitoring Methods

Measurements were taken with the following instruments:

- Road Surface Deflectometer (RSD), measuring surface deflection;
- Multi-depth Deflectometer (MDD), measuring elastic deflection and permanent deformation at different depths in the pavement;
- Laser Profilometer, measuring surface profile (at each station);
- Falling Weight Deflectometer (FWD), measuring elastic deflection before and after testing, and
- Thermocouples, measuring pavement temperature and ambient temperature.

Instrument positions are shown in Figure 2.2. Detailed descriptions of the instrumentation and measuring equipment are included in Reference 4. Intervals between measurements, in terms of load repetitions, were selected to enable adequate characterization of the pavement as damage developed.

2.3. Underlying Pavement Design

The pavement for the first phase of HVS trafficking was designed according to the Caltrans Highway Design Manual Chapter 600 using the computer program *NEWCON90.* Design thickness was based on a tested subgrade R-value of 5 and a Traffic Index of 7 (~121,000 ESALs) (3). The pavement design for the test road and the preliminary as-built pavement structure for Section 587RF (determined from cores removed from the edge of the section) are illustrated in Figure 2.3.

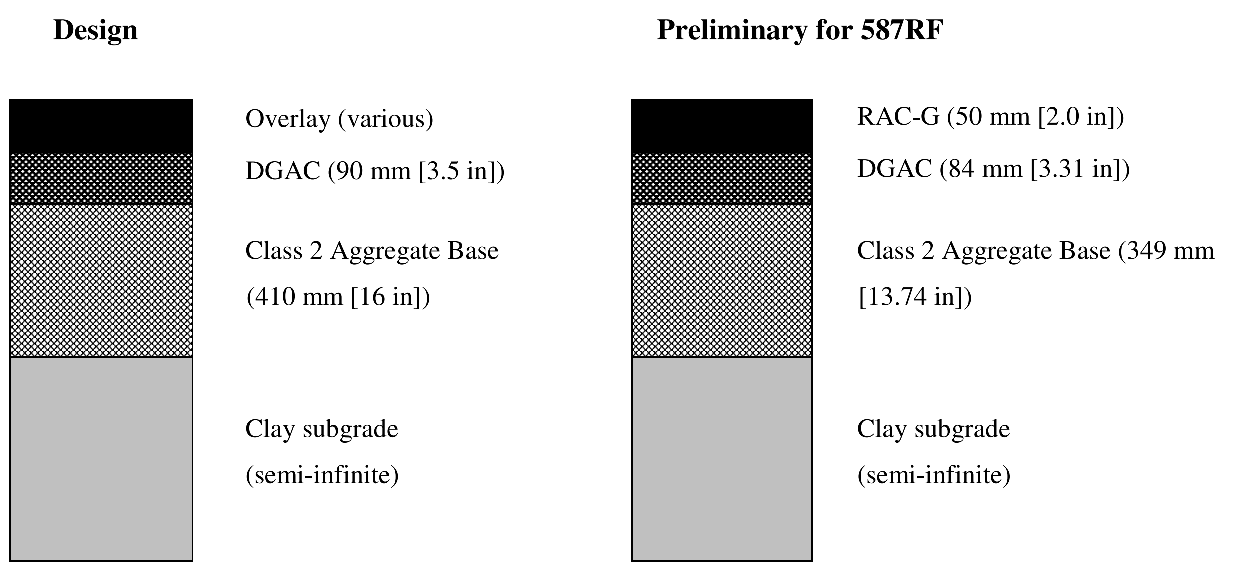

Figure 2.2: Pavement design for the Reflective Cracking Study test track
(Design and preliminary actual for 587RF)

The existing subgrade was ripped and reworked to a depth of 200 mm (8 in) so that the optimum moisture content and the maximum wet density met the specification per Caltrans Test Method CTM 216. The average maximum wet density of the subgrade was 2,180 kg/m^3 (136 pcf). The average relative compaction of the subgrade was 97 percent (3).

The aggregate base was constructed to meet the Caltrans compaction requirements for aggregate base Class 2 using CTM 231 nuclear density testing. The maximum wet density of the base determined according to CTM 216 was 2,200 kg/m^3 (137 pcf). The average relative compaction was 98 percent.

The DGAC layer consisted of a dense-graded asphalt concrete (DGAC) with AR-4000 binder and aggregate gradation limits following Caltrans 19-mm (0.75 in) maximum size coarse gradation (3). The target asphalt content was 5.0 percent by mass of aggregate, while actual contents varied between 4.34 and 5.69 percent. Nuclear density measurements and extracted cores were used to determine a preliminary as-built mean air-void content of 9.1 percent with a standard deviation of 1.8 percent. The air-void content after traffic compaction and additional air-void contents from cores taken outside the trafficked area will be determined on completion of trafficking of all sections and will be reported in the second-level analysis report.

2.4. Summary of Testing on the Underlying Layer

Trafficking of the underlying Section 568RF took place between January 14, 2002, and February 12, 2002, during which 377,556 repetitions were applied. Figure 2.3 presents the final cracking pattern after testing. Cracking was mostly transverse. Total crack length was 41.72 m (136.88 ft) and crack density was 5.96 m/m^2 (1.82 ft/ft^2).

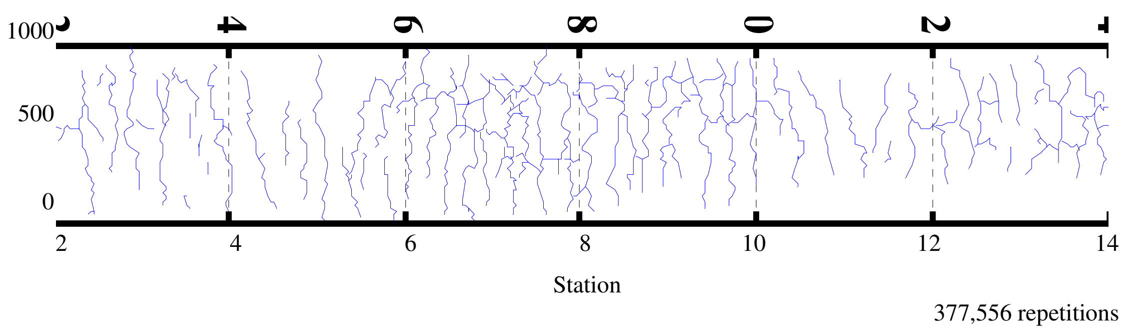

Figure 2.3: Cracking pattern on Section 568RF after Phase I HVS testing.

2.5. Reflective Cracking Section Design

Section 587RF consisted of a 45-mm rubber asphalt concrete gap-graded (RAC-G) overlay constructed precisely on top of Section 568RF. Section 568RF had significant transverse cracking over most of the area subjected to HVS trafficking (Figure 2.3). The overlay thickness for the experiment was determined according to Caltrans Test Method CTM 356 using Falling Weight Deflectometer data from the Phase 1 experiment. The actual layer thickness of Section 587RF was measured from cores extracted from the edge of the test section and from Dynamic Cone Penetrometer (DCP) tests. The measured average thicknesses for the section from cores and DCP measurements taken outside the trafficked area were:

- RAC-G Overlay: 50 mm (min 41 mm; max 56 mm; standard deviation, 6.1 mm)
  [2.0 in (min 1.6 in; max 2.2 in; standard deviation, 0.2 in)]
- Cracked DGAC layer: 84 mm (min 77 mm; max 90 mm; standard deviation, 4.4 mm)
  [3.3 in (min 3.0 in; max 3.5 in; standard deviation, 0.2 in)]
- Aggregate base: 349 mm (13.7 in)

Exact layer thicknesses will be determined from measurements in test pits after HVS testing has been completed on all sections.

Laboratory testing was carried out by Caltrans and UCPRC on samples collected during construction to determine actual binder properties, binder content, aggregate gradation, and air-void content. The RAC-G binder met the Caltrans binder specification, based on testing performed by Caltrans. The ignition-extracted binder content, corrected for aggregate ignition, showed an average value of 8.49 percent, marginally higher than the design binder content of 8.0 percent. The aggregate gradation met Caltrans specifications for a 19.0 mm (3/4 inch) maximum size gap gradation, with material passing the 0.3 mm (#50), 0.6 mm (#30) and 2.36 mm (#8) sieves on the limit for fine gradation. Gradation is illustrated in Figure 2.4. The preliminary as-built air-void content was 8.8 percent with a standard deviation of 1.3 percent, based on cores taken outside of the HVS sections. Final air-void contents will be determined from trenching and coring to be performed after trafficking of all sections.

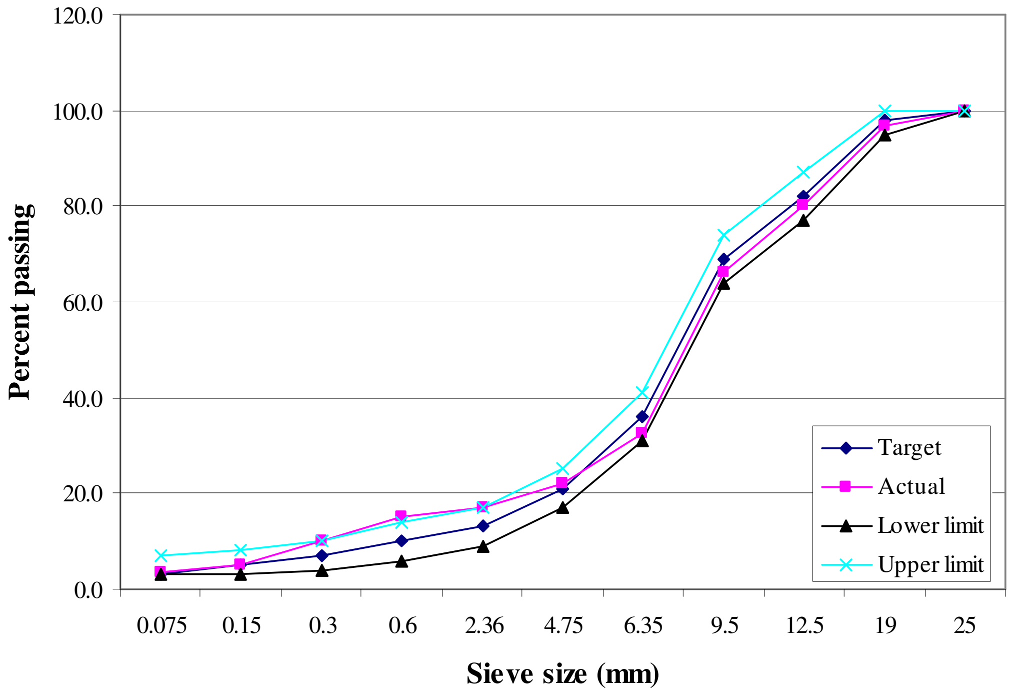

Figure 2.4: Actual vs. target gradation for RAC-G overlay.

2.6. Test Summary

2.6.1 Test Section Failure Criteria

Failure criteria for analyses were set at:

- Cracking density of 2.5 m/m^2 (0.76 ft/ft^2) or more, and/or
- Average maximum surface rut depth of 12.5 mm (0.5 in) or more.

2.6.2 Environmental Conditions

For the first one million repetitions, the pavement surface temperature was maintained at 20°C±4°C (68°F±7°F) to minimize rutting in the asphalt concrete and to promote fatigue damage. Thereafter, the pavement surface temperature was reduced to 15°C±4°C (59°F±7°F) to further accelerate fatigue damage. A temperature control chamber (5) was used to maintain the test temperatures.

The pavement surface received no direct rainfall as it was protected by the temperature control chamber. The section was tested predominantly during the dry season (March to October) and hence any water infiltration into the pavement from the side drains and through the raised groundwater table was unlikely.

2.6.3 Test Duration

HVS trafficking of Section 587RF was initiated on March 15, 2005, and completed on October 10, 2005, after the application of over two million (2,024,793) load repetitions. Testing was interrupted twice:

- During a breakdown between March 30 and April 26, 2005, when the cumulative traffic repetitions were approximately 51,733, and
- For temperature conditioning between June 28 and July 2, 2005, when the repetition count was 1,000,000.

2.6.4 Loading Program

The HVS test program is summarized in Table 2.1.

Table 2.1: Summary of Load History

Start Date	Start Repetition	Wheel Load (kN) - [lb]		Wheel	Tire Pressure (kPa) - [psi]	Direction
		Planned	Actual			
03/15/05*	0	40 - [9,000]	60	Dual	720 - [104]	Bi
05/03/05	208,896	60 - [13,500]	90	Dual	720 - [104]	Bi
05/16/05	410,255	80 - [18,000]	80	Dual	720 - [104]	Bi
06/07/05**	1,000,001	100 - [22,500]	100	Dual	720 - [104]	Bi

* Testing was interrupted during a breakdown between 03/30/04 and 04/26/05.
** Testing was interrupted during temperature conditioning between 06/28/05 and 07/02/05.

The loading program followed differs from the original test plan due to an incorrect hydraulic control system setup on loads less than 65 kN (14,600 lb) in the Phase 1 experiment. The loading pattern from the Phase 1 experiment was thus retained to facilitate comparisons of performance between all tests in the Reflective Cracking Study. Testing was undertaken with a dual-wheel configuration, using radial truck tires (Goodyear G159 - 11R22.5 - steel belt radial) inflated to a pressure of 720 kPa (104 psi), in a bidirectional loading mode. Lateral wander over the one-meter (39.4 in) width of the test section was programmed to simulate traffic wander on a typical highway lane.

Cumulative traffic applications and the loading history are shown in Figure 2.5. The shorter 60 kN (13,500 lb) and 90 kN (20,250 lb) and longer 80 kN (18,000 lb) and 100 kN (22,500 lb) loading phases adopted for Section 589 (second HVS test) were also used in this test. A total of 2,024,793 load repetitions were applied consisting of:

- 208,896 repetitions of a 60 kN (13,500 lb) load
- 201,359 repetitions of a 90 kN (20,250 lb) load
- 589,745 repetitions of an 80 kN (18,000 lb) load, and
- 1,024,793 repetitions of a 100 kN (22,500 lb) load.

This loading equates to approximately 66 million equivalent standard axles, using the Caltrans conversion of $(\text{axle load}/18000)^{4.2}$, which in turn equates to a Traffic Index of 15.

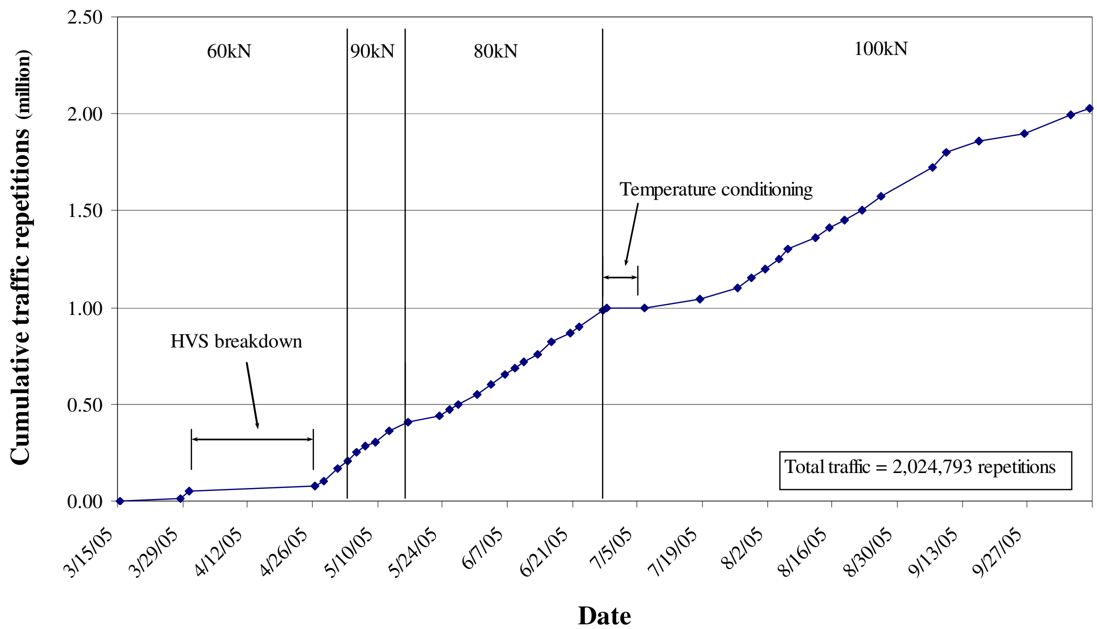

Figure 2.5: Cumulative traffic applications and loading history.

2.6.5 Measurement Summary

Table 2.2 (pages 14 and 15) lists the reading schedule of MDD and RSD measurements at various wheel loads. Surface deflection measurements with the RSD were obtained at the reference points along the centerline (CL) of the section and at locations 200 mm (8.0 in) on either side of the centerline (traffic and caravan side), as shown in Figure 2.2. MDD and RSD measurements were taken with a 60 kN (13,500 lb) load throughout the test as well as with the load being applied at the time of measurement (i.e., 80 kN [18,000 lb], 90 kN [22,500 lb], or 100 kN [22,500 lb]). The figures in Chapter 3 only show the measurements taken with the 60 kN (13,500 lb) load.

Measurements of surface rut depth taken by transverse scans with the Laser Profilometer were obtained at each station (Figure 2.2) on the same schedule as that of the MDD and RSD. The following rut parameters, which are discussed in more detail in Chapter 3, were determined from these measurements:

- Location and magnitude of the maximum rut depth,
- Average rut depth for the entire test section, and
- Rate of rut development.

Falling Weight Deflectometer (FWD) measurements were taken before and after testing at the center of and on the outside of the trafficked area. A summary of the measurement schedule is provided in Table 2.3.

Table 2.3: Summary of FWD Measurements

Date	Time	Location	Interval (m) - [ft]
02/18/05	10:53	Center & side	0.3 - [1.0]
02/24/05	05:43	Center & side	0.3 - [1.0]
10/19/05	07:30	Center & side	0.3 - [1.0]
10/19/05	15:14	Center & side	0.9 - [3.0]

Pavement temperature measurements were derived from thermocouples (depths and surface locations shown in Figure 2.2) at one-hour intervals during HVS operation. Air temperatures were measured in a weather station next to the test section and recorded at the same intervals as the thermocouples.

Crack development was monitored using visual inspection of the road surface and photographs.

