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ACCELERATED TESTING FOR STUDYING PAVEMENT DESIGN AND PERFORMANCE (FY 99)

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16 **Abstract**

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Four mixes were tested in this experiment. These are denoted as follows:

Mix 1: a standard KDOT Marshall-type mix, BM-2C
Mix 2: a Superpave mix SM-2A with 20% sand
Mix 3: a Superpave mix SM-2A with 30% sand
Mix 4: a Superpave mix SM-2A with 15% sand

By comparing the final rutting at the end of 80,000 load repetitions of a dual tandem axle of 150 kN (34 kips), it was observed that, except for the mix with 30% sand, Superpave mixes show less rutting less than the Marshall mix. The best performing mix of all the four sections tested is Mix 2, indicating that 20% ratio is the optimum sand content in these Superpave mixes. On the other hand, 30% ratio is the worst sand content and resulted in the most rutting (unacceptable, more than one inch).

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Final Report on

Accelerated Testing for Studying Pavement Design and Performance (FY 99)

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July 2000

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Acknowledgments

The research experiment described in this report was selected, designed, and monitored by the members of the Midwest States Accelerated Testing Pooled Fund Technical Committee. The committee includes Mr. Andrew Gisi, Kansas Department of Transportation (KDOT), Chair, Mr. George Woolstrum, Nebraska Department of Roads (NDOR), Mr. Tom Keith, Missouri Department of Transportation (MDOT), and Mr. Mark Dunn (Iowa DOT). Their help, input, and support are acknowledged. The efforts of Mr. Richard McReynolds (KDOT) in administrating both the contract and the Technical Committee activity are appreciated.

The research idea of varying the river sand ratio in Superpave mixes was initially proposed by Dr. Mustaque Hossain, Associate Professor of Civil Engineering at KSU, in consultation with Mr. Glenn Fager from KDOT, as a K-TRAN pre-proposal. Consequently, the strain gauges, pressure cells, and thermocouples associated with this research experiment were purchased with funds from the K-TRAN:KSU-98-2 project entitled “Pilot Instrumentation of a Superpave Test Section at the Kansas Accelerated Testing Laboratory.” Dr. Hossain was the principal investigator and Mr. Zhong Wu was the graduate student for that project. Mr. Fager is also commended for designing the Superpave mixes, coordinating the placement of the test sections with the highway construction projects, and overseeing the base and pavement construction. The members of the KDOT Falling Weight Deflectometer (FWD) crew are commended for diligently conducting the periodic FWD tests on the pavement sections.

The authors would like to acknowledge the rest of the Kansas Accelerated Testing Lab team who participated in this project: Dr. Stuart Swartz, professor of Civil Engineering; Dr. Vijayanath Bhuvanagiri, post-doctorate research associate; and Mr. Paul Lewis, Research Technologist at the ATL. The following students have worked at the ATL throughout the duration of this experiments: Jenny Chin, Jason Dewald, and Jason Hoy. Mr. Jeffrey Davies helped with data collection, results classification, and graphics generation. The dedication of the research team is acknowledged.

Table of Contents

Abstract ii

Acknowledgments iii

List of Figures vi

List of Tables viii

1.0 INTRODUCTION 1
1.1 Report Organization 1
1.2 Project Overview 2

2.0 BACKGROUND 4
2.1 Theory For Rutting 4
2.2 Instrumentation 9
2.3 Transverse Rut Measuring Device 11

3.0 DESCRIPTION OF THE FACILITY USED 12
3.1 Laboratory Space and Test Pits 12
3.2 Test Frame 13
3.3 Wheel Load Assembly 13
3.4 Heating System--Infrared Radiant Heaters 16

4.0 DESCRIPTION OF THE TEST EXPERIMENT 17
4 .1 Mix Types and Pavement Construction 17
4.1.1 Pavement Structure 17
4.1.2 Subgrade Soil 18
4.1.3 Base Layer and Compaction 18
4.1.4 Pavement Placement 20
4.2 Loading Conditions 23
4.3 Heat Application and Temperature Setting 24
4.3.1 Heat Application Procedure 24
4.3.2 Heating/Loading Combination 24
4.3.3 Effect of Loading Time Sequence 25
4.4 Sensor Installation and Data Acquisition 26
4.4.1 Instrumentation and Sensor Placement 26
4.4.1.1 Soil Pressure Cells 28
4.4.1.2 Strain Gauges 29
4.4.1.3 Thermocouples 31
4.4.2 Data Acquisition System 32
4.5 Performance Monitoring Plan 32
4.5.1 Nuclear Density Measurements 33
4.5.2 Transverse Profile Measurements with Face Dipstick 33
4.5.3 Transverse Profile Measurements with Rut Measuring Device 33

4.5.4 Longitudinal Profile Measurements with Face Dipstick 34
4.5.5 Deflection Measurements by FWD 34
4.6 Other Tasks and Responsibilities 35

5.0 TEST RESULTS AND PAVEMENT PERFORMANCE 37
5.1 Vertical Soil Pressure 39
5.2 Horizontal Tensile Strains 43
5.3 Pavement Temperature 46
5.4 Asphalt Concrete Density 46
5.5 Pavement Surface Rutting 49
5.5.1 Longitudinal Profiles 49
5.5.2 Transverse Profiles 54
5.6 Cores and Trenches 62
5.7 Summary and Conclusions 63

APPENDIX A SUPERPAVE MIX DESIGNS 67

APPENDIX B BASE LAYER SOIL TEST RESULTS 79

APPENDIX C DATA ACQUISITION SYSTEMS' SETUP 82

References 98

List of Figures

		Page
Figure 2.1	Factors Affecting Rutting [5]	4
Figure 2.2	Rutting in Accelerated Testing Experiments	5
Figure 2.3	Effect of Vehicle Speed on Rutting	6
Figure 2.4	Effect of Tire Pressure on Rutting	6
Figure 2.5	Simulated Wheel Wander at the K-ATL	7
Figure 2.6	Effect of Wander on Rutting [5]	8
Figure 2.7	Rutting with: (a) 15 in. Wander, (b) Fixed Path (zero wander)	8
Figure 2.8	Longitudinal Strains from Accelerated testing Reported by Heck, *et al.* [8]	10
Figure 2.9	Influence Line for one Soil Pressure Cell Reported by Ullidtz & Ekdahl [9]	10
Figure 3.1	Test Frame and Wheel Load Assembly	14
Figure 3.2	Wheel Assembly and Tandem Axles	15
Figure 3.3	Wheel Assembly Completing One Repetition	15
Figure 4.1	Location of Control and Test Sections at the K-ATL and Corresponding Mix Types	19
Figure 4.2	Roller Soil Compaction for ATL-Exp #7	20
Figure 4.3	Plate Soil Compaction for ATL-Exp #7	21
Figure 4.4	Construction of Control Sections in the North Pit of the K-ATL	22
Figure 4.5	Placement of Asphalt Concrete Specimen in Middle Pit of K-ATL	22
Figure 4.6	Location of Sensors on Plan and Through Section Depth	27
Figure 4.7	Geokon Pressure Cell with Pressure Transducer and Conductor Cable	28
Figure 4.8	Location of Installed Pressure Cells	29
Figure 4.9	An Asphalt Mix Cover was Used for Protection of Gages	30