Table 2.2: Summary of MDD and RSD Measurements

Date	Reps (x1m)	Temp (°C)	MDD4				MDD8				MDD12				RSD Center line[1]				RSD Sides[2]			
			60*	90	80	100	60	90	80	100	60	90	80	100	60	90	80	100	60	90	80	100
03/15/05	0.00	12.8	×				×				×				✓				✓			
03/28/05	0.02	12.8	×				×				×				✓							
03/30/05	0.05	13.8	×				×				×				✓							
04/28/05	0.11	16.0	×				×				×				✓							
05/01/05	0.17	17.3	×				×				×				✓							
05/03/05	0.21	18.5	×	×			×	×			×	×			✓	✓			✓	✓		
05/05/05	0.25	17.1	×	×			×	×			×	×			✓	✓						
05/07/05	0.28	18.5	×	×			×	×			×	×			✓	✓						
05/09/05	0.31	16.4	×	×			×	×			×	×			✓	✓						
05/12/05	0.36	18.5	×	×			×	×			×	×			✓	✓						
05/16/05	0.41	19.5	×	×	×		×		×		×		×		✓		✓		✓	✓	✓	
05/23/05	0.44	19.6	×	×	×		×		×		×		×		✓		✓					
05/25/05	0.47	18.9	×	×	×		×		×		×		×		✓		✓					
05/27/05	0.50	17.6	×	×	×		×		×		×		×		✓		✓					
05/31/05	0.55	18.7	×	×	×		✓		✓		✓		✓		✓		✓					
06/03/05	0.61	20.1	×	×	×		✓		✓		✓		✓		✓		✓					
06/06/05	0.66	20.3	×	×	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
06/08/05	0.69	18.6	×		×	×	✓		✓	×	✓		✓	×	✓		✓	×				
06/10/05	0.72	19.1	×		×	×	✓		×	×	✓		×	×	✓		✓	×				
06/13/05	0.76	20.5	×		×	×	✓		✓	×	✓		✓	×	✓		✓	×				
06/16/05	0.82	18.3	×		×	×	✓		✓	×	✓		✓	×	✓		✓	×				
06/20/05	0.87	20.2	×		×	×	✓		✓	×	✓		✓	×	✓		✓	×				
06/22/05	0.90	20.6	×		×	×	✓		✓	×	✓		✓	×	✓		✓	×				
06/27/05	0.99	18.7	×		×	×	✓		✓	×	✓		✓	×	✓		✓	×				
06/28/05	1.00	18.7	×		×	×	✓		✓	✓	✓		✓	✓	✓		✓	✓	✓		✓	✓
07/06/05	1.00	16.7	×		×	×	✓		✓	✓	✓		✓	✓	✓		✓	✓	✓		✓	✓
07/18/05	1.05	16.1	×		×	×	✓		×	✓	✓		×	✓	✓		✓	✓				
07/26/05	1.10	16.7	×		×	×	×		×	×	×		×	×	✓		✓	✓				
07/29/05	1.15	17.5	×		×	×	✓		×	✓	✓		×	✓	✓		×	✓				
08/01/05	1.20	17.1	×		×	×	×		×	×	×		×	×	✓		×	✓				
08/04/05	1.25	16.9	×		×	×	×		×	×	×		×	×	✓		×	✓				
08/06/05	1.30	17.8	×		×	×	✓		×	✓	✓		×	✓	✓		×	✓				
08/12/05	1.36	16.9	×		×	×	✓		×	✓	✓		×	✓	✓		×	✓				

* Wheel load in kN
[1] Measurements at 4, 6, 8, 10, and 12
[2] Measurements at 4, 8, and 12

✓ Data collected
× Suspect data, not used
(shaded) No data collection scheduled

Table 2.2: Summary of MDD and RSD Measurements (cont)

Date	Reps (x1m)	Temp (°C)	MDD4				MDD8				MDD12				RSD Centerline[1]				RSD Sides[2]			
			60*	90	80	100	60	90	80	100	60	90	80	100	60	90	80	100	60	90	80	100
08/15/05	1.41	16.6	×		×	×	✓		×	✓	✓		×	✓	✓		×	✓				
08/18/05	1.45	16.7	×		×	×	✓		×	✓	✓		×	✓	✓		×	✓				
08/22/05	1.50	16.8	×		×	×	✓		×	✓	✓		×	✓	✓		✓	✓	✓		✓	✓
08/26/05	1.57	17.0	×		×	×	✓		✓	✓	✓		✓	✓	✓		×	✓				
09/06/05	1.72	16.1	×		×	×	✓		×	✓	✓		×	✓	✓		×	✓				
09/12/05	1.80	17.0	×		×	×	✓		×	✓	✓		×	✓	✓		×	✓	✓		✓	✓
09/16/05	1.86	19.3	×		×	×	✓		×	✓	✓		×	✓	✓		✓	✓				
09/26/05	1.89	17.3	×		×	×	✓		×	✓	✓		×	✓	✓		✓	✓				
10/06/05	2.00	16.4	×		×	×	×		✓	×	×		✓	×	✓		✓	✓				
10/10/05	2.02	14.5	×	×	×	×	✓	×	×	✓	✓	×	×	✓	✓		✓	✓	✓	✓	✓	✓

* Wheel load in kN
[1] Measurements at 4, 6, 8, 10, and 12
[2] Measurements at 4, 8, and 12
✓ Data collected
× Suspect data, not used
(shaded) No data collection scheduled

3. DATA SUMMARY

This chapter provides a summary of the data collected from Section 587RF and a brief discussion of the first-level analysis. Interpretation of the data in terms of pavement performance will be discussed in a separate second-level analysis report.

3.1. Temperatures

Pavement temperatures were controlled using the temperature control chamber. Both air (inside and outside the temperature box) and pavement temperatures were monitored and recorded hourly during the entire loading period. Figure 3.1 illustrates the frequencies of recorded temperatures at each hour in the testing period from March 15 to October 10, 2005, a total of 209 days. Hourly temperatures were collected for approximately 75 percent of the test period. No temperatures were recorded during the periods of breakdown. As seen in the figure, the hour counts from 09:00 to 14:00 hours (on a 24-hour clock) are relatively low, this being the period when measurements were taken. As a consequence, temperature interpolation/extrapolation will be necessary when interpreting the backcalculation results from the MDD and RSD measurements (second-level analysis). In assessing fatigue performance, the temperature at the bottom of the asphalt concrete and the temperature gradient are the two important controlling temperature parameters used to evaluate the stiffness of the asphalt concrete and to compute the maximum tensile strain as accurately as possible.

3.1.1 Air Temperatures in the Temperature Control Unit

Air temperatures inside the temperature control chamber ranged from 8°C to 24°C during the entire testing period. Temperatures were adjusted to maintain a pavement temperature at 50 mm depth of 20°C±4°C for the first one million repetitions and 15°C±4°C for the remainder of the test. These temperature ranges are expected to promote fatigue damage leading to reflective cracking while minimizing rutting of the asphalt concrete layer. The temperature distributions for the various stages of the test were:

- Zero to one million repetitions: mean of 19.8°C with a standard deviation of 1.9°C.
- One million to end of test: mean of 16.1°C with a standard deviation of 2.3°C.

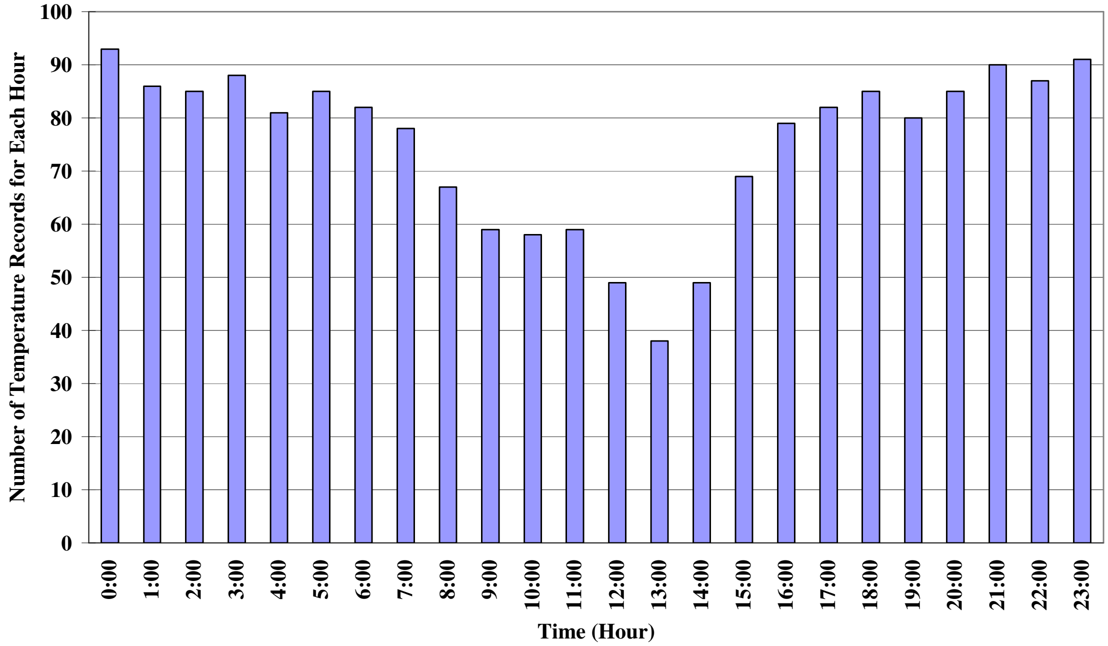

Figure 3.1: Frequencies of recorded temperatures.

The daily average temperatures recorded in the temperature control unit, calculated from the hourly temperatures recorded during HVS operation, are shown in Figure 3.2. Vertical errors bars on each point on the graph show daily temperature range.

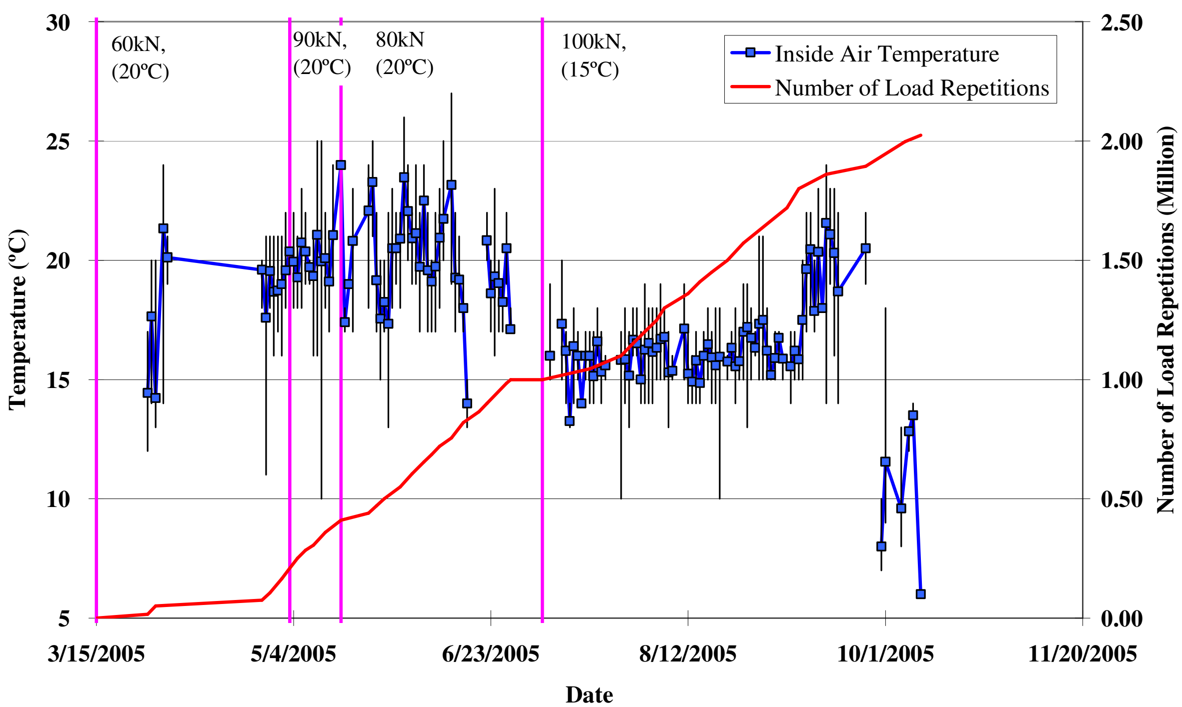

Figure 3.2: Daily average air temperatures inside the temperature control chamber.

3.1.2 Outside Air Temperatures

Outside air temperatures ranged from 9.3°C to 23.0°C with an average of 15.1 C and are summarized in Figure 3.3. Vertical error bars on each point on the graph show daily temperature range.

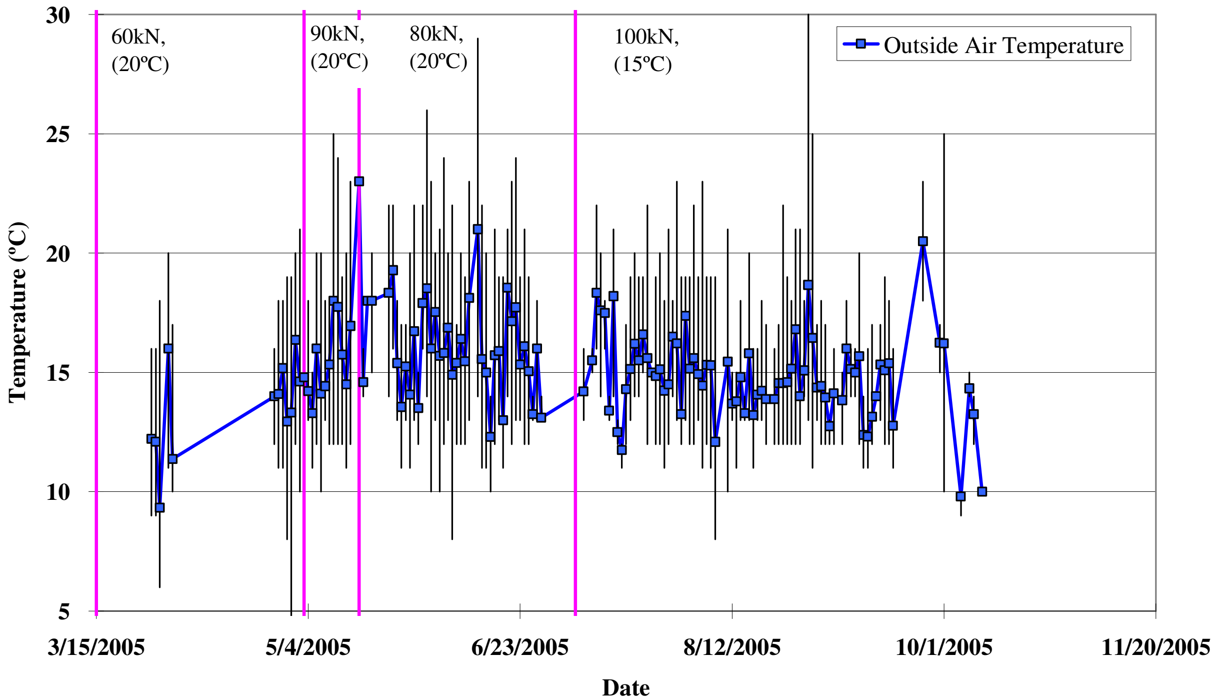

Figure 3.3: Daily average air temperatures outside the temperature control chamber.

3.1.3 Temperature in the Asphalt Concrete Layer

Daily averages of the surface and in-depth temperatures are listed in Table 3.1 and shown in Figure 3.4. Pavement temperatures increased during the early part of the test with very little difference in temperature at the various depths. After one million repetitions, pavement temperatures dropped sharply after conditioning, with temperatures at the various depths showing little variation. Pavement temperatures did not appear to be significantly influenced by outside air temperatures.

Table 3.1: Temperature Summary for Air and Pavement

Temperature	0 - 1,000,000		1,000,000 - 1,700,000		1,700,000 - 2,024,793	
	Average	Std Dev	Average	Std Dev	Average	Std Dev
Outside air	15.5	3.5	14.9	2.6	14.0	2.6
Inside air	19.8	2.4	16.0	1.3	17.8	4.4
Pavement surface	18.4	1.7	16.8	0.7	18.1	1.7
- 25-mm below surface	18.4	1.7	16.8	0.7	18.1	1.7
- 50-mm below surface	18.5	1.7	16.9	0.6	18.1	1.6
- 90-mm below surface	18.4	1.7	16.9	0.6	18.1	1.6
- 120-mm below surface	18.4	1.7	16.9	0.6	18.0	1.5

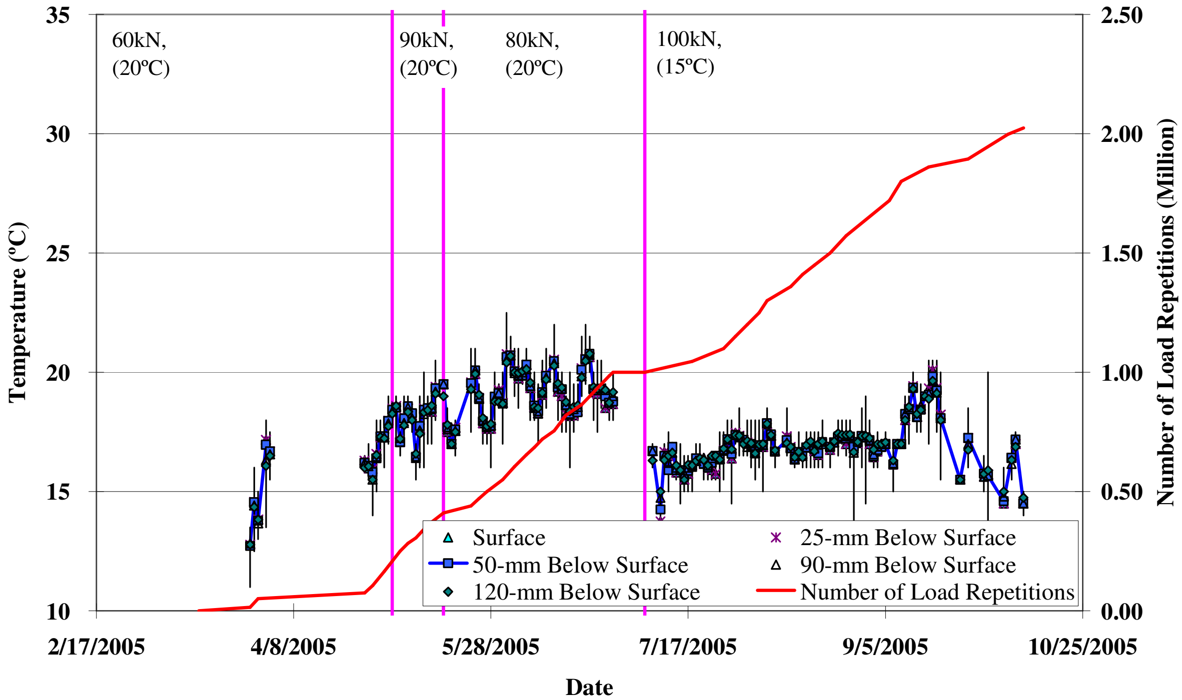

Figure 3.4: Daily average temperatures at pavement surface and various depths.

3.2. Rainfall

Figure 3.5 shows the monthly rainfall data from February 2005 to October 2005 as adapted from the Richmond Field Station HVS site and from the National Climatic Data Center (NCDC) recording station in Richmond. No data were available from the HVS test site for March and April due to a data recorder malfunction.