List of Figures (Continued)

		Page
Figure 4.10	Installed Strain Gages at Mid-Depth of Slab	30
Figure 5.1	Pressure Cells Numbering and Location	39
Figure 5.2	Representative Pressure Traces from Cells Located at Mid-Span	41
Figure 5.3	Variation of Peak Pressure with Number of Load Repetitions	42
Figure 5.4	Strain Gages Numbering and Location	44
Figure 5.5	Representative Strain Traces from Gages Located at Mid-Span	45
Figure 5.6	Variation of Peak Stains with Number of Load Repetitions	47
Figure 5.7	Variation of Asphalt Concrete Density with Number of Load Repetitions	48
Figure 5.8	Change in Longitudinal Profile with Loading for Mix 1	50
Figure 5.9	Change in Longitudinal Profile with Loading for Mix 2	51
Figure 5.10	Change in Longitudinal Profile with Loading for Mix 3	52
Figure 5.11	Change in Longitudinal Profile with Loading for Mix 4	53
Figure 5.12	Transverse Profile and Progression of Rutting for Mix 2	55
Figure 5.13	Transverse Profile and Progression of Rutting for Mix 1	56
Figure 5.14	Transverse Profile and Progression of Rutting for Mix 4	57
Figure 5.15	Transverse Profile and Progression of Rutting for Mix 3	58
Figure 5.16	Wheel Marks on the Test Sections at the end of 80,000 Load Applications of the ATL 36 Kip-Tandem Axle	59
Figure 5.17	Side Wall of Cut Trench in SM-2A Test Section with 15% Sand	62
Figure 5.18	Side Wall of Cut Trench in SM-2A Test Section with 30% Sand	63

List of Tables

		Page
Table 4.1	Task Distribution and Responsibilities	36
Table 5.1	Executed Monitoring Plan for North (Control) Section	38
Table 5.2	Executed Monitoring Plan for Test Sections (South Pit)	38
Table 5.3	Rutting Depths (in.) for North Pit, North Wheel Path (BM-2C)–Mix 1	60
Table 5.4	Rutting Depths (in.) for North Pit, South Wheel Path (SM-2A, 20% Sand)–Mix 2	60
Table 5.5	Rutting Depths (in.) for Middle Pit, North Wheel Path (SM-2A, 30% Sand)–Mix 3	61
Table 5.6	Rutting Depths (in.) for Middle Pit, South Wheel Path (SM-2A, 15% Sand)–Mix 4	61
Table 5.7	Summary of Rutting	64

1.0 INTRODUCTION

1.1 Report Organization

This manuscript is the final report that describes the research project conducted under KDOT Contract C119, “Accelerated Testing for Studying Pavement Design and Performance - FY 99" (KSU Account 5-33961). This contract is funded by the Midwest States Accelerated Testing Pooled Fund Program. States participating in this program are Iowa, Kansas, Missouri, and Nebraska.

The purpose of the project is to conduct the experiment selected by the Midwest States Accelerated Testing Pooled Funds Technical Committee for Fiscal Year 1999 (FY-99). During its meeting on April 28, 1998 in St. Joseph, Missouri, the Committee selected the then-called “Kansas Two” experiment as the main activity to be conducted during Fiscal Year 1999. The title of the experiment selected was “Rut Resistance of Superpave Mixtures Containing River Sands.”

This experiment is the seventh experiment conducted at the Kansas Accelerated Testing Lab (K-ATL) and is therefore identified as ATL-Exp #7. The first two experiments, ATL-Exp #1 and #2, were reported in “Development of an Accelerated Testing Laboratory for Highway Research in Kansas [1],” and ATL-Exp #3 through #6 were reported in “Accelerated Testing for Studying Pavement Design and Performance - FY97-98 [2].”

This report describes the following aspects of ATL-Exp #7:

1. The test setup and testing strategies followed.
2. The pavement structure and material used for subbase and pavement construction.
3. The executed monitoring plan.
4. A description of the experiment: This includes the experimental work performed in terms of the total number of cycles applied to each specimen, testing conditions (loads, temperatures, etc.), and the testing activity and corresponding time schedule.
5. A summary of the data collected, results from instrumentation, and processed data in form of rutting profiles, variations (curves/histograms) of measured quantities as a function of load cycles applied, and comparison of the responses of the different pavement mixes.
6. The preliminary conclusions that may be drawn from the obtained results and observed performance.

The remainder of this chapter is a general overview of the project. Chapter 2 provides a background on the theory of rutting, and the types of instrumentation used in this project to evaluate rutting and other related pavement performance. Chapter 3 is a brief description of the testing facility with special emphasis on the particular features used in this experiment. This includes the lab space and test pits, test frame, wheel load assembly, and the surface radiant heating system. Chapter 4 gives a detailed description of the test experiment including the mix types and pavement construction process, loading conditions, heat application and temperature setting, sensor installation and data acquisition, and the executed performance monitoring plan. Finally, Chapter 5 discusses the test results, pavement performance, and conclusions.

1.2 Project Overview

The objectives of the project described in this report are to perform the experimental work and associated data acquisition/data processing for the research study entitled "Rut Resistance of Superpave Mixtures Containing River Sands." The goal of the research is to compare the rut-resistance of Superpave mixtures in which different ratios of river sands have been used. The work described in this report deals with the experimental aspects of the research study. This mainly entails the applications of realistic wheel/axle load cycles to large-scale full-depth pavement slabs in controlled thermal conditions. The experiment was conducted at the Kansas Accelerated Testing Laboratory of Kansas State University. The experimental work also includes monitoring and measuring the degree of rutting of the asphalt surface, and recording the states of strains, soil pressure, and temperature gradients in and below the pavement slabs being tested.

This experimental investigation, when compared with the performance of similar mixes used in control sections on in-service highways, and supplemented with further analytical studies, can help the Kansas Department of Transportation (KDOT) and other state agencies establish or modify existing special provisions for Superpave mixtures. It may also lead to standard guidelines for instrumentation of in-service highway pavement in the States participating in the Pooled Fund Program. These would include numerical modeling, evaluation of mechanistic responses, analysis of Falling Weight Deflectometer (FWD) data, and comparative studies with other research in the United States and abroad. This may necessitate further experimental investigations, and possibly additional testing at the K-ATL.

The instrumentation (strain gauges, pressure cells, and thermocouples) associated with this research experiment were purchased with funds from a separate project entitled "Pilot Instrumentation of a Superpave Test Section at the Kansas Accelerated Testing Laboratory [3]." This project was funded by KDOT as K-TRAN: KSU-98-2. Detailed data analysis and correlation of the mechanistic responses with the pavement performance in terms of fatigue damage, rutting and/or serviceability and Superpave mixture composition have been proposed in the K-TRAN project. Research implementation in the form of revised special provisions for the Superpave mixture in Kansas, as far as natural (river) sand content is concerned, and full-scale in-service Superpave pavement instrumentation in Kansas may result from that study [3]. A preliminary analysis of the data, and the comparison of Falling Weight Deflectometer (FWD) results with estimated values obtained from a multi-layer elastic analysis, are presented in "Instrumentation of the Superpave Test Sections at the Kansas Accelerated Testing Laboratory [4]."