3.3. Elastic Deflection

Elastic (recoverable) deflections provide an indication of the overall stiffness of the pavement structure and, therefore, a measure of the load-carrying capacity. As the stiffness of a pavement structure deteriorates, its ability to resist the deformation/deflection caused by a given load and tire pressure decreases. During HVS testing elastic deflections are measured with two instruments: the RSD to measure surface deflections and the MDD to measure in-depth deflections. MDD modules could not be installed at the surface (0 mm) due to the limited thickness of the overlay and thus it is not possible to directly compare surface deflections between the two instruments. In addition to RSD and MDD measurements, FWD measurements were taken before and after HVS trafficking to evaluate the initial and final conditions of the pavement.

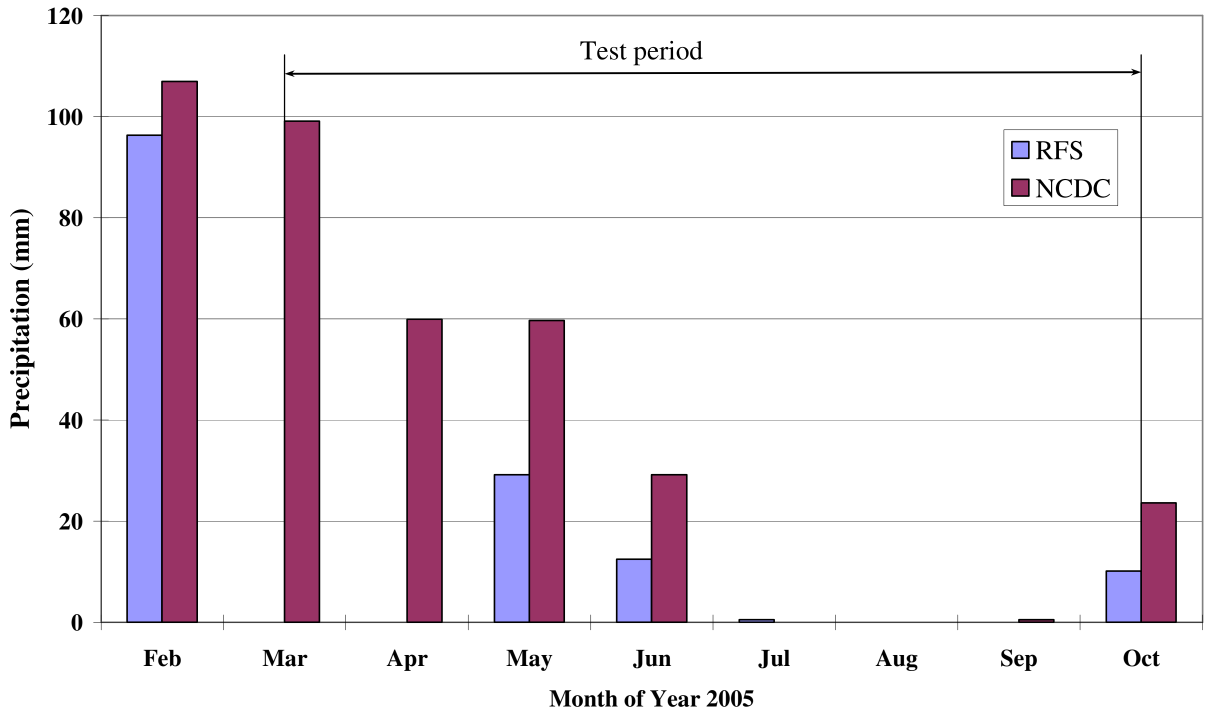

Figure 3.5: Monthly rainfall for Richmond Field Station.

3.3.1 Surface Elastic Deflection Using RSD

In this section of the report, surface deflections as measured by the RSD under a load of 60 kN are summarized (note that the HVS trafficking load does not remain the same during the course of the experiment).

Table 3.2 compares the average 60 kN RSD deflections for centerline locations 4, 6, 8, 10, and 12 before and on completion of testing. The relatively high standard deviation for the average deflection after trafficking is attributed to variability in the cracking of the underlying DGAC layer, which is discussed below.

Table 3.2: Average 60 kN RSD Centerline Deflections Before and After Testing

Position	Parameter	Deflection (microns)		
		Before Trafficking	After Trafficking	Ratio of Final/Initial
All	Average	368	1,718	4.67
	Std. Deviation	11	132	-
4CL	Average	369	2,060	5.58
6CL	Average	380	2,012	5.29
8CL	Average	391	1,811	4.63
10CL	Average	354	1,519	4.29
12CL	Average	344	1,186	3.45

At the start of the test, initial deflections were all within 0.05 mm of each other, with slightly higher deflections (i.e., weaker pavement) recorded at positions 4CL, 6CL, and 8CL, overlying that part of the DGAC with the highest density of cracking. During the course of the test, substantial damage occurred on the overlay over the entire section under HVS trafficking, with higher values at the one end. This is confirmed by the ratio of final-to-initial deflections for all RSD locations, which show that surface deflections increase by between three and five times along the length of the test section, indicating significant damage in the pavement structure in terms of loss of stiffness. Although the ratio of final-to-initial deflections is fairly consistent across the section, when the results are considered in conjunction with Figure 2.3, lower deflections (10CL and 12CL) were recorded at the end of the section that had the least amount of cracking in the underlying pavement (stiffer pavement), while those with the highest deflections (4CL, 6CL, and 8CL) are over the more severely cracked area (weaker pavement).

Deflections and damage rates both increased with increase in load. Figures 3.6 to 3.11 compare the deflection bowls at the same locations at test start, load change intervals, 1,500,000 repetitions and at test completion. The same scale is used on all figures, and the increasing deflection over time and with load is clearly evident. The higher deflections at points 4CL, 6CL, and 8CL over the cracked underlying DGAC are obvious.

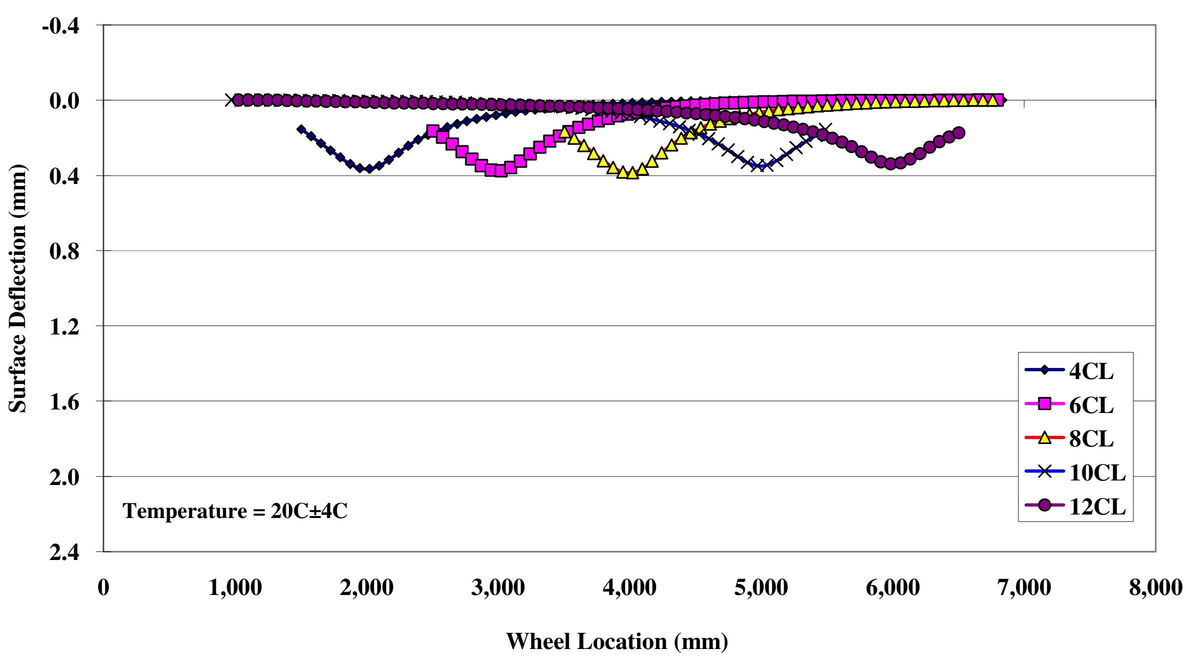

Figure 3.6: RSD deflections at CL locations with 60 kN test load at test start.

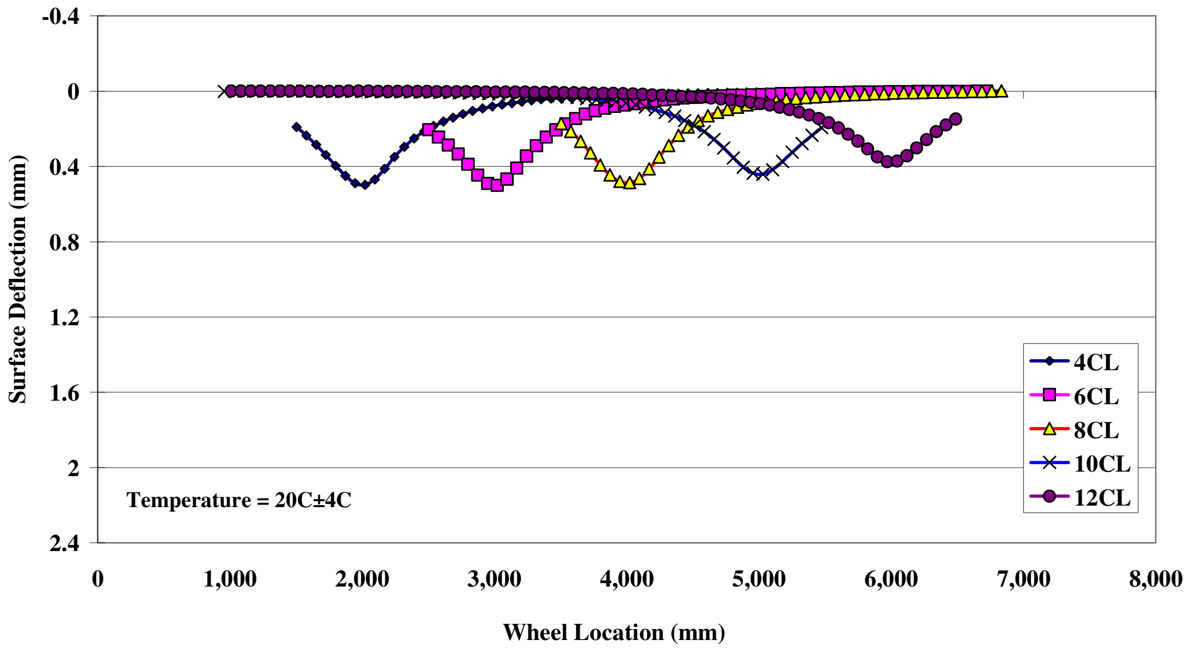

Figure 3.7: RSD deflections at CL locations with 60 kN test load after 208,896 repetitions.

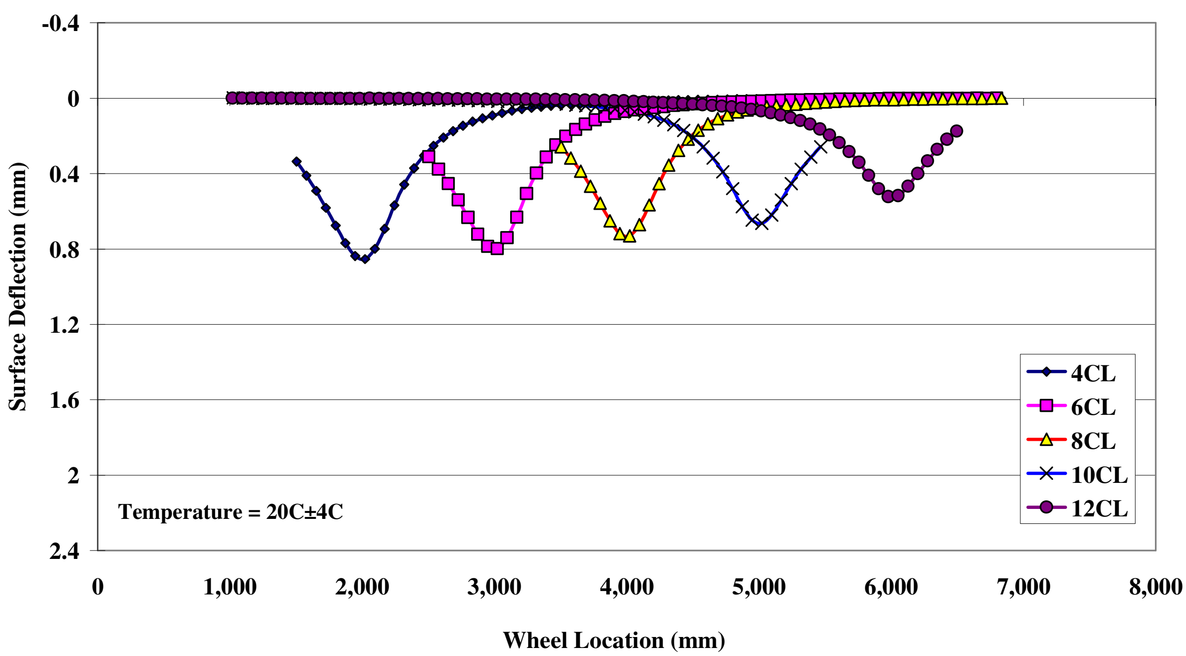

Figure 3.8: RSD deflections at CL locations with 60 kN test load after 410,255 repetitions.

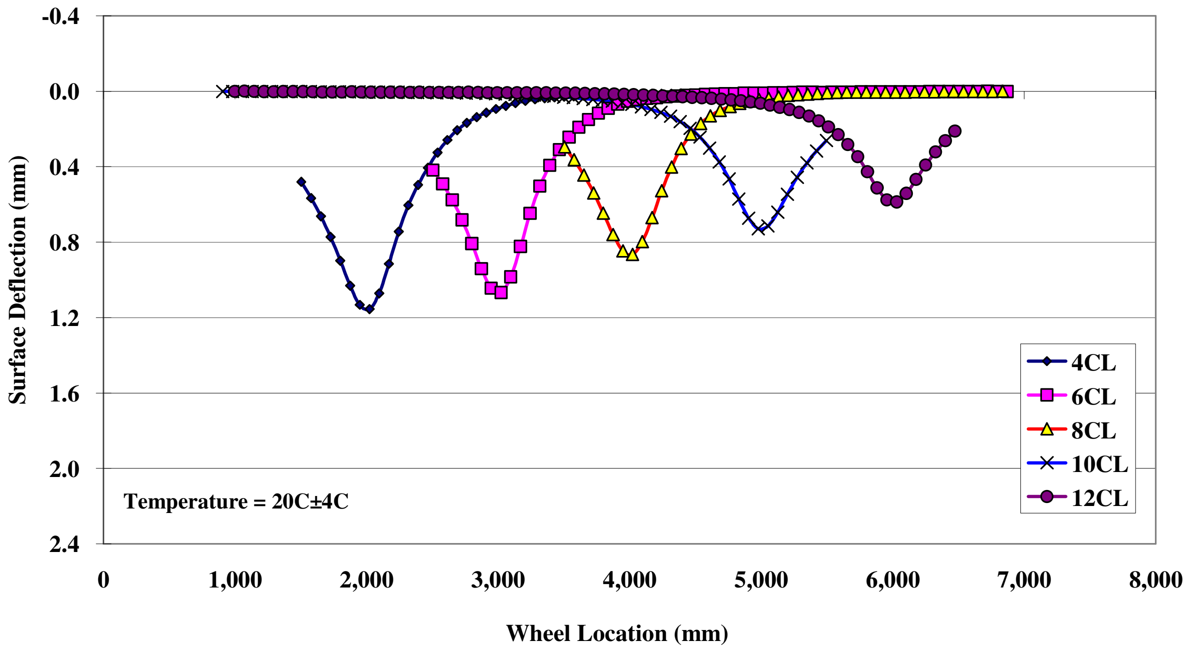

Figure 3.9: RSD deflections at CL locations with 60 kN test load after 1,000,000 repetitions.

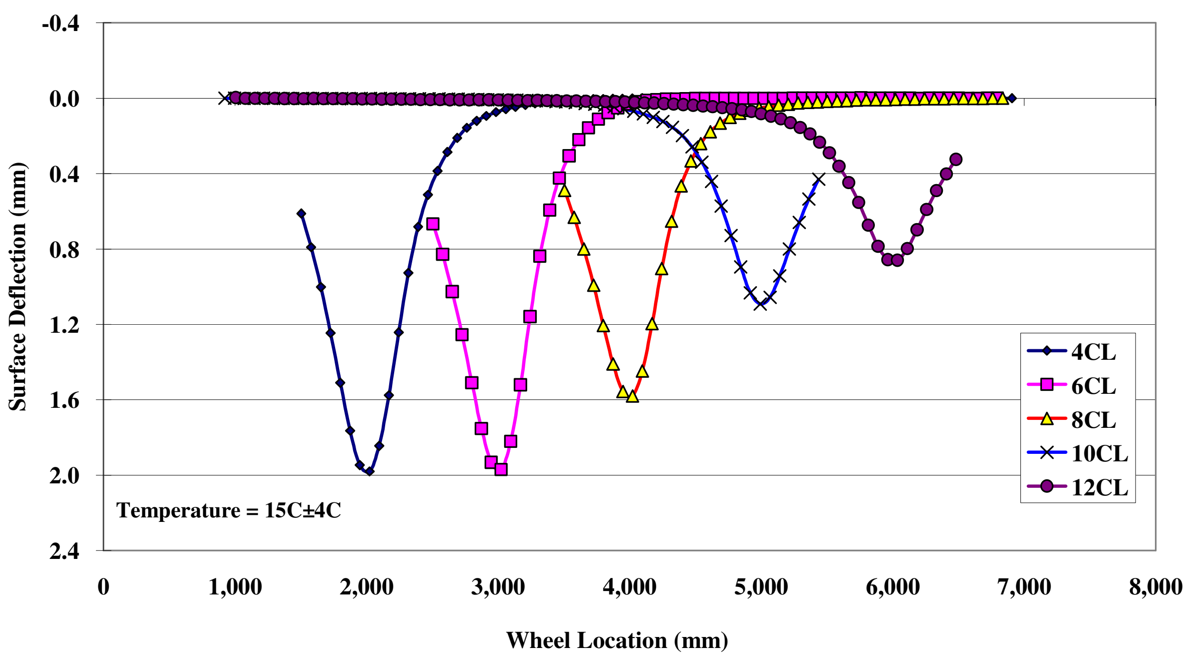

Figure 3.10: RSD deflections at CL locations with 60 kN test load after 1,500,000 repetitions.

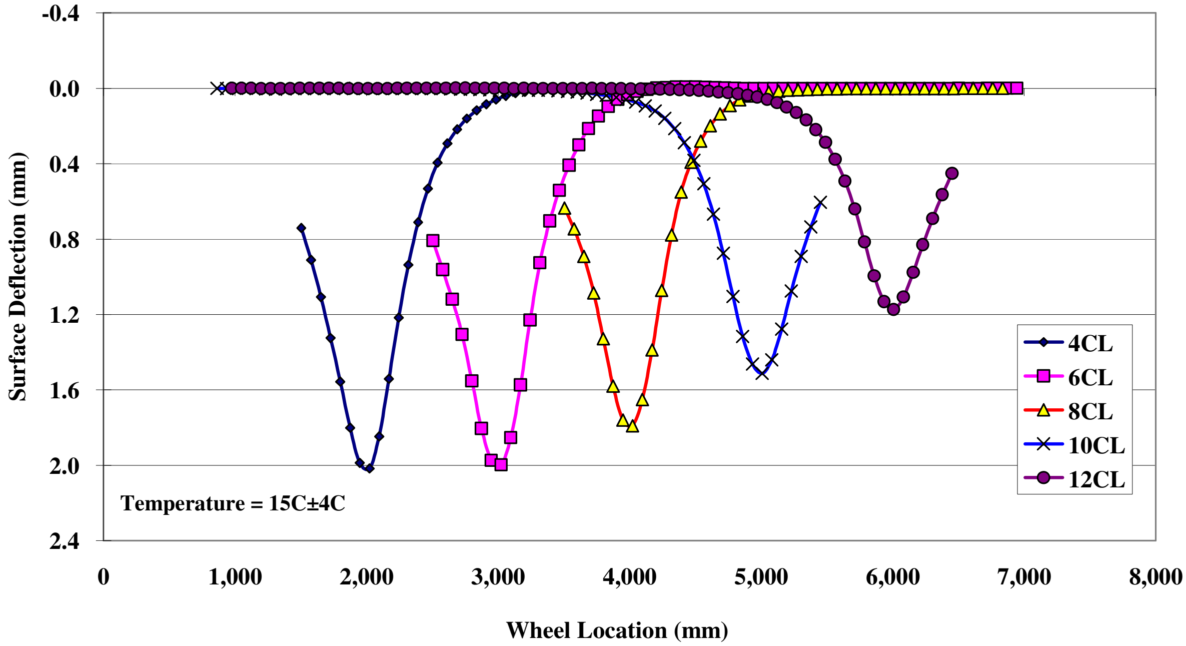

Figure 3.11: RSD deflections at CL locations with 60 kN test load at test completion.

The average 60 kN RSD deflections at centerline and side locations (200 mm from centerline within the trafficked area) are illustrated in Figure 3.12. These deflections are mostly all within 0.2 mm of each other, although as expected the side deflections are less than those of the centerline. These results indicate that damage was somewhat greater in the vicinity of the centerline compared to the area away from the centerline where fewer repetitions are applied by the programmed wander of the HVS trafficking pattern.

Figure 3.13 shows the average 60 kN deflection at centerline as well as the averages for measurements taken at the end of the section with more severely cracked DGAC underneath (4CL, 6CL and 8CL) and the end with less severe cracking (10CL and 12CL). The difference in deflections is evident between the two ends. In Figures 3.12 and 3.13, some sensitivity of RSD deflection to temperature is evident, for example at approximately 100,000, 350,000, 750,000, the load change at 1,000,000, and at 1,750,000 repetitions. The influence of temperature on deflection will be discussed in the second-level analysis report. The sensitivity of the RSD to a load reduction is evident in the early phase of 80 kN loading.

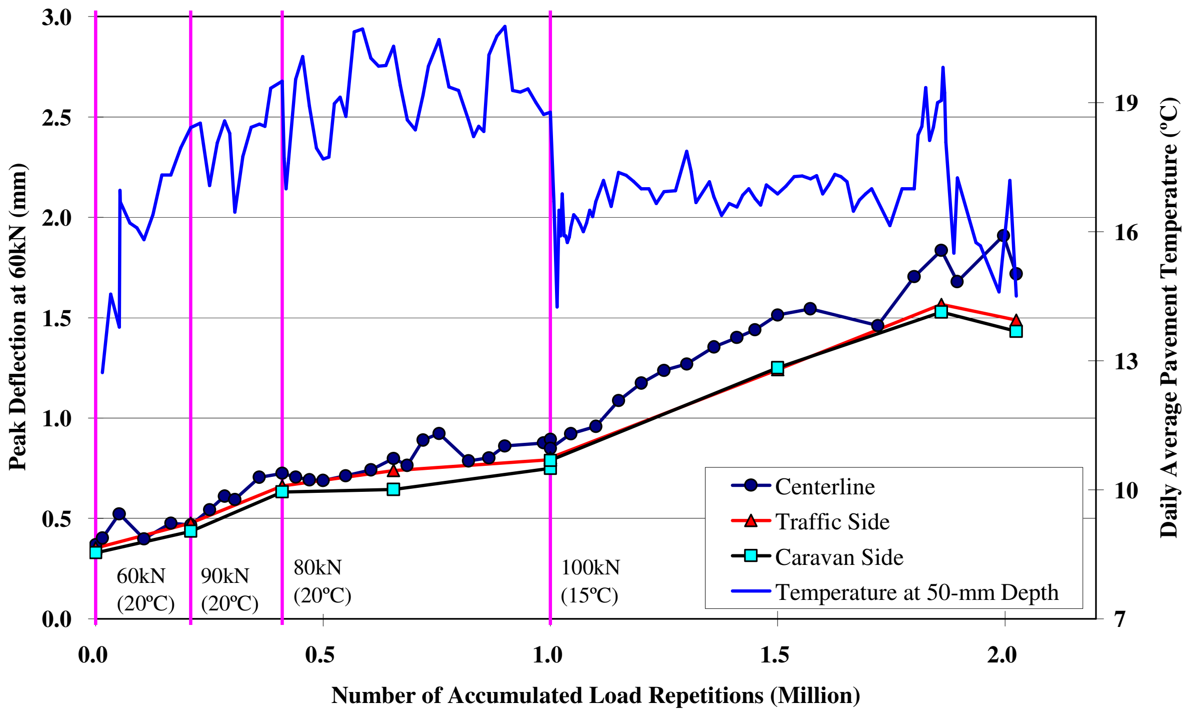

Figure 3.12: Average surface deflections with 60 kN test load (centerline and sides).

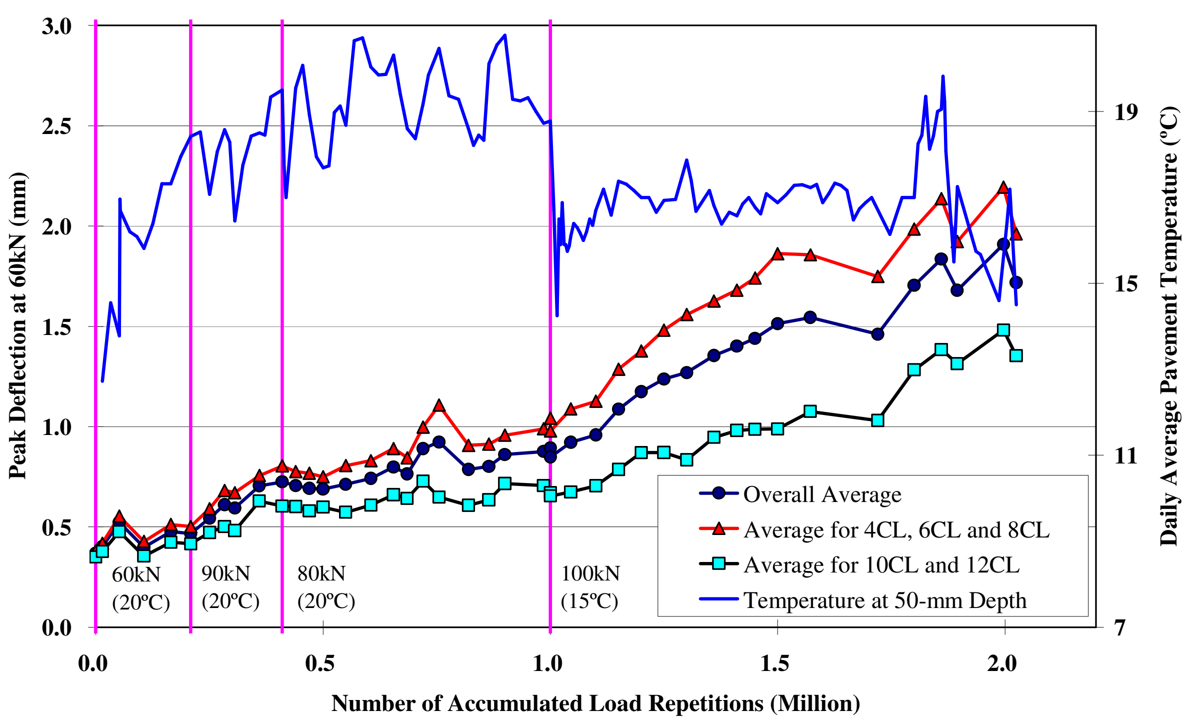

Figure 3.13: Average surface deflections with 60 kN test load (centerline and subsection).

3.3.2 Surface Elastic Deflection Using FWD

FWD testing was conducted on the section before and after HVS trafficking to monitor the changes in layer moduli. Table 3.3 summarizes the date, location, temperatures, and average deflections for the section. Temperatures listed are average temperatures. Recordings from two sensors (1 and 6) and two locations (section centerline and side of section) are shown. Sensor 1 (the sensor directly under the falling weight) provides an indication of the deflection of the composite pavement. Sensor 6 provides an indication of the deflection in the subgrade. Centerline readings show deflection on the trafficked area, while readings from the side of the section are used to compare trafficked and untrafficked areas. Figures 3.14 through 3.18 show the FWD deflection measurements recorded on the section. Note that scales differ between plots. Backcalculation of these results will be discussed in the second-level analysis report.

Table 3.3: Summary of FWD Measurements

Date	Location	Temperatures (°C)		FWD Deflection at 40 kN (microns)[1]			
				Sensor 1		Sensor 6	
		Air	Surface	Average	Std. Dev.	Average	Std. Dev.
After completion of Section 568RF							
2/14/02	Centerline	N/A	17.6	519	17	43	2
Before start of Section 587RF							
2/18/05	Centerline	14.3	18.4	104	10	36	3
2/24/05	Centerline	11.0	14.1	110	6	35	2
2/24/05	Side[2]	11.0	13.2	145	19	51	5
After completion of Section 587RF							
10/19/05	Centerline	14.2	16.8	510	146	47	4
10/19/05	Centerline	18.1	23.9	557	155	48	5
10/19/05	Side	14.5	16.9	162	11	55	3
10/19/05	Side	17.1	20.0	165	5	54	1

[1] Deflections based on measurements between Stations 3 and 13 inclusive
[2] Side location is 1.0 m from the test section, representing untrafficked area

Figure 3.14 shows the effect of damage on the pavement over the course of the experiment. Deflection measured on Section 568RF prior to placing the overlay was relatively high, especially in the area of significant cracking. Placement of the overlay considerably reduced the deflection. However, considerable damage was again caused by the HVS trafficking, with higher damage recorded after the test on parts of the section (Stations 3 through 8) when compared to that after completion of testing on Section 568RF. The overlay provided some structural improvement over the area with less severe cracking (Stations 10 through 13). The figure also shows that deflections were influenced by temperature, with lower deflections measured in the morning (lower temperature) compared to those measured in the afternoon (higher temperature) at the end of the test.

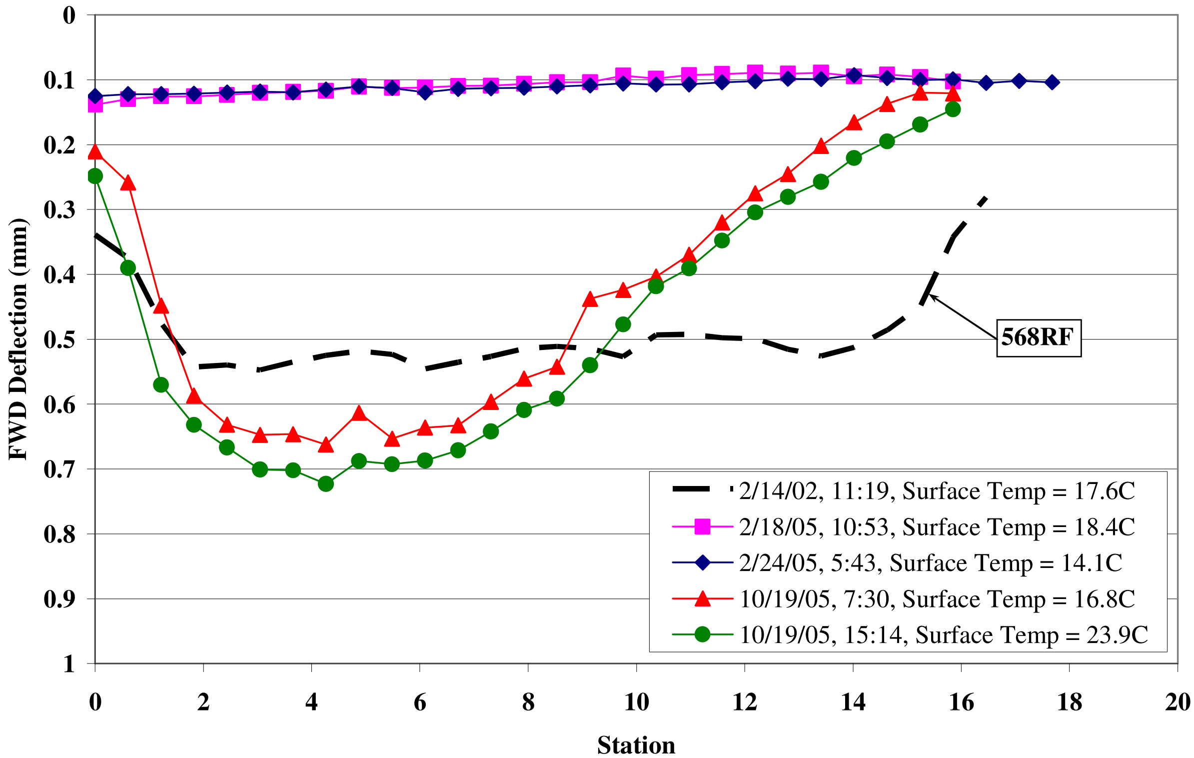

Figure 3.14: Composite pavement stiffness (FWD Sensor 1) on section centerline.

Figure 3.15 shows deflections in the subgrade before and after the test. These measurements indicate that there was no significant change (0.02 mm) during the course of the experiment, and that the overlay did not provide any significant structural improvement to the overall pavement structure in terms of protection of the subgrade. It appears that the subgrade was less stiff at the end of the section that had more cracking in the underlying DGAC (Stations 3 through 8). The slight increase in deflection on completion of the test could be attributed to moisture in the subgrade and/or increased deflections in the upper layers.

Figures 3.16 and 3.17 show FWD deflections taken along the side of the HVS test section but outside the trafficked area (i.e., the area tested did not have traffic damage). These figures can be used to understand the influence of environmental conditions on the performance of the section. The figures show very little change over the course of the experiment. The temperature difference between the two measurements was only 3.1°C and hence little influence of this parameter on deflection was noted.

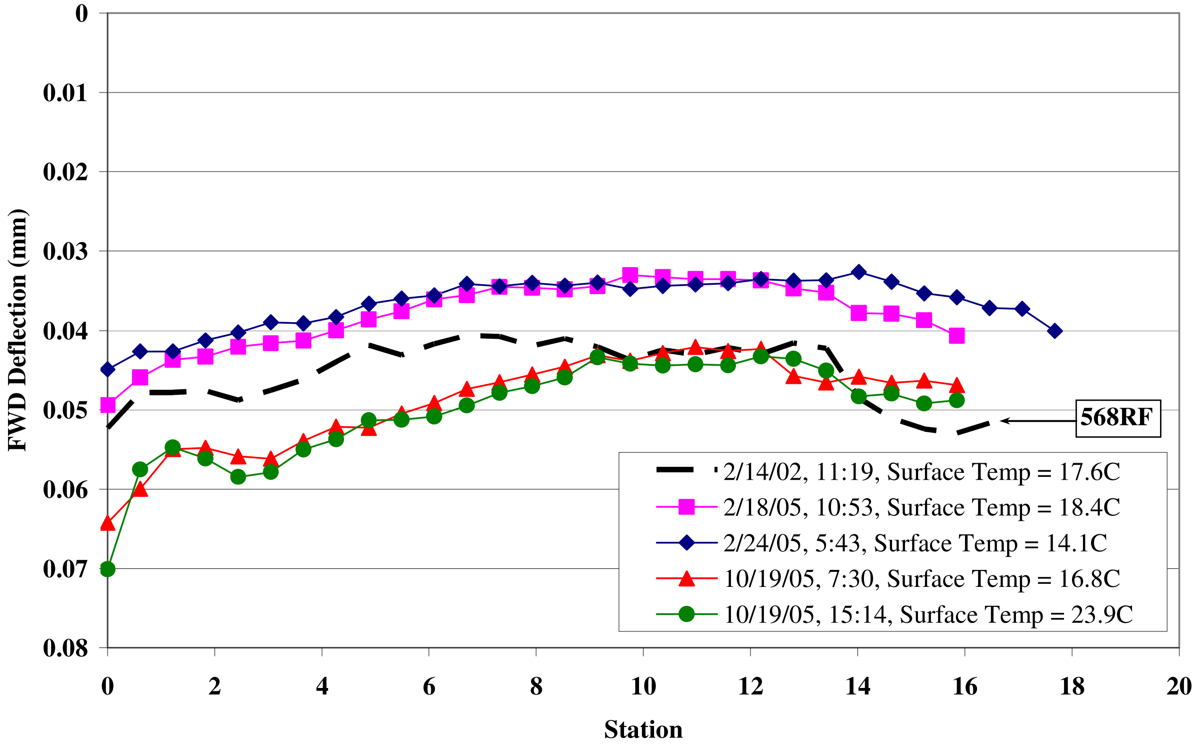

Figure 3.15: Subgrade pavement stiffness (FWD Sensor 6) on section centerline.