The effort outlined in this report encompasses the application of truck axle loads in a controlled environment as dictated by the physical requirements for this experiment. The load cycles and surface temperature were applied according to a tight and detailed monitoring plan in order to obtain the necessary data on tensile strains, soil pressure, rut depth, pavement density, and surface profile. The monitoring plan is discussed in Section 4.5.

Four asphalt concrete mixes were tested in this experiment. One was a standard KDOT Marshall-type mix (BM-2C) and the other three were Superpave mixes (SM-2A) each with a different sand content (15%, 20%, and 30%). All four sections were placed together at the start of the experiment. The material placed at the K-ATL came from batches used in a construction project on Interstate 70 near Topeka. The same contractor working on the construction project was asked to bring material (trucks) to the ATL facility. Testing the same pavement mixes as those that were being placed on portions of the actual highway system can allow KDOT and future research studies to compare laboratory and field performances.

2.0 BACKGROUND

2.1 Theory For Rutting

Asphalt concrete mixtures subjected to repeated loads exhibit elastic, plastic, visco-elastic, and visco-plastic responses. Permanent deformation is cumulative under repeated loading and is mostly attributed to plastic properties. The following creep rate model is commonly used to characterize the permanent deformation:

$$\frac{d}{dt} \qquad A \;\; {}^{n} t^{m} \tag{1}$$

where ∈ is the creep deformation, σ is the Mises equivalent stress, *t* is the total time, and *A, m,* and *n* are parameters related to material properties. In-service pavement rutting is affected by several factors as shown in Figure 2.1.

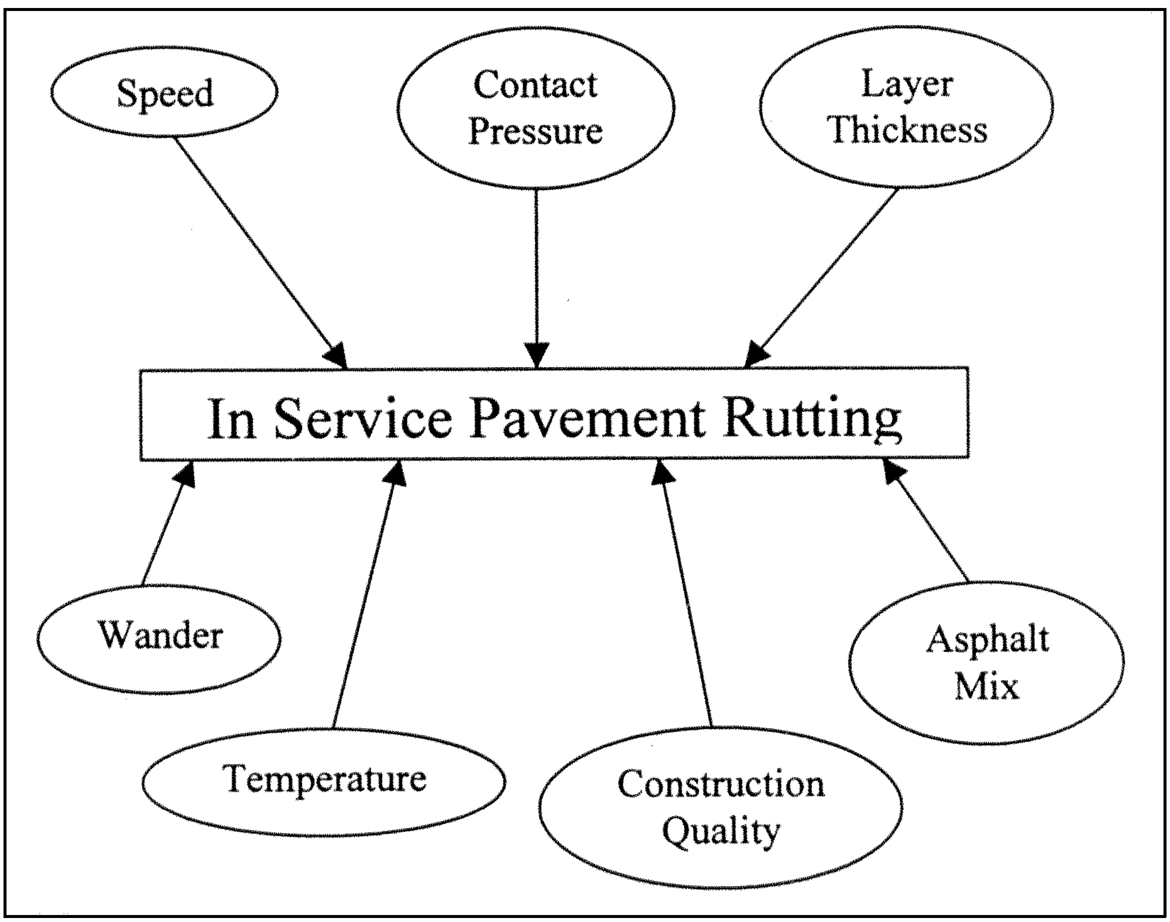


Figure 2.1 Factors Affecting Rutting [5]

Over the past few years, continuing research at Purdue University identified factors that have the most impact on rutting [5]. Based on the creep model of Equation 1, an analysis was conducted using the finite element software ABAQUS to study the effect of the three main factors, which are:

1. Vehicle speed
2. Tire contact pressure, and
3. Lateral wheel wander.

The first two factors can be directly represented in the creep model as time and normal pressure. Lateral wander is accounted for in the simulation of load sequence and load distribution. The other factors namely temperature, asphalt mixture and construction quality are determined experimentally and are inherent in the values of the material constants in the creep model. Layer thickness is accounted for in the pavement geometry and structure. Test results for rutting are shown in Figure 2.2. Experimental data from accelerated pavement testing were used to calibrate the creep model and compare measured and predicted rutting.