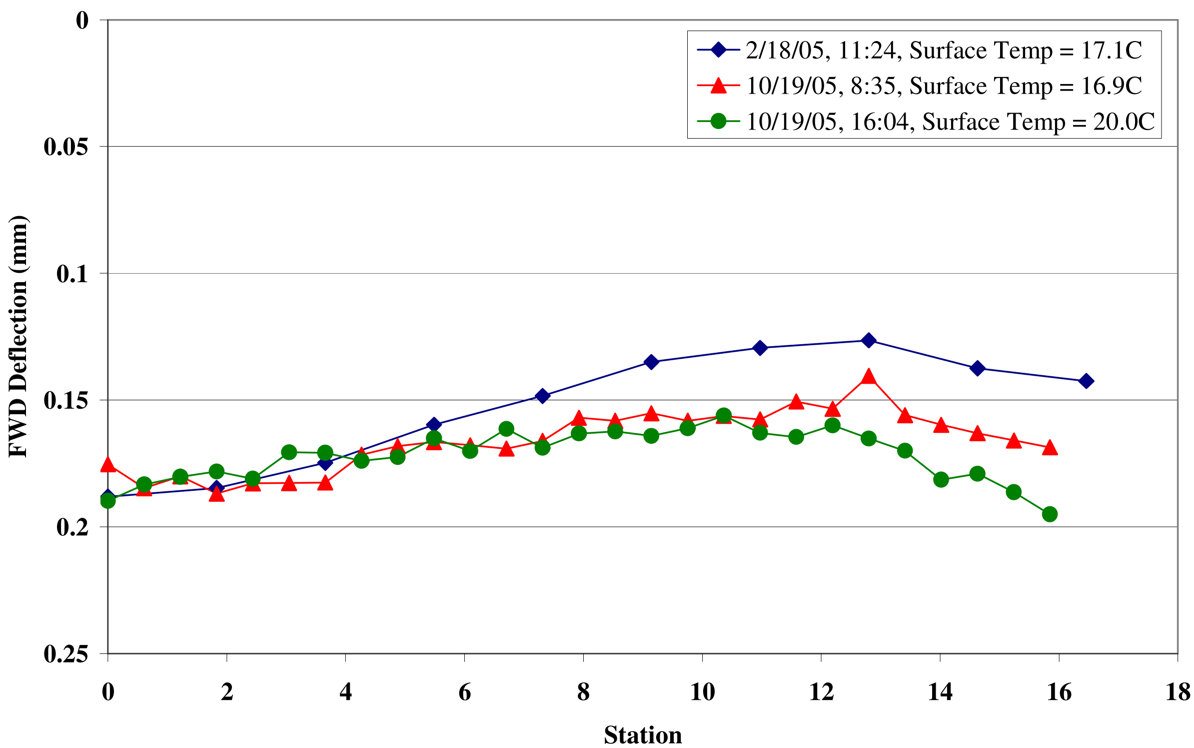

Figure 3.16: Composite pavement stiffness (FWD Sensor 1) outside trafficked area.

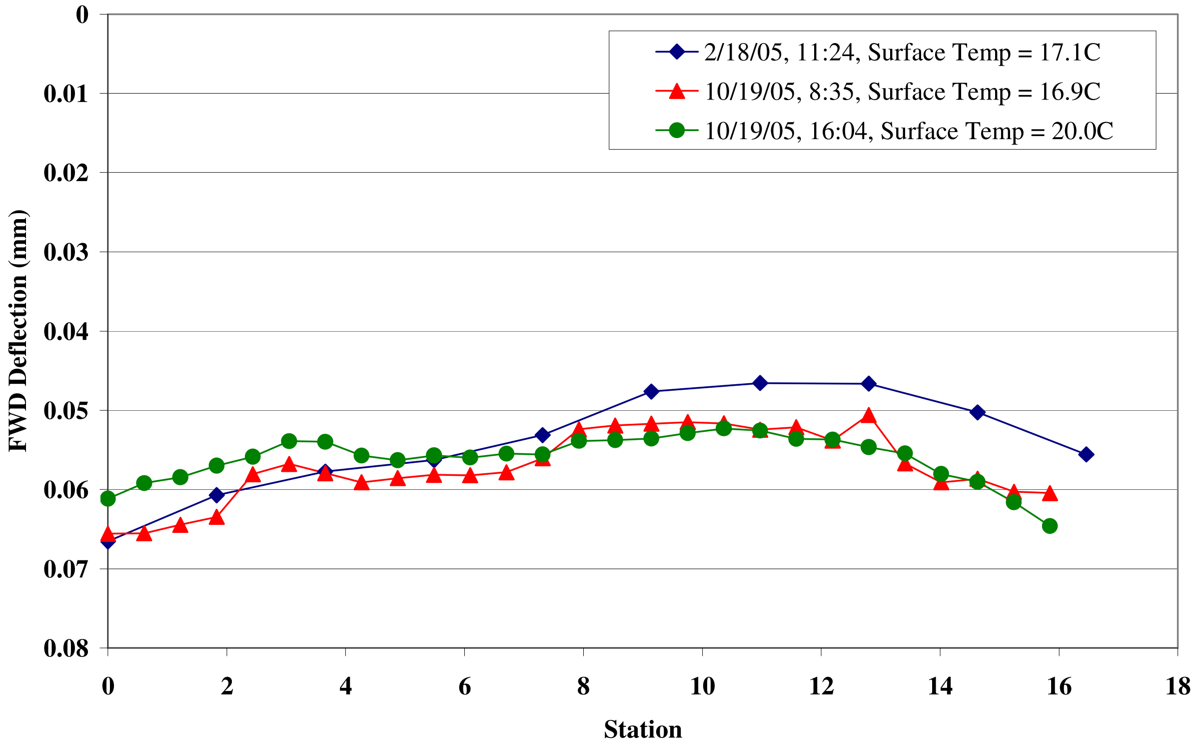

Figure 3.17: Subgrade pavement stiffness (FWD Sensor 6) outside trafficked area.

3.3.3 In-depth Elastic Deflection

The schedule of MDD measurements with various test loads is listed in Table 2.2. Data acquisition and MDD linear variable displacement transducer (LVDT) problems resulted in questionable data being collected at various times through the experiment and specifically at the 90 kN, 80 kN, and 100 kN test loads. The LVDTs are delicate instruments and can not be repaired once installed in the pavement. In line with other reports in this study, the following discussion will focus on results obtained with the 60 kN load only.

Table 3.4 and Figures 3.18 through 3.20 summarize the in-depth elastic deflections measured at various depths with MDD4, MDD8 and MDD12 respectively. The figures include RSD measurements taken on the surface at the same locations as the MDDs. Note that scales differ for each instrument.

Table 3.4: Summary of 60 kN In-depth Elastic Deflections

Depth (mm)	Layer	Elastic Deflection at 60 kN (microns)		
		Before Trafficking	After Trafficking	Ratio of Final/Initial
		MDD4		
0	Surface (from RSD)	370	2,250	6.08
132	Bottom of cracked DGAC	220	N/A	-
337	Middle of aggregate base	180	N/A	-
542	Bottom of aggregate base	160	N/A	-
847	300 mm below top of subgrade	N/A	N/A	-
		MDD8		
0	Surface (from RSD)	390	2,020	5.12
132	Bottom of cracked DGAC	230	1180	5.13
337	Middle of aggregate base	180	N/A	-
542	Bottom of aggregate base	150	1180	7.87
847	300 mm below top of subgrade	50	520	10.4
		MDD12		
0	Surface (from RSD)	340	1,270	3.74
132	Bottom of cracked DGAC	N/A	N/A	-
337	Middle of aggregate base	180	N/A	-
542	Bottom of aggregate base	130	N/A	-
847	300 mm below top of subgrade	N/A	380	-

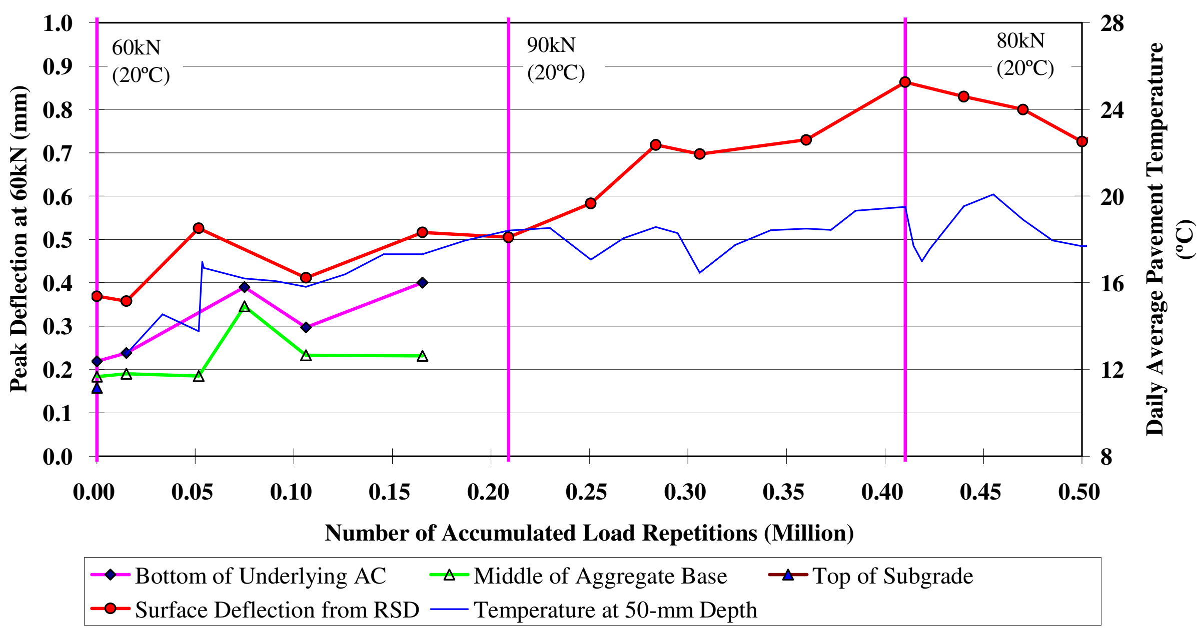

Figure 3.18: Elastic deflections at MDD4 with 60 kN test load.

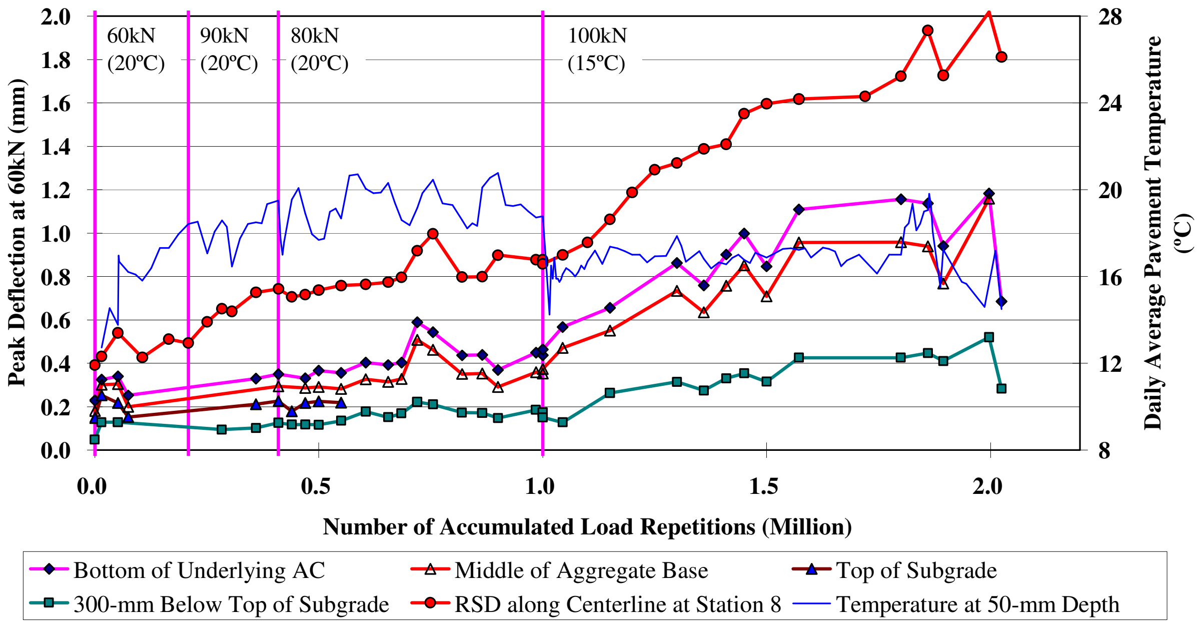

Figure 3.19: Elastic deflections at MDD8 with 60 kN test load.

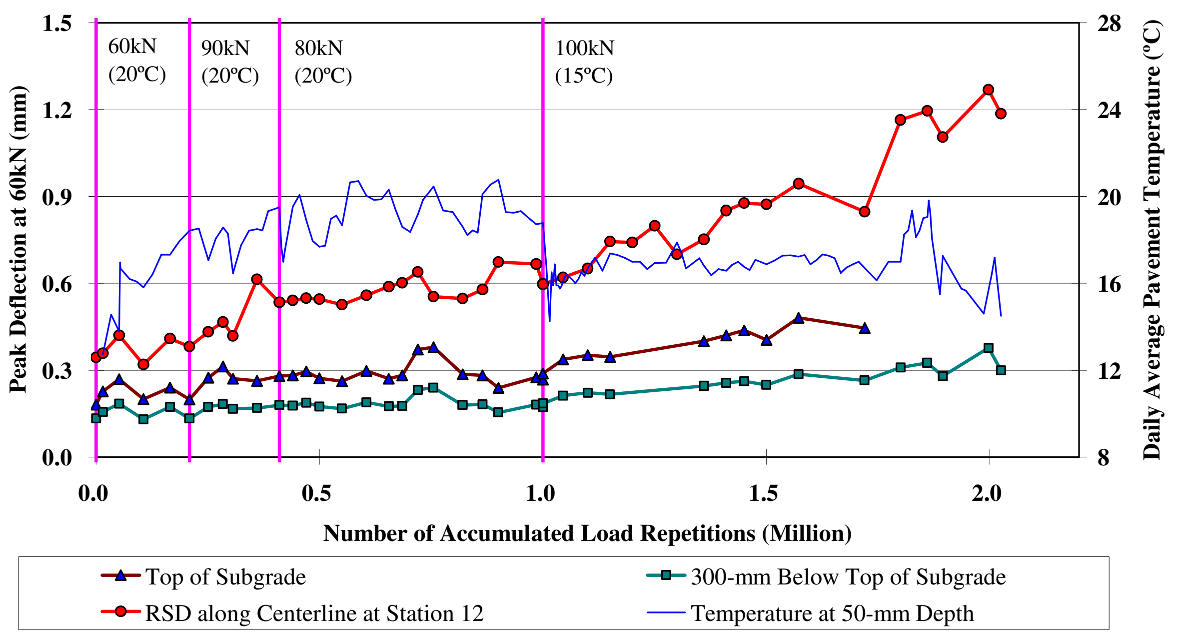

Figure 3.20: Elastic deflections at MDD12 with 60 kN test load.

The following observations were made from the data collected:

- Very little data was collected from MDD4 and hence no observations can be made apart from an early increase in deflection at the beginning of the experiment, which is a typical trend. These early deflections appeared to be sensitive to temperature increase. Surface deflections (measured with the RSD) show the same sensitivity (increasing) to temperature.

- At MDD8 (overlay on area of significant cracking), the damage rate climbs sharply during the early phase of 60 kN trafficking. Part of this damage could be reversal of temporary "healing" in the underlying DGAC that occurred during the absence of trafficking in the approximately 12 months between the Phase 1 and Phase 2 HVS tests. Pavement temperature also increased at the start of the experiment, which would have also influenced the rate of damage. After this initial phase, the rate of damage moderates through the remainder of the 60 kN trafficking phase and through the 90 kN trafficking phase. During the 80 kN trafficking phase, damage rates increase slowly with increasing load repetitions, with some peaks attributed to temperature changes. After the 100 kN load change, damage rates increase more rapidly in the upper layers of the pavement (AC layers and top 200 mm of the aggregate base), but remain relatively constant in the subgrade. Throughout the 100 kN phase, deflections continue to show sensitivity to temperature.
- At MDD12 (overlay over less severe cracking), data was only collected from the surface RSD measurements, the bottom of the aggregate base and 300 mm below the top of the subgrade. Damage rates show similar trends to MDD8, but are not as high.
- The in-depth elastic deflections increase at all depths whenever trafficking loads increase, as expected. Deflections initially decreased during the 80 kN loading phase and then increased with increasing number of repetitions.
- The effect of trafficking load on elastic deformation decreases with increasing depth, as expected. Most of the damage observed appeared to occur in the upper portion of the pavement. This will be verified when test pits are excavated in the section.
- Ratios of final-to-initial MDD deflections show that deflections increased significantly at all depths in the pavement structure by the end of trafficking. The limited data available shows that the final-to-initial deflection ratio is greater for MDD4 and MDD8 compared to MDD12, indicating that the structure nearer the former two instruments endured more damage, in terms of loss of pavement stiffness, than that around MDD12. This loss of stiffness indicates damage in the asphalt concrete layers, which increases shear stresses in the underlying layers.

3.4. Permanent Deformation

Permanent deformation at the pavement surface (rutting) was monitored with the Laser Profilometer and at various depths within the pavement with three Multi-depth Deflectometers (MDDs). These measurements are discussed below.

3.4.1 Permanent Surface Deformation (Rutting)

Deformation and rutting on HVS tests are usually analyzed using two definitions, namely maximum rut depth and maximum deformation (4), as illustrated in Figure 3.21. The Laser Profilometer is used to measure these distresses and provides sufficient information to evaluate the evolution of permanent surface deformation of the entire test section at various loading stages.

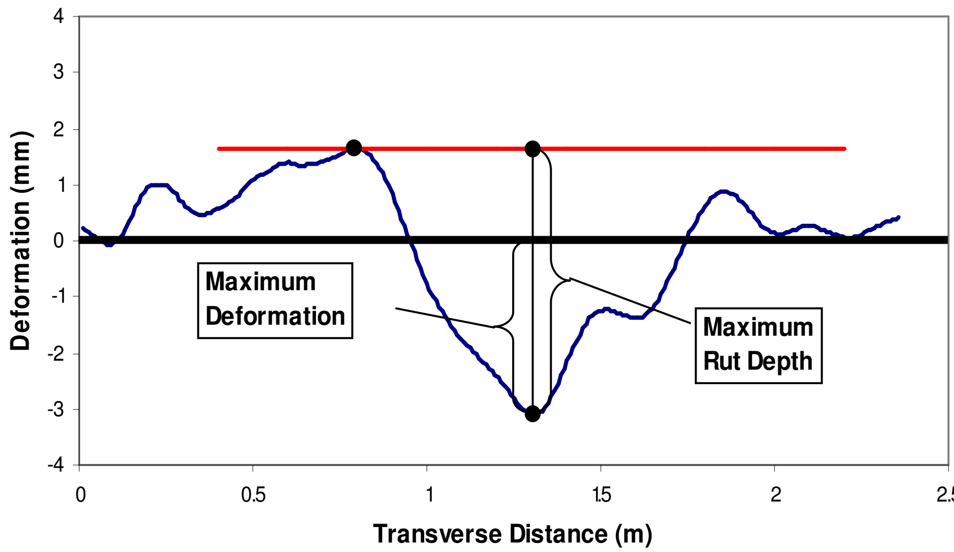

Figure 3.21: Illustration of maximum rut depth and maximum deformation of a leveled profile.

Figure 3.22 shows the average transverse cross section measured with the Profilometer at various stages of the test. This plot clearly shows the increase in rutting and deformation over the duration of the test.

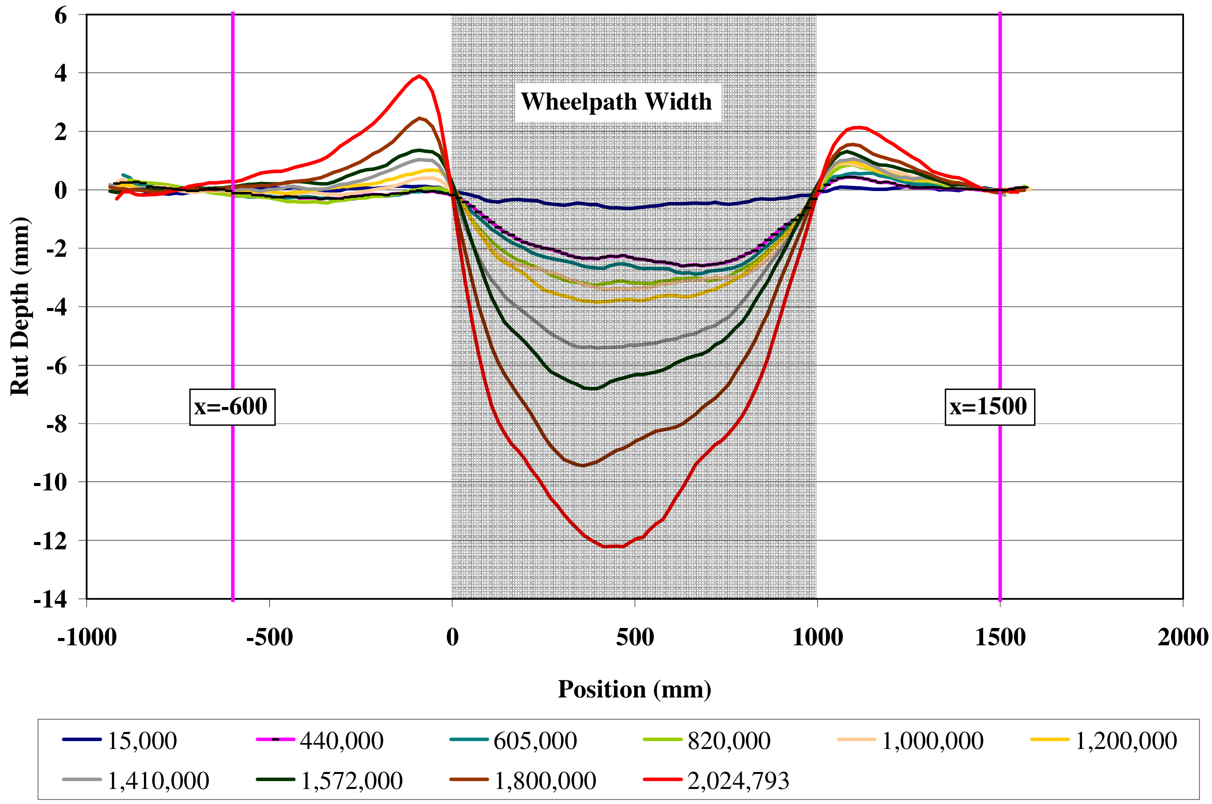

Figure 3.22: Profilometer cross section at various load repetitions.

During HVS testing, rutting usually occurs at a high rate initially and then typically diminishes as trafficking progresses until reaching a steady state. If the load level is subsequently increased, the pavement will normally undergo another phase of rapid rutting development until a steady phase for that new load level is reached. This initial phase is referred to as the "embedment" phase. Figures 3.23 and 3.24 show the development of permanent deformation (maximum deformation and maximum rut, respectively) with load repetitions as determined by the Laser Profilometer for the test section with an embedment phase only apparent at the beginning of the experiment. Rut development is relatively constant until the 100 kN load change, after which it increases at a much higher rate. Error bars on the average reading indicate variation along the length of the section. The figures also show average maximum deformation and average maximum rut for Stations 3 to 8 and 9 to 13. Stations 3 to 8 are over the end of the section where the underlying DGAC was significantly cracked, while Stations 9 to 13 are over the end with less severe cracking. The figures show that deformation and rut are considerably higher over the significantly cracked section.

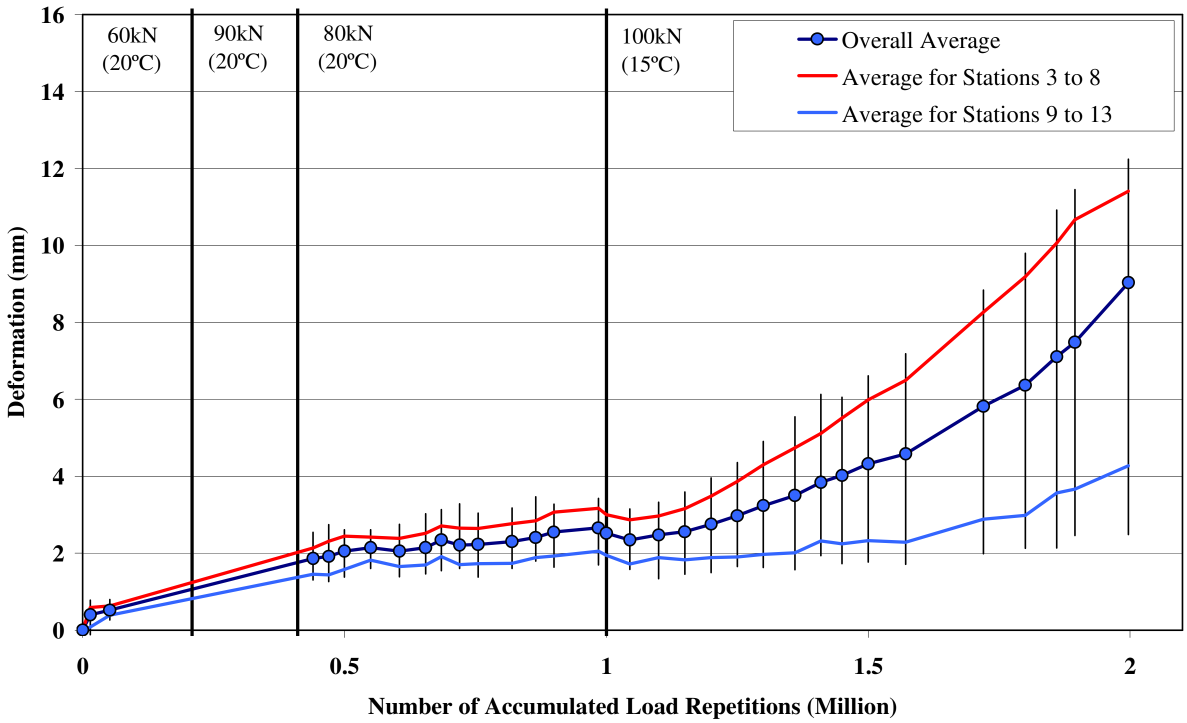

Figure 3.23: Average maximum deformation determined from Laser Profilometer data.

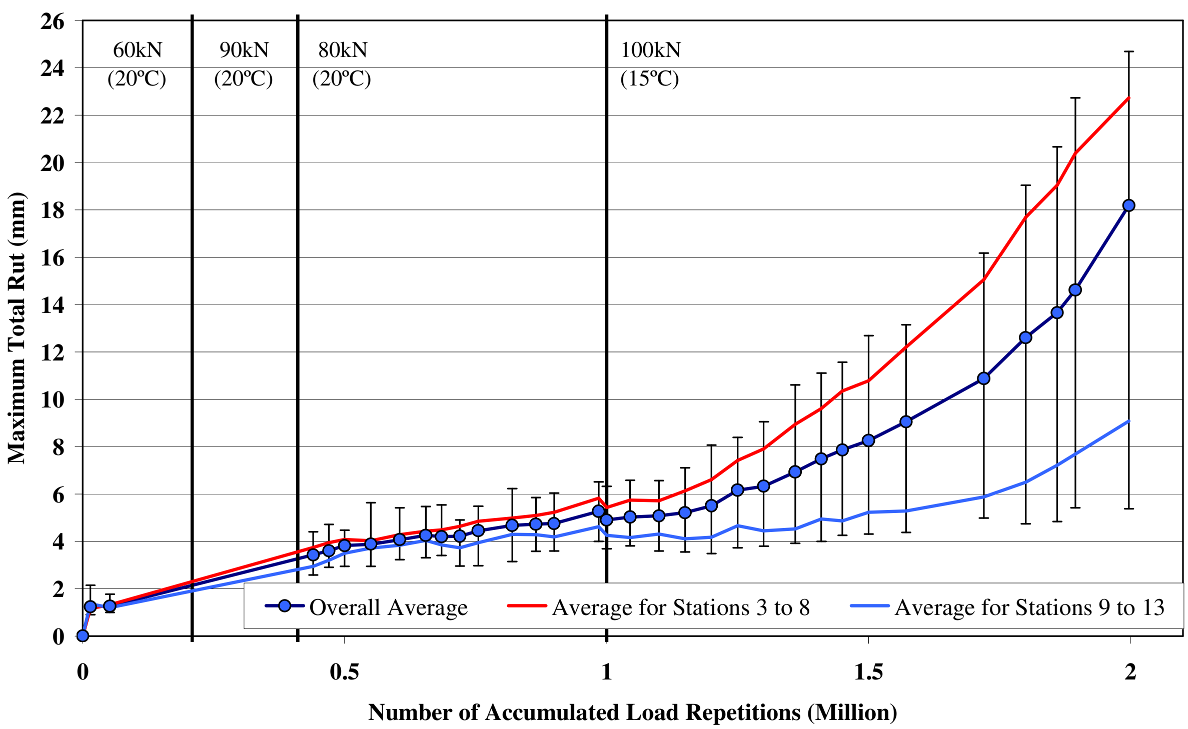

Figure 3.24: Average maximum rut determined from Laser Profilometer data.

Figure 3.25 shows a contour plot of the pavement surface after 50,000 repetitions, when the initial embedment phase had steadied. Figures 3.26 through 3.31 show contour plots of the rutting progression on the surface from 500,000 repetitions up to test completion. The increase in rutting after the 100 kN load change is clearly evident in Figure 3.29 when compared to Figure 3.28.

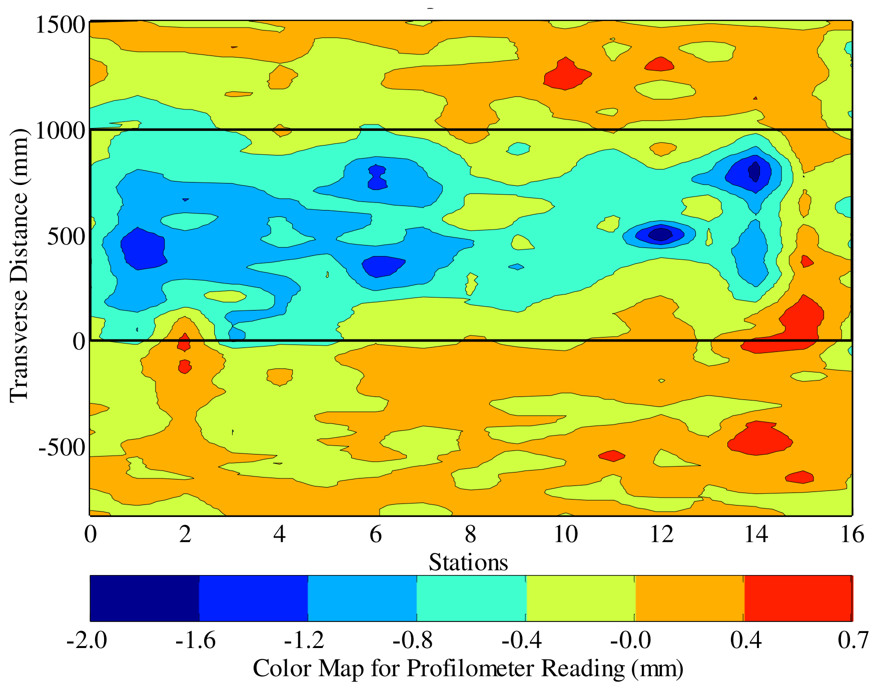

Figure 3.25: Contour plot of permanent deformation after 50,000 repetitions.

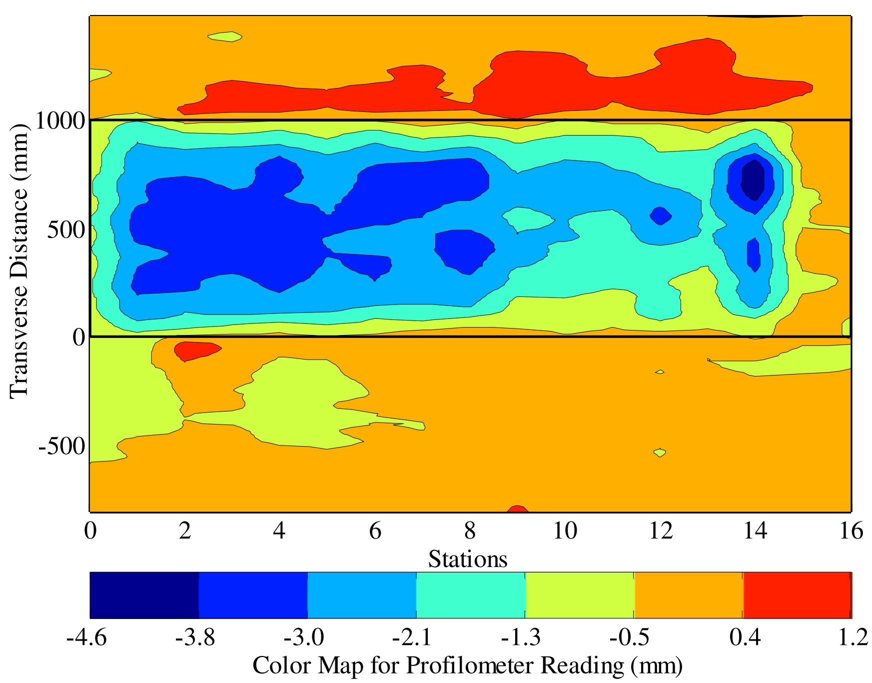

Figure 3.26: Contour plot of permanent deformation after 500,000 repetitions.

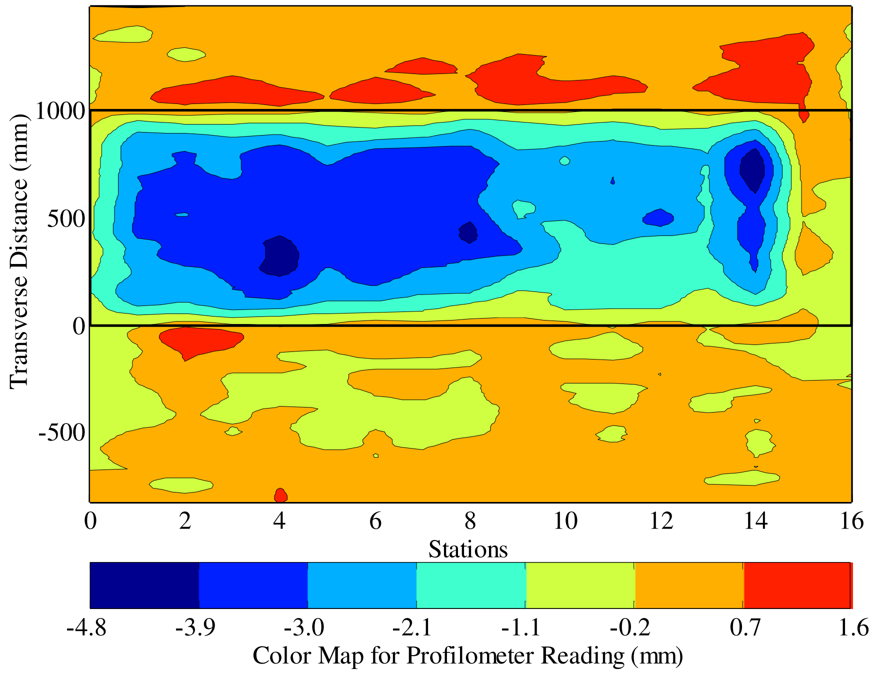

Figure 3.27: Contour plot of permanent deformation after 760,000 repetitions.

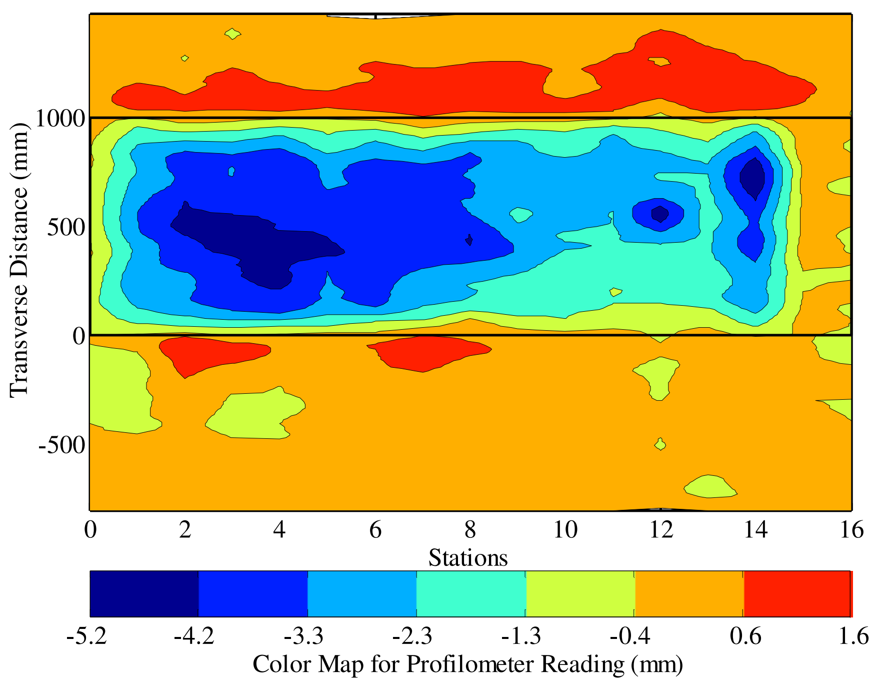

Figure 3.28: Contour plot of permanent deformation after 1,000,000 repetitions.

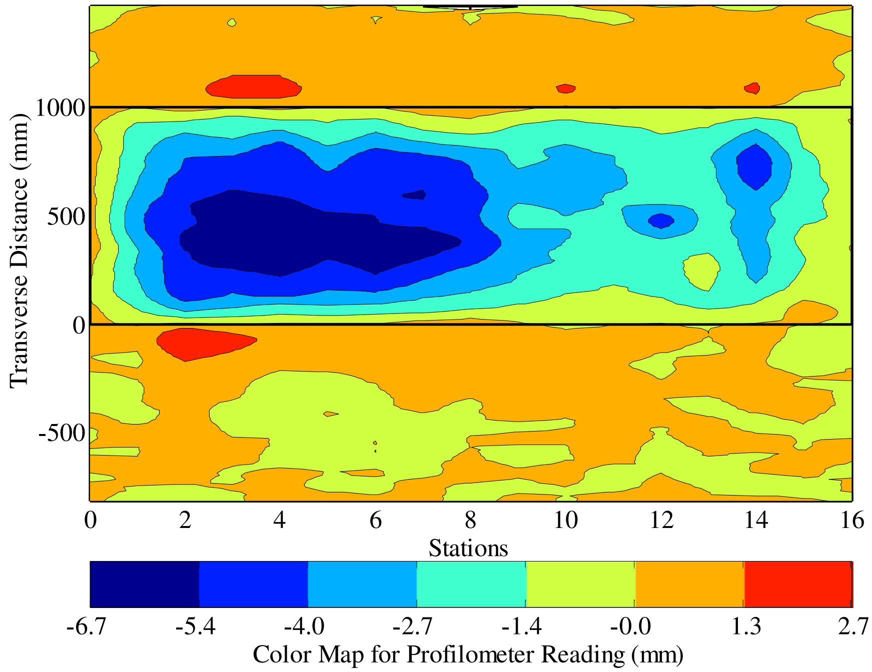

Figure 3.29: Contour plot of permanent deformation after 1,250,000 repetitions.