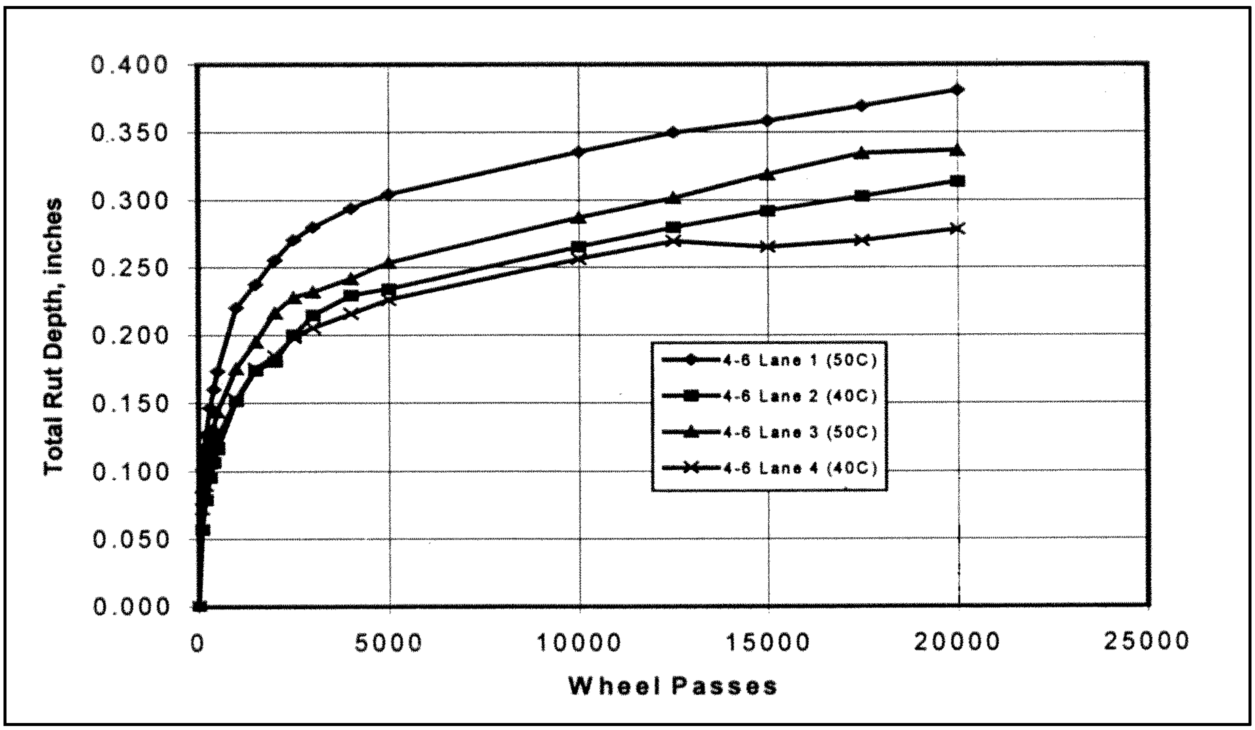


Figure 2.2 Rutting in Accelerated Testing Experiments

Good agreement between the measured and predicted rutting was obtained up to 5000 wheel passes. Effects of vehicle speed on rut depth are shown in Figure 2.3. Results of tests at 8 km/h (5 mph) can be extrapolated to higher traffic speed.

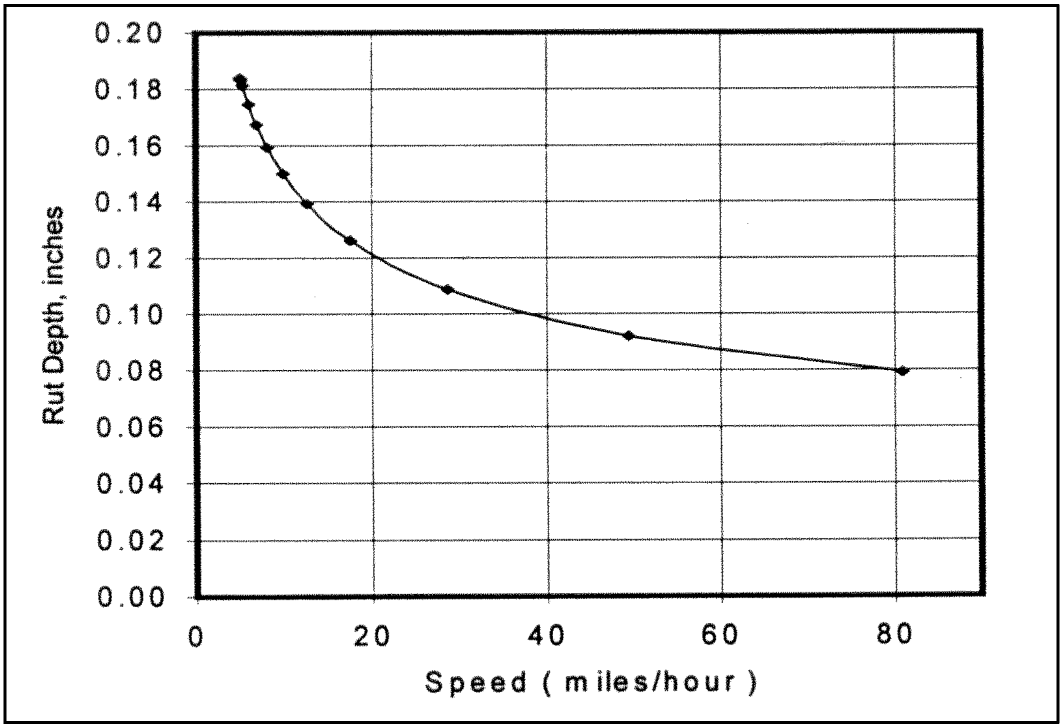


Figure 2.3 Effect of Vehicle Speed on Rutting

The effect of tire pressure is shown in Figure 2.4. The gross contact pressure was computed based on wheel load and measured gross tire print area. The gross tire contact pressure was found to be approximately equal to the tire pressure. Therefore, rutting at tire pressure of 621 kPa (90 psi) can be extrapolated to other levels of pressure.

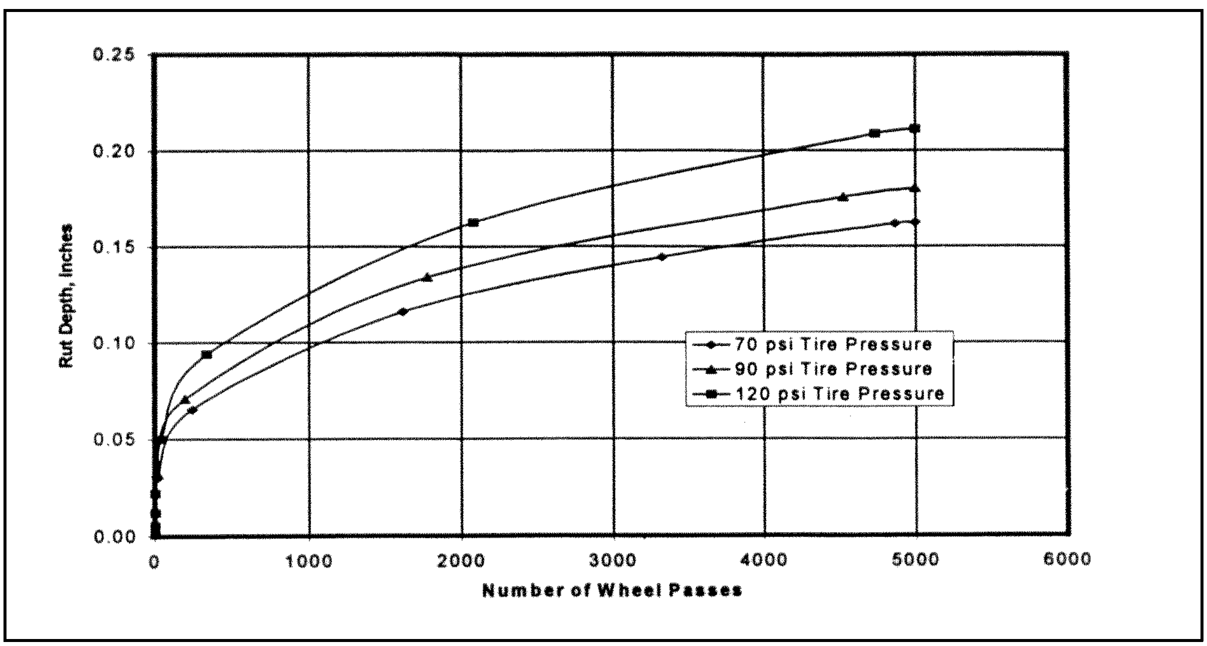


Figure 2.4 Effect of Tire Pressure on Rutting

Of particular importance to accelerated testing is the effect of lateral wheel wander. Because the testing machine at the K-ATL was not designed to include automated lateral wander, it would be preferable to avoid such a test procedure. Although simulated wheel wander has been done previously at the K-ATL as shown in Figure 2.5, it required quite a deal of manual labor.

For each 10,000 repetitions:

Displ (ft)	-1.5	-1	-0.5	0	0.5	1	1.5	**Sum =**
No. Reps.	712	1,316	1,899	2,146	1,899	1,316	712	**10,000**

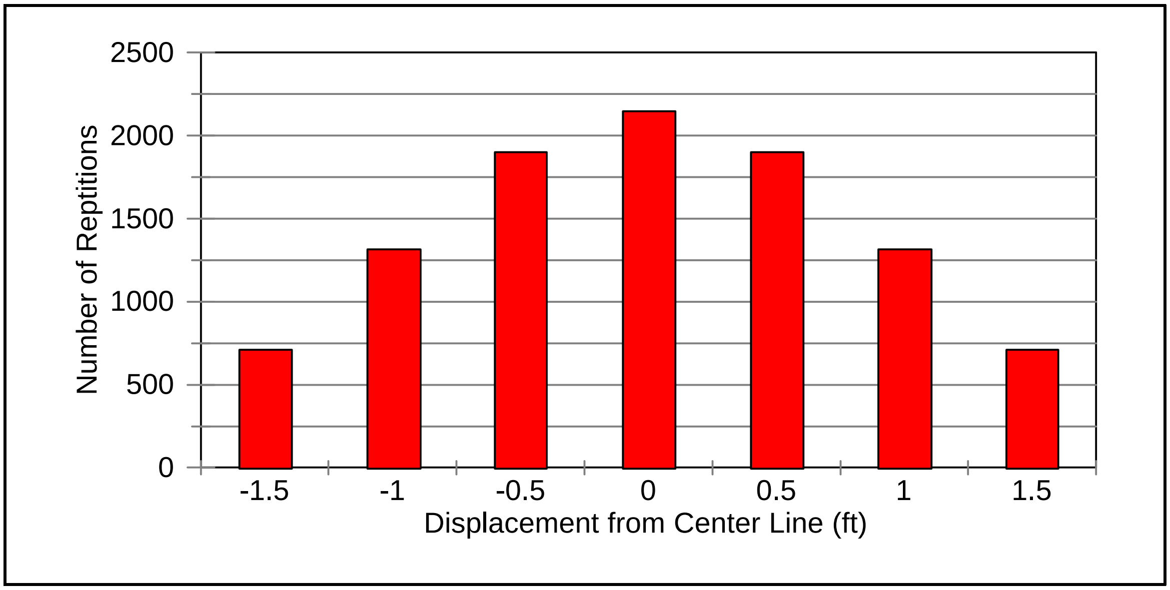


Figure 2.5 Simulated Wheel Wander at the K-ATL

Every so many cycles according to the chart shown in Figure 2.5, the test frame had to be released at the end-anchors, raised off the floor, and moved laterally to simulate a normal distribution with a discrete number of intervals. Heaters and other instruments had to be moved accordingly. This resulted in a significant increase in the testing operation time. However, tests at Purdue University have established a direct correlation between rut depth and wheel wander as shown in Figure 2.6.

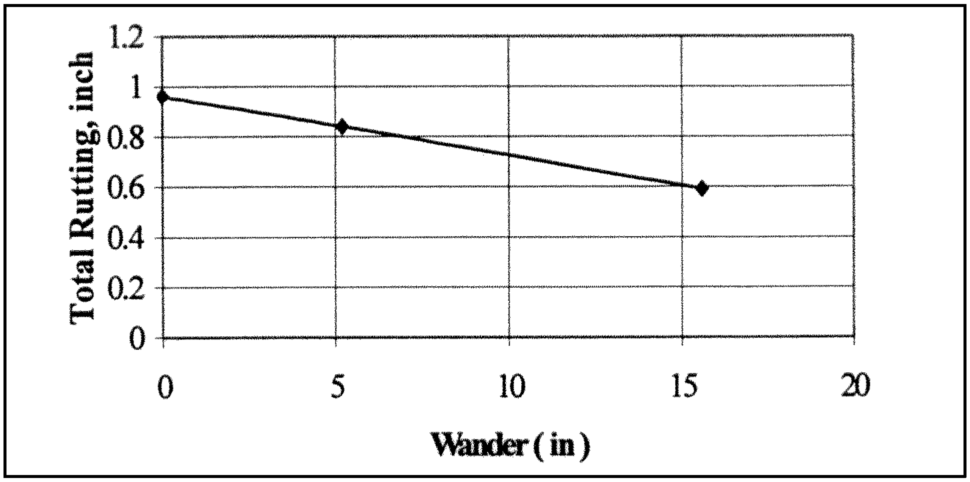


Figure 2.6 Effect of Wander on Rutting [5]

The effect of traffic with wander is to distribute load over a certain width of the pavement. Consequently loading time of any given wheel path is reduced. On the other hand, loads are applied where there would otherwise be a heave formed by the fixed path traffic, and such area is rather compacted and flattened. White and Hua predicted transverse surface profiles for different values of wander and conducted a number of tests which showed that predicted (computed) and measured results were in excellent agreement [5]. Figure 2.7 shows rutting under wheel path with and without wander.

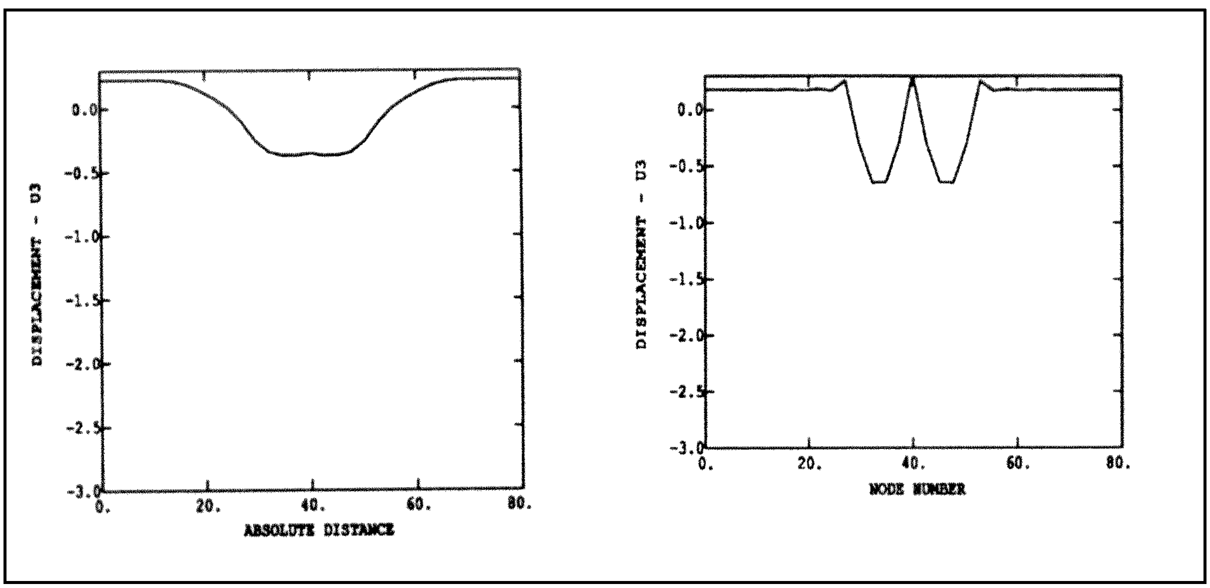


Figure 2.7 Rutting with: (a) 15 in. Wander, (b) Fixed Path (zero wander)

Subsequent personal communication with Dr. White confirmed testing with lateral wheel wander is not necessary when effects of other parameters such as asphalt mixture or temperature and load effects are the primary objectives of the study.

The tests performed at the K-ATL and described in this report applied loads only in a fixed wheel path. Other complementary research studies are being conducted in Indiana and elsewhere that will study different aspects of rutting. For instance, a National Pooled Fund study is underway at Purdue University to validate Superpave mixture criteria, and therefore the effect of asphalt mix on rutting.

2.2 Instrumentation

The following sensors were to be placed and monitored during the experiment (in the *test sections* only):

1. Strain Gauges (Dynatest PAST-2AC),
2. Dynamic Soil Pressure Cells (Geokon), and
3. Thermocouples (fabricated in-house at KSU).

These sensors were purchased using funds from the K-TRAN instrumentation project [3]. The number of sensors is specified in that project. These types of sensors have been used previously at the K-ATL and were successfully installed according to the manufacturer's guidelines and following procedures recommended by the MnRoad research program [6,7].

Data from similar strain gauges were observed and digitally recorded by K-ATL personnel during the FY-98 Accelerated Testing project. Thermocouple data were observed and digitally recorded during the FY-97 project. Response traces similar to those reported by other experimental researchers [8,9] and shown in Figures 2.8 and 2.9 were obtained at the K-ATL.

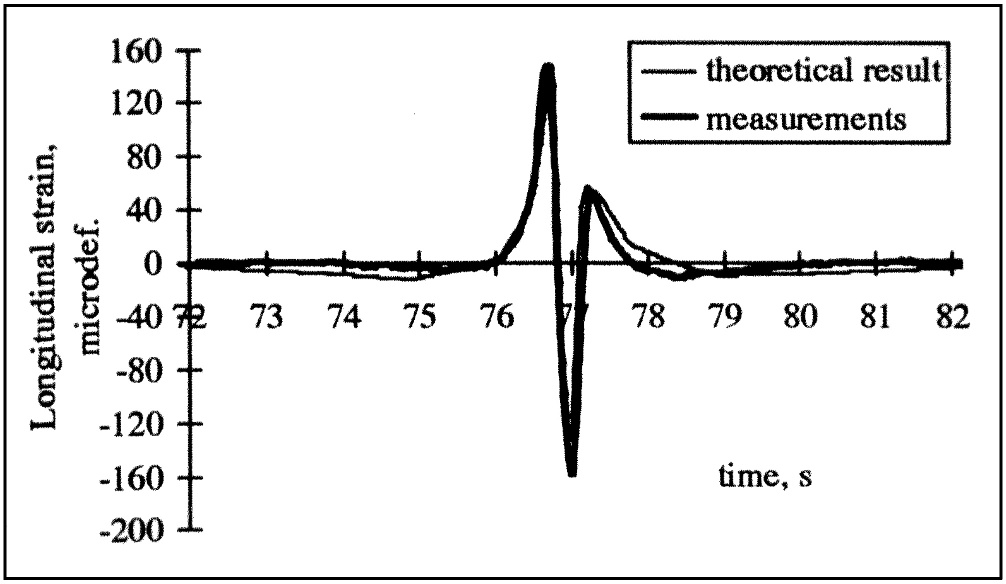


Figure 2.8 Longitudinal Strains from Accelerated testing Reported by Heck, *et al.* [8]

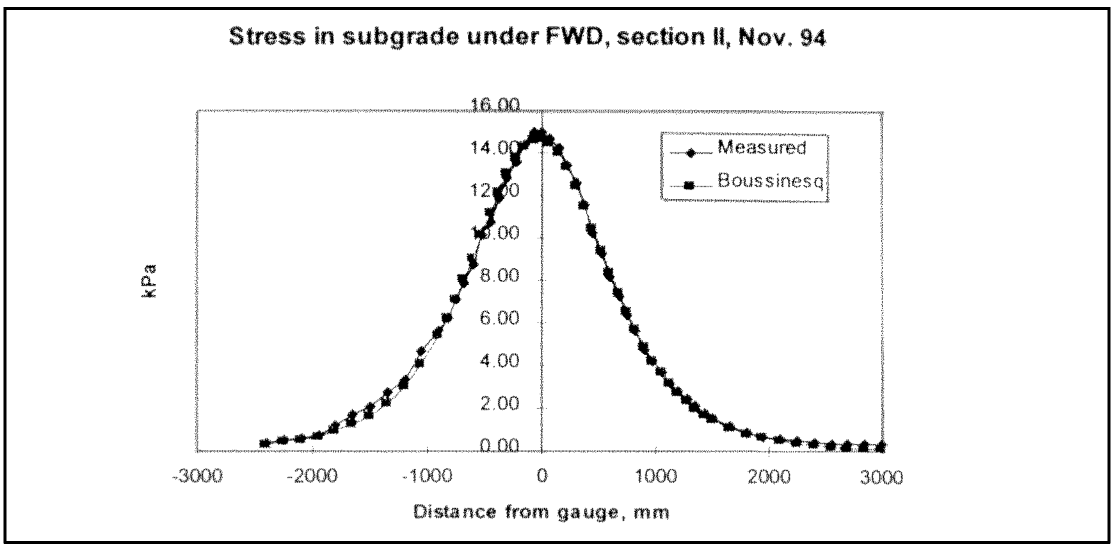


Figure 2.9 Influence Line for one Soil Pressure Cell Reported by Ullidtz & Ekdahl [9]

The sensors were installed by K-ATL personnel. Data was collected using the existing data acquisition system developed at the K-ATL through previous research contracts. The hardware consists of several terminal blocks on a number of corresponding SCXII modules mounted on instrumentation chassis. Data acquisition boards are installed in PC computers with Pentium processors. The software consist of the LabView package of which the Department of Civil Engineering at KSU has a license for 10 users. All hardware and software are products of National Instruments, Inc.

Additional boards and computer upgrades were acquired by the K-TRAN project ([4], p. 13). This is necessary to be able to record strain and pressure data simultaneously and to the extent proposed in the instrumentation project as described in Tasks 4 and 5 ([3], p. 14). Modifications to the previously developed computer programs (or VI's, standing for Virtual Instruments) were made as part of both this and the K-TRAN activities.

2.3 Transverse Rut Measuring Device

When studying rutting of asphalt pavement, in order to obtain accurate transverse profiles such as those shown in Figure 2.7, a better device needs to be used rather than relying on the Face dipstick apparatus. The dipstick gives readings every 305 mm (12 in.), and unless several passes are made, many of the heaves and valleys will be missed. Readings at much smaller intervals along the width of the pavement section are needed, such as every 13 mm (½ in.) or 6.5 mm (1/4 in.). The mechanical parts of such a device consist of a 3.66 m (12 ft) aluminum square tube mounted on two end-brackets with four screws each for level adjustment. A sliding mechanism, to which a dial indicator was attached, traverses the tube to measure surface variation and rutting. In order to obtain accurate and correct readings, the dial indicator was later replaced with a digital transducer. To eliminate human error digital data needed to be recorded electronically. For this purpose the electronic digital indicator and associated laptop computer were acquired with funds from this project.

3.0 DESCRIPTION OF THE FACILITY USED

A detailed description of the facility can be found in “Development of an Accelerated Testing Laboratory for Highway Research in Kansas [1].” This chapter presents an overview of the main features of the Kansas Accelerated Testing Lab (K-ATL) including new improvements to the equipment and additional capabilities implemented at the lab since the original report was prepared.

The K-ATL is part of a broader facility named the “Kansas State University Testing Laboratory for Civil Infrastructure.” The facility also includes the Kansas Falling Weight Deflectometer (FWD) state calibration room, and a shake-table for structural dynamic testing and earthquake engineering research. The FWD room is adjacent to the main testing lab and the shake-table is installed in an empty test pit, similar to those filled with compacted soil and used for pavement testing.

3.1 Laboratory Space and Test Pits

The laboratory area consists of about 537 m^2 (5775 sq. ft) of test space which includes the main test area of about 418 m^2 (4500 sq. ft) with the test pits at the center, about 93 m^2 (1000 sq. ft) for the FWD calibration room, and about 26 m^2 (275 sq. ft) for the electrical and mechanical rooms where the pavement cooling and heating equipment is installed.

Two 1.8 m (6 ft) deep test pits are located in the center of the lab. The main pit is 9.8 m×6.1 m×1.8 m (32'×20'×6') and has been partitioned into a 6.1 m×6.1 m×1.8 m (20'×20'×6') pit for pavement testing, and a 3.7 m×6.1 m×1.8 m (12'×20'×6') pit presently used for earthquake research.

Next to this pit is an insulated environmental pit which is 6.1 m×3.7 m×1.8 m (20'×12'×6') and which has metal (stainless steel) U-tubes buried in the soil underneath the specimen and in which a glycol solution is circulated to freeze or heat both the subgrade and the slab. Adjacent to the environmental pit is a 1.2 m (4 ft) wide access pit. It is used to allow easy access to instrumentation and heating/cooling U-tubes. It currently includes the main headers used to distribute and collect the glycol solution to and from the U-tubes. The headers have ball-valves on the supply and return sides of each U-tube.

The lab floor is 457 mm (18 in.) thick throughout the ATL area and is structurally integral with the pit walls. Floor beams are buried in the concrete floor on both sides of the pit to guide the testing frame and provide attachment (tie-down) against uplift when the load is applied to the specimens. The floor design includes provisions for confining the edges of concrete slab specimens that tend to contract when cooled in the environmental pit. This simulates the thermal tensile stresses created in a section of a continuous concrete highway where the joints would restrain the contraction in the direction parallel to the highway centerline. For these reasons, 19 mm (3/4 in.) threaded rods are used to attach the test slabs to the top of the 457 mm (18 in.)-thick vertical pit walls. The rods, embedded in the concrete slabs, pass through 25 mm (1 in.)-diameter sleeves staggered at 76 mm (3 in.) intervals.

3.2 Test Frame

The test frame is shown in Figure 3.1. The two main girders and four columns are made of W30×99 rolled beams. The frame span is 12.8 m (42 ft) center-to-center. This allows the carriage to get off the specimen before it hits the end of the track where a system of air springs redirect the carriage in the opposite direction.

The elevation at which the girders are connected to the columns was raised by 102 mm (4 in.) prior to testing an AC overlay that was placed over a previously tested PCCP section. The frame is designed such that the beam/column rigid connection can be altered at 76 mm (3 in.) vertical increments.

3.3 Wheel Load Assembly

The test frame and loading devices were designed and fabricated by Cardwell International, Ltd., of Newton, Kansas. The wheel assembly consists of a tandem axle assembly (TAM) with air suspension system (air-bags). The wheel assembly (carriage) is an actual bogie from a standard truck (see Figure 3.2). A manually controlled air-compressor provides pressure in the air-suspension system and therefore applies load to the wheel axles. The wheel load versus air pressure relation was verified for each set of wheels using a portable weigh-scale of the local Highway Patrol authority. The air-bag pressure was increased linearly at 69 kPa (10 psi) increments and the load was recorded until it reached 178 kN (40,000 lbs), including the self weight of the bogie and reaction frame.

The arrangement allows the system to load one or both axles as desired. One or more pairs of tires may be replaced by a super-single if a test requires so. Normally the system would be loading in both direction as the wheel assembly moves back and forth. However, one-way traffic simulation can be achieved through a hydraulic system that can lift the wheel axles either manually or automatically. The automatic mode will cause the eight wheels to be lifted off the ground when the carriage reaches the end of the track until it goes back to its initial position and starts a new load cycle. The manual mode is used when the whole test frame needs to be moved off the specimen or across the laboratory space. The frame is moved by pulling it using an overhead crane. Accurate positioning is achieved manually with a pry-bar.

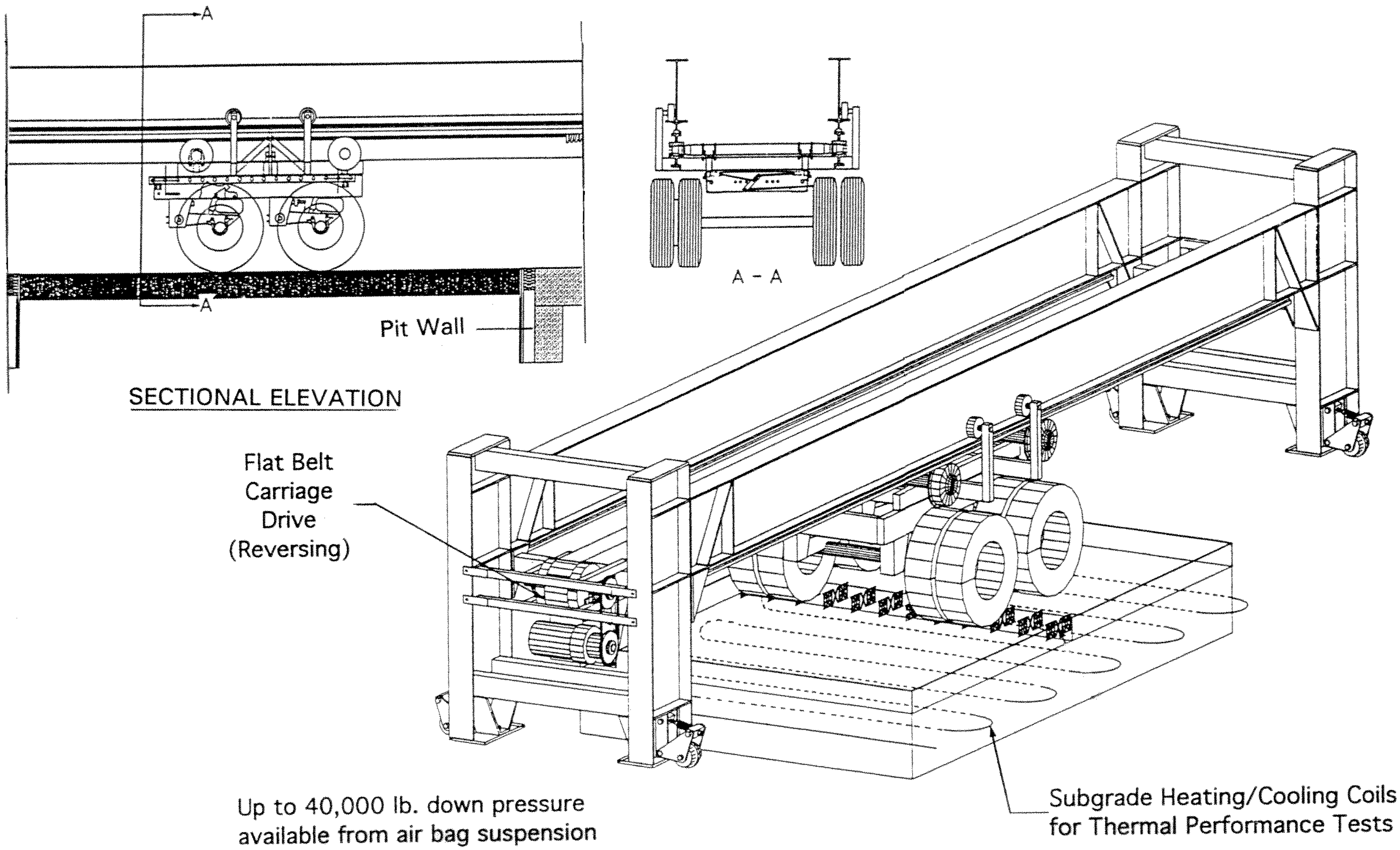


Figure 3.1 Test Frame and Wheel Load Assembly (Design by Cardwell International, Inc.)

Figure 3.2 Wheel Assembly and Tandem Axles

Figure 3.3 Wheel Assembly Completing One Repetition
(photo taken by KSU Photographic Services)

The TAM is moved back and forth along the track using a flat conveyor belt driven by a 14.9 kW (20 HP) variable speed electric motor which reverses direction every time the carriage reached one end or the other of reaction frame (Figure 3.3). The fastest safe operating speed achieved is 300 cycles per hour, or 600 load applications per hour for the two-way passage operation. At this rate, the average speed of the wheel's axles is 5.6 km/h (3.5 mph) over the total travel distance of 9.1 m (30 ft); however, the speed over at least 5.5 m (18 ft) at the middle portion of the 12.8 m (42 ft) track is about 11.3 km/h (7 mph).

3.4 Heating System--Infrared Radiant Heaters

This system is designed only for surface heating and uses infrared radiant heaters. It best simulates heating of a roadway surface by direct radiation from the sun. It consists of four lines mounted on supporting brackets parallel to the direction of the rolling of the carriage, two for each set of wheels of the axle assembly, one line on each side of a wheel path. A separate sensor and control unit is installed on each individual line to monitor/cycle its operation and maintain the desired surface temperature of the pavement. The lines radiate heat the full 6.1 m (20-ft) length of the wheel path, but only heat the width of the pavement at the wheel paths. Temperatures as high as 121°C (250°F) can be achieved, but values up to 50°C (122°F) are more realistic for highway pavement applications.

4.0 DESCRIPTION OF THE TEST EXPERIMENT

This chapter gives a detailed description of the test experiment including the hot asphalt mix types and pavement placement, loading conditions, heat application and temperature setting, sensor installation and data acquisition, and the performance monitoring plan.

4 .1 Mix Types and Pavement Construction

4.1.1 Pavement Structure

Four mixes were tested in this experiment. These are denoted as follows:

Mix 1: a standard KDOT Marshall-type mix, BM-2C (1B97016A)
Mix 2: a Superpave mix SM-2A with 20% sand (1G98006)
Mix 3: a Superpave mix SM-2A with 30% sand (1G98011)
Mix 4: a Superpave mix SM-2A with 15% sand (1G98012)

Each of these mixes was used to construct a pavement specimen. In this report--mainly for simplicity–the pavement specimens or sections are identified by their corresponding mix number: for example, test specimen #1 will be referred to as Section 1, or simply Mix 1.

Pavement specimens constructed with the first two mixes were used as control sections. These two sections were tested under the K-ATL wheel load to compare the performance of a typical Superpave mix with a conventional Marshall mix. The sections were about 1.8 m (6 ft) wide each and were placed in the north (environmental) pit of the K-ATL. The typical testing strategy in K-ATL experiments has been that pavement sections be placed side-by-side in the same test pit and tested in pairs such that each half of the load axle is rolling on one of the two adjacent sections. The third and fourth mixes were used to construct two additional sections used as the main test sections. These were about 2.4 m (8 ft) wide and were placed side-by-side in the central pit of the K-ATL. All sections were 6.1 m (20 ft) long.

The mix designs were performed by KDOT bituminous pavement engineers. Production and placement were made under KDOT supervision and Quality Control/Quality Assurance tests were performed at the contractor laboratory in Manhattan, Kansas following KDOT current special provisions for Superpave bituminous pavement construction. Mix 3 was designed to have marginal Superpave volumetric properties. Mix 4 transitioned the “restricted zone” but still satisfactorily met most of the volumetric properties. The details of the Superpave mix