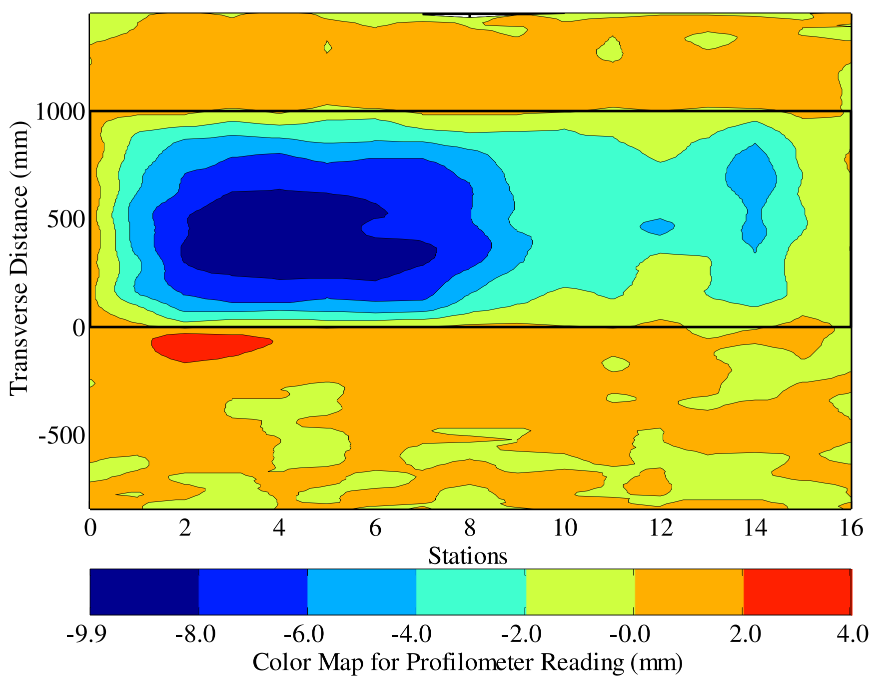

Figure 3.30: Contour plot of permanent deformation after 1,500,000 repetitions.

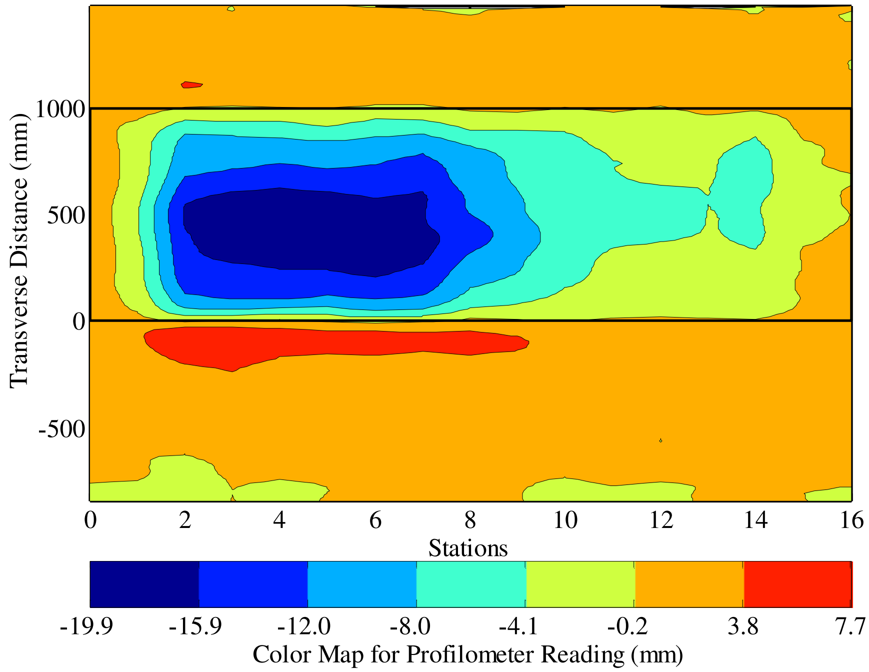

Figure 3.31: Contour plot of permanent deformation after 2,024,793 repetitions.

After completion of trafficking (2.02 million load repetitions), the average maximum deformation and the average maximum rut depth were 12.1 and 16.1 mm, respectively. The maximum rut depth measured on the section was 26.3 mm. Testing was halted after the average maximum rut depth had exceeded 12.5 mm, in line with the failure criteria determined for the experiment. The final surface rutting pattern of the overlay generally corresponds with the fatigue cracking pattern of the cracked DGAC layer as shown in Figure 3.32, with the deepest rut occurring on that half of the section with the highest density of cracking in the underlying layer.

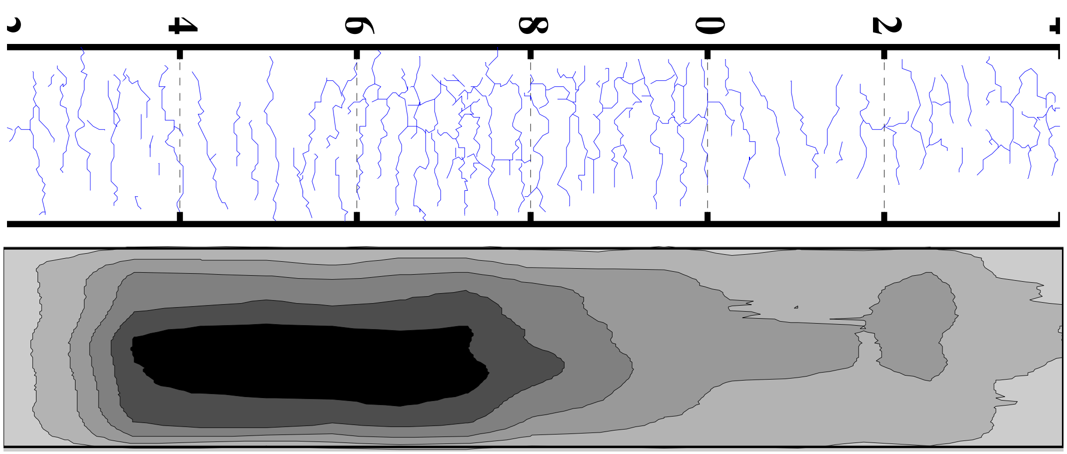

Figure 3.32: Comparison of cracking pattern from Phase 1 and rutting in Phase 2.

3.4.2 Permanent In-depth Deformation

The accumulation of vertical deformation at various depths in the pavement was measured with the MDD linear variable displacement transducer (LVDT) modules during the course of the HVS test. Permanent deformation measured by each LVDT is the total permanent deformation of the pavement between the anchoring depth (3.0 m) and the depth of the module. Accordingly, LVDT modules in the upper part of the pavement typically measure larger permanent deformation than those in the lower part. The difference in measured permanent deformation between two LVDT modules represents the permanent deformation accumulated in the layers between those two modules. This is known as differential permanent deformation. Module locations are shown in Figure 2.6 and are listed below.

- 132 mm: near the bottom of the cracked DGAC layer,
- 337 mm: in the middle of the aggregate base layer
- 542 mm: at the bottom of the aggregate base layer
- 842 mm: 300 mm below the top of the subgrade

A module was not installed on the surface of the RAC-G overlay due to thickness constraints. Data from MDD4 were considered unreliable and were not used for analysis purposes.

Table 3.5 and Figures 3.33 to 3.36 provide an indication of the permanent deformation recorded at MDD8 and MDD12 respectively. Figures 3.33 and 3.35 show permanent deformation at the MDD modules, while Figures 3.34 and 3.36 show the permanent deformation calculated for the various layers. As some of the modules did not operate for parts of the experiment, no firm conclusions can be drawn about the permanent deformation and a better understanding of it on the section will be obtained only after excavation and assessment of the test pit.

For the first one million repetitions, most permanent deformation at MDD8 and MDD12 occurred in the overlay and cracked DGAC layers, with very little permanent deformation in the aggregate base and in the subgrade. At the 100 kN load change, permanent deformation at the bottom of the asphalt concrete layers at both MDDs was approximately 0.5 mm. After the load change, permanent deformation increased at a continuous rate in the surfacing layers (surface deformation measured with the Laser Profilometer minus deformation measured at the 132 mm MDD module) and the upper part of the aggregate base (deformation at the 542 mm module minus deformation at the 132 mm module) at both MDDs, but with the rate of increase significantly higher at MDD8 (area of the section overlying the significantly cracked DGAC) than at MDD12. This is attributed to the more severe cracking of the underlying DGAC in the vicinity of MDD8 compared to that around MDD12. On completion of testing, permanent deformation in the surfacing layers and upper part of the aggregate base at MDD8 was approximately double that at MDD12. Although the data from the subgrade modules is suspect, there appears to have been very little permanent deformation in this layer at either MDD, with only a marginal increase (1.0 mm) recorded after the 100 kN load change at MDD8. These trends confirm that the effect of increasing wheel load on permanent deformation diminishes with depth in the pavement structure. The planned forensic investigation will confirm these findings and will be reported on in the second-level analysis report.

Table 3.5: Vertical Permanent Deformation in Pavement Layers

Layer	Thickness (mm)	Vertical Permanent Deformation (mm)		Percentage Total Deformation (%)	
		MDD8	MDD12	MDD8	MDD12
After 1,000,000 load repetitions					
Surface (Profilometer)	-	3.7	3.5	86	88
Bottom of cracked DGAC	135	0.3	0.4	7	10
Upper aggregate base	205		Not measured		Not determined
Lower aggregate base	205	0.2	Not measured	5	Not determined
Top 300 mm of subgrade	300	0.1	0.1	2	2
Subgrade to anchor	2,158	Not measured	Not measured	Not determined	Not determined
Total (AC+base)	3,000	0.6	Not determined	100	100
After 2,024,793 load repetitions (test completion)					
Surface (Profilometer)	-	6.0	3.6	29	49
Bottom of cracked DGAC	135	7.7	3.8	38	51
Upper aggregate base	205	5.7	Not measured	28	Not determined
Lower aggregate base	205		Not measured		Not determined
Top 300 mm of subgrade	300	1.0	0.0	5	0
Subgrade to anchor	2,158	Not measured	Not measured	Not determined	Not determined
Total (AC+base)	3,000	14.4	Not determined	100	100

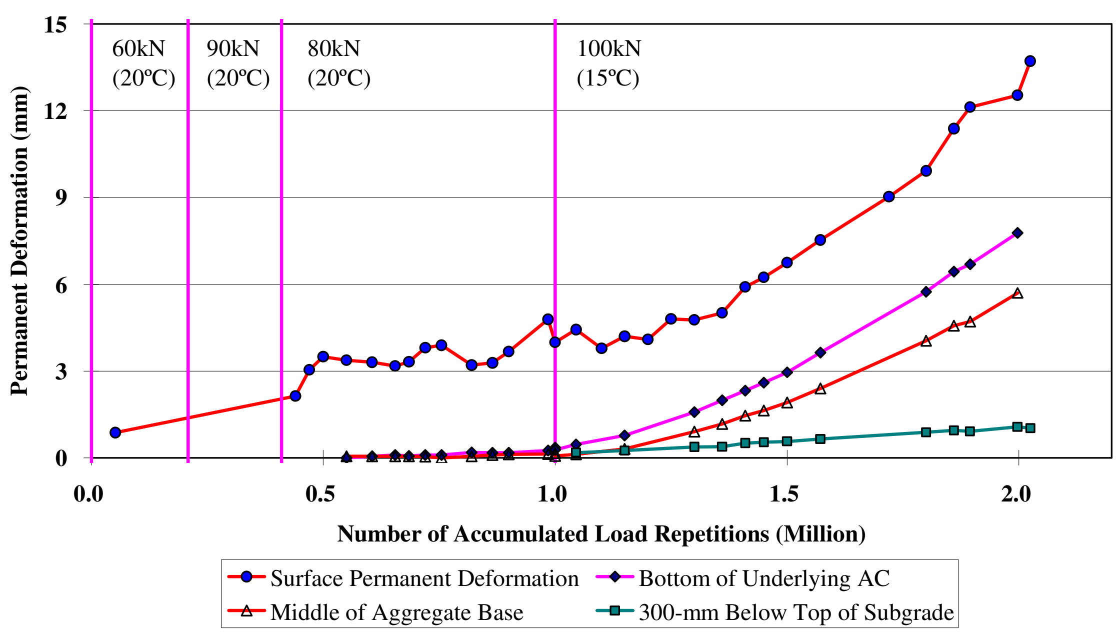

Figure 3.33: In-depth permanent deformation at MDD8.

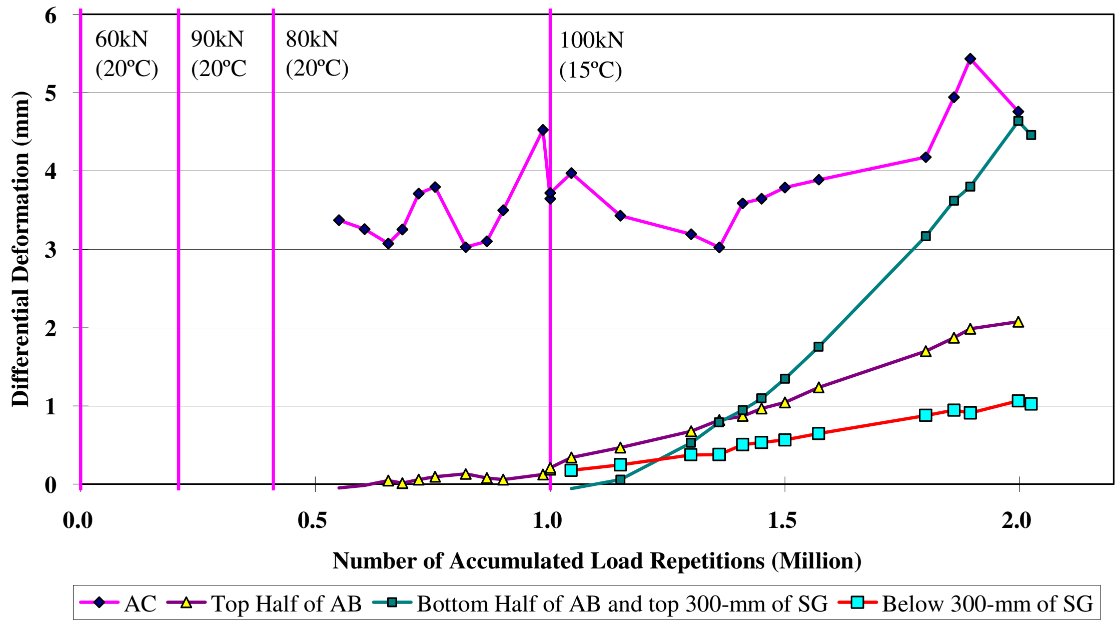

Figure 3.34: In-depth differential deformation at MDD8.

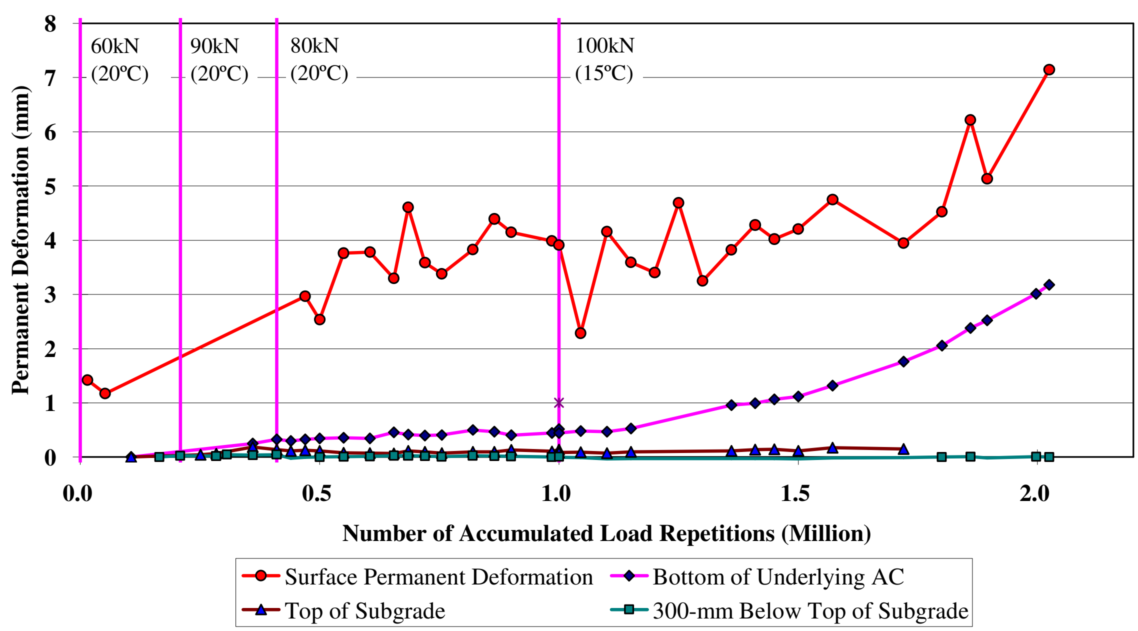

Figure 3.35: In-depth permanent deformation at MDD12.

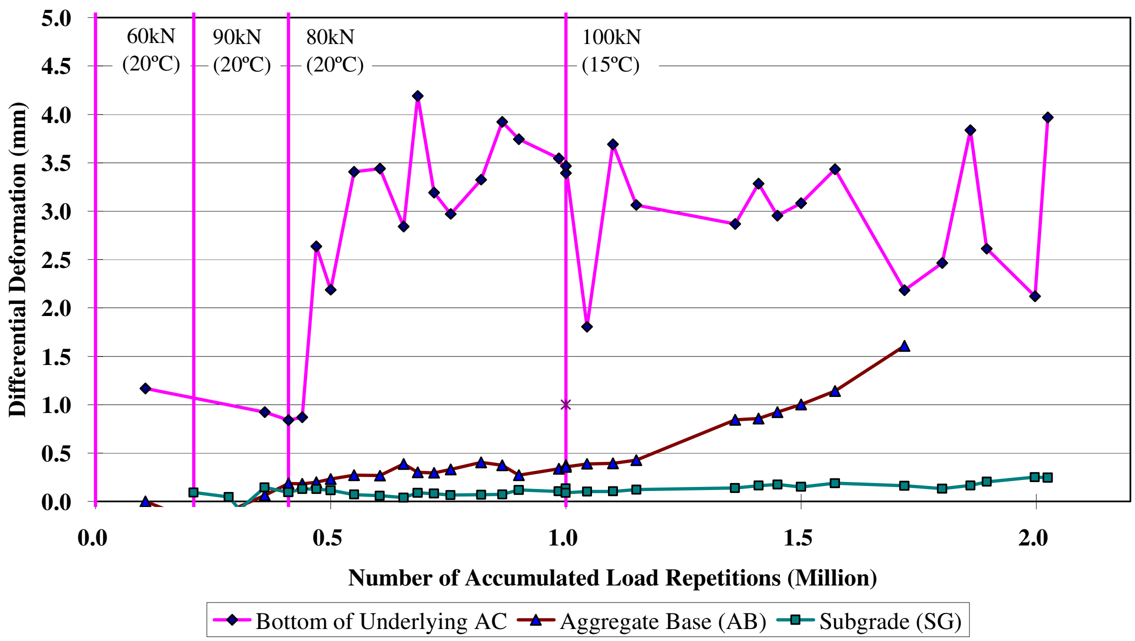

Figure 3.36: In-depth differential deformation at MDD12.

3.5. Visual Inspection

Fatigue distress in an asphalt concrete pavement manifests itself in the form of surface cracks. Since this study centered on fatigue cracking and the ability of the overlay to limit reflective cracking from the underlying layer, crack monitoring was an essential component of the data collection program. This entails:

- Visual inspections of the test section and marking of visible cracks,
- Photographic documentation of the marked cracks,
- Correction of the photos for camera angle,
- Digitization of the photos,
- Calculation of the crack length using *Optimas*™ software, and
- Presentation of the cracking in terms of crack length per area of pavement.

Regular crack inspections were made from the time that the first crack was detected through to the end of testing. The first cracks appeared around the MDD top caps after about 1.5 million repetitions. The first cracks not associated with instrumentation appeared shortly after and then continued to appear throughout the remainder of the trafficking. The observed cracks were less than 1.0 mm wide and difficult to detect visually. The cracks did not spall or increase in width during testing. Most cracking was transverse as with the underlying layer. At the end of testing, 21 transverse cracks were identified with a total length of 25.09 m and an average spacing of 200 mm. This equates to a crack density of 3.58 m/m^2, which exceeds the failure criterion of 2.5 m/m^2 set for the experiment, reached after approximately 1.9 million repetitions. Figure 3.37 shows the last photograph taken of the surface between Stations 7 and 8.

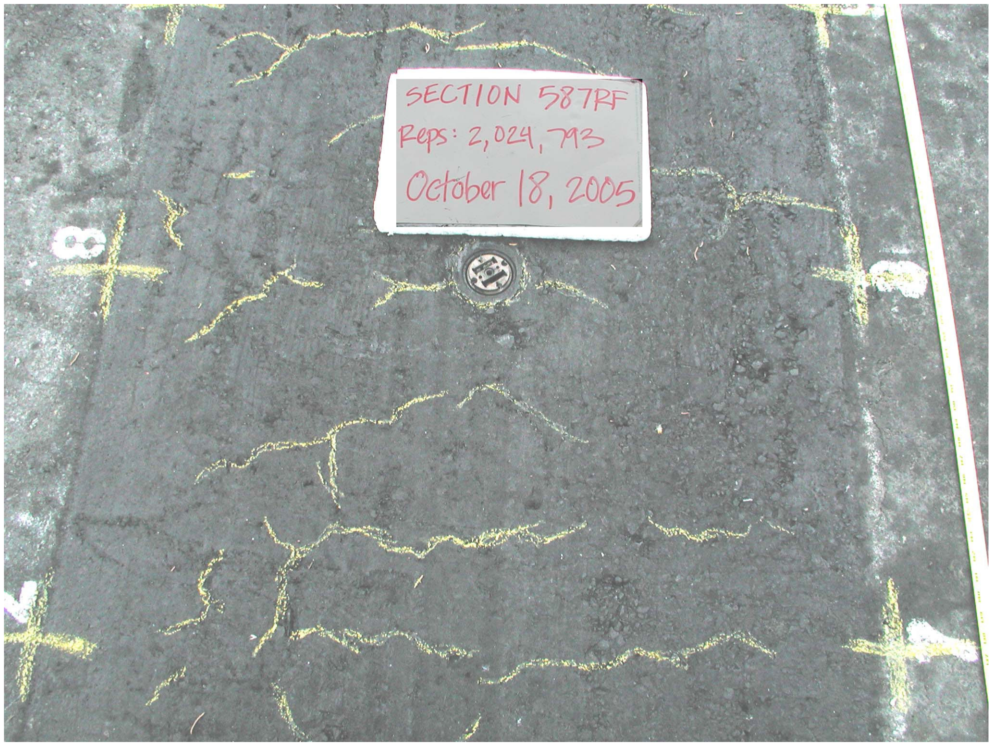

Figure 3.37: Surface cracks marked with crayon between Stations 7 and 8 at end of test.

Figure 3.38 illustrates the sequence of surface crack patterns at various load applications. In some instances, cracks marked in one inspection did not appear in the following inspection. This is attributed to the difficulty of identifying the very thin cracks on the dark asphalt concrete surface and to the accumulation of rubber on the surface during trafficking. Despite this, the data collected is considered to provide a satisfactory representation of surface cracking development.

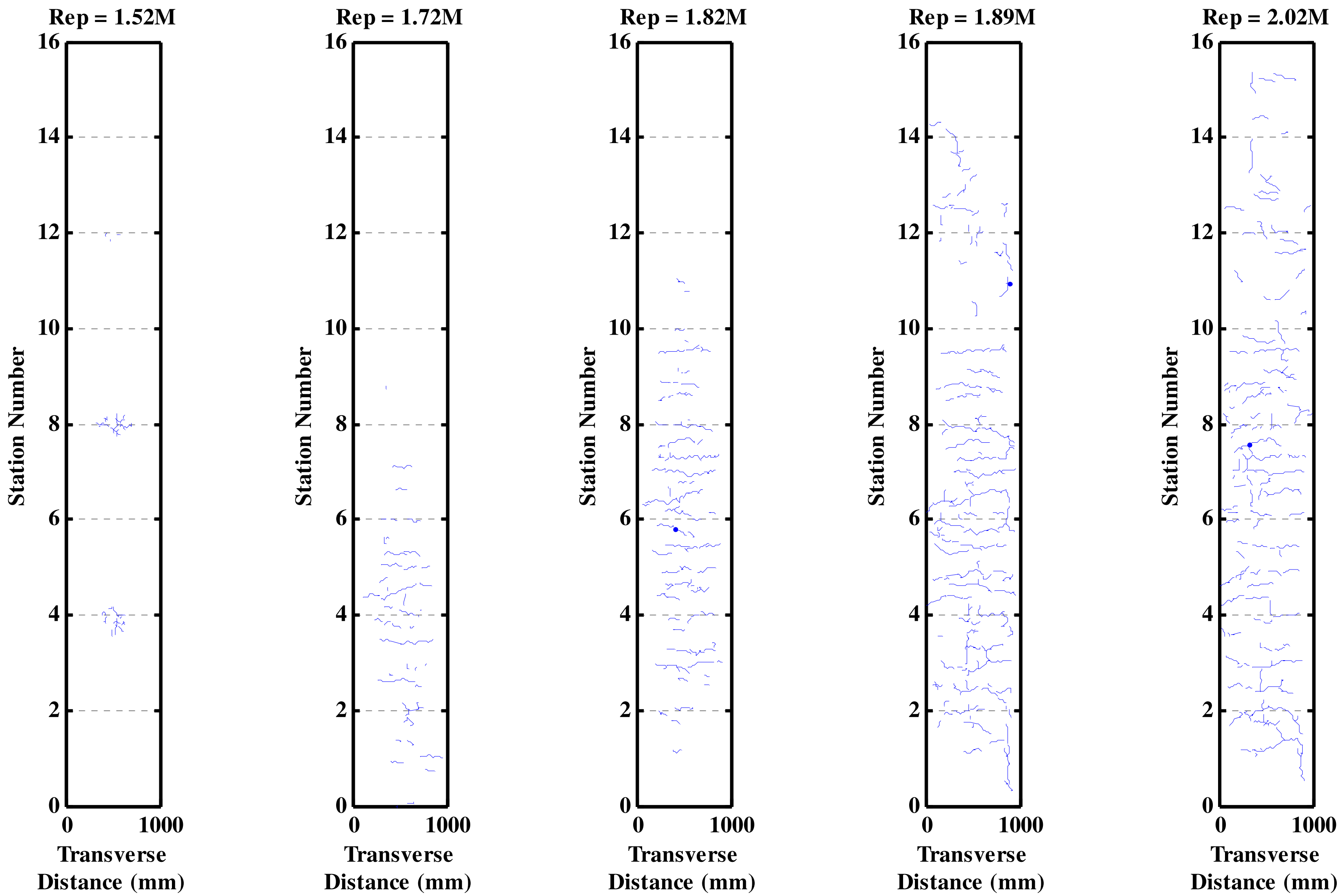

Figure 3.38: Crack development between 1.52 million repetitions and test completion.

Figure 3.39 compares the cracking on Section 587RF with that on the underlying Section 568RF. The cracks do not match exactly, but provide an indication of reflection from the underlying layer. The areas of severe cracking in the underlying layer are matched in the overlay, specifically between Stations 6 and 10.

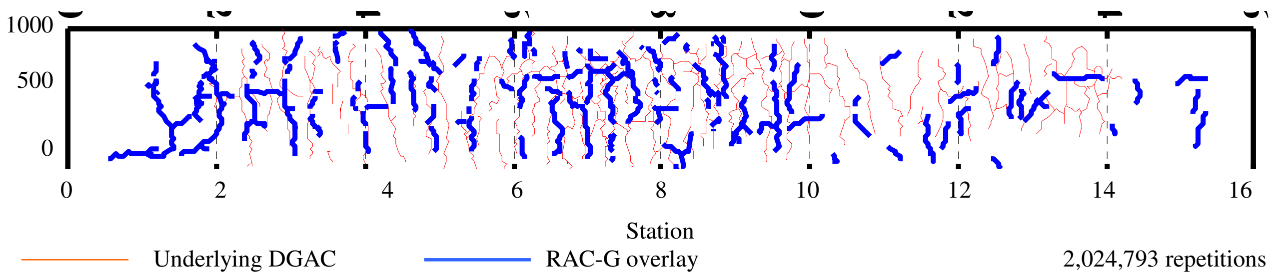

Figure 3.39: Cracking pattern comparison between underlying layer and overlay.

Further analysis of the cracks indicated that the crack accumulation history can be fitted reasonably well with the following exponential function (Figure 3.40):

$$CD = 0.0001^{5.2209N} \qquad \textbf{Equation 3.1}$$

Where: CD is the crack density in m/m^2
N is the number of accumulated load repetitions in millions.

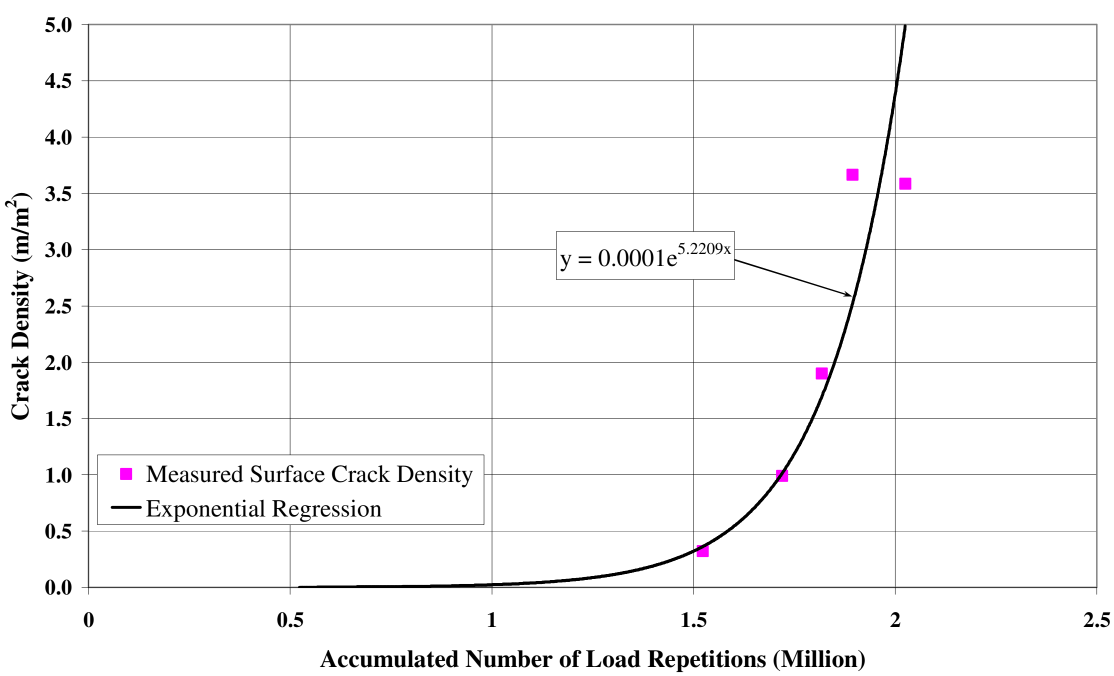

Figure 3.40: Crack accumulation with trafficking.

3.6. Forensic Evaluation

A forensic evaluation (coring and test pit) can only be undertaken when HVS testing on all of the six sections has been completed. Results of the forensic evaluation will be discussed in a second-level analysis report on completion of the tests.

3.7. Second-level Analysis

A second-level analysis report will be prepared on completion of all HVS testing and a forensic evaluation. This report will include:

- Actual layer thicknesses,
- Backcalculation of moduli from RSD, MDD, and FWD measurements,
- Verification of data collected from in-depth measurements with visual observations from test pits,
- Comparison of performance between test sections,
- Comparisons of HVS test results with laboratory test results, and
- Recommendations.

4. CONCLUSIONS

This First-level Report is the third in a series of studies detailing the results of HVS testing being performed to validate Caltrans overlay strategies for the rehabilitation of cracked asphalt concrete. It describes the results of the third HVS reflective cracking testing section, designated 587RF, carried out on a 45 mm (1.7 in) half-thickness RAC-G overlay, included in the experiment as a control for performance comparison purposes. Other overlays that will be tested during the course of the experiment include:

- Half-thickness (45 mm) MB4 gap-graded overlay (45 mm MB4-G);
- Full-thickness (90 mm) MB4 gap-graded overlay (90 mm MB4-G);
- Half-thickness (45 mm) MB4 gap-graded overlay with minimum 15 percent recycled tire rubber (MB15-G);
- Half-thickness (45 mm) MAC15TR gap-graded overlay with minimum 15 percent recycled tire rubber (MAC15-G), and
- Full-thickness (90 mm) AR4000-D overlay, included as a control for performance comparison purposes.

The pavement was designed according to the Caltrans Highway Design Manual Chapter 600 using the computer program *NEWCON90*. Design thickness was based on a subgrade R-value of 5 and a Traffic Index of 7 (~121,000 ESALs). The overlay thickness was determined according to Caltrans Test Method (CTM) 356 using Falling Weight Deflectometer (FWD) deflections.

HVS trafficking on the section commenced on March 15, 2005, and was completed on October 10, 2005. A temperature chamber was used to maintain the pavement temperature at 20°C±4°C (68°F±7°F) for the first one million repetitions, then at 15°C±4°C (59°F±7°F) for the remainder of the test. A total of 2,024,793 load repetitions (tire pressure of 720 kPa [104 psi], and bi-directional trafficking pattern with wander) were applied during this period consisting of:

- 208,896 repetitions of a 60 kN (13,500 lb) half-axle load,
- 201,359 repetitions of a 90 kN (20,250 lb) load,
- 589,745 repetitions of an 80 kN (18,000 lb) load, and
- 1,024,793 repetitions of a 100 kN (22,500 lb) load.

This loading equates to approximately 66 million equivalent standard axles, using the Caltrans conversion of $(\text{axle load}/18000)^{4.2}$, which in turn equates to a Traffic Index of 15.

Testing was interrupted during a breakdown between March 30 and April 26, 2005, when the cumulative traffic repetitions were approximately 51,733 and for temperature conditioning between June 28 and July 2, 2005, at the 100 kN (22,500 lb) load change when the cumulative traffic repetitions were one million.

Laboratory fatigue and shear studies have been conducted in parallel with HVS testing. Results of these studies will be detailed in separate reports. Comparison of the laboratory and test section performance, including the results of a forensic investigation to be conducted when all testing is complete, will be discussed in a second-level report once the data from each of the studies have been collected.

Findings and observations based on the data collected during this HVS study include:

- Cracking was first observed after approximately 1.5 million repetitions. On completion of testing, the surface crack density was 3.6 m/m^2 (1.10 ft/ft^2), considerably lower than the 5.4 m/m^2 (1.65 ft/ft^2) recorded after 377,556 repetitions on the underlying layer during Phase 1 trafficking. The surface crack density reached 2.5 m/m^2 (0.76 ft/ft^2), the failure criterion set for the experiment, after about 1.9 million load repetitions. Cracking on the overlay was predominantly transverse, as was that on the underlying layer. The crack patterns of the two layers did not match exactly, however, the areas of most severe cracking corresponded.
- The average maximum rut depth across the entire test section at the end of the test was 18.2 mm (0.7 in), which was higher than the failure criterion of 12.5 mm (0.5 in) set for the experiment, reached after approximately 1.8 million repetitions. The maximum rut depth measured on the section was 26.3 mm (1.1 in). The rate of rutting was relatively slow during the early part of the experiment, but increased significantly after the 100 kN (22,500 lb) load change, despite the pavement temperature being reduced to 15°C±4°C (59°F±7°F). The average maximum rut depth across the entire test section at the end of the test was 18.2 mm, which was higher than the failure criterion of 12.5 mm set for the experiment, reached after approximately 1.8 million repetitions.
- Both of the failure criteria set for the experiment were reached within 100,000 load repetitions of each other.
- Ratios of final-to-initial elastic surface deflections under a 60 kN (13,500 lb) wheel load increased by between 3.4 and 5.5 times along the length of the section. The ratios for in-depth deflections show that damage had increased significantly at all depths in the pavement structure by the end of trafficking. The limited data available shows that loss of stiffness in the section was highest in the area of most severe cracking in the underlying layer.
- Analysis of surface profile and in-depth permanent deformation measurements indicate that most of the permanent deformation occurred in the asphalt-bound surfacing layers (overlay and cracked

DGAC) with approximately twice as much damage occurring in the area of most severe cracking in the underlying DGAC layer. Permanent deformation was also recorded in the upper part of the aggregate base in this area. Negligible deformation was recorded in the subgrade.

No recommendations as to the use of the modified binders in overlay mixes are made at this time. These recommendations will be included in the second-level analysis report, which will be prepared and submitted on completion of all HVS and laboratory testing.

5. REFERENCES

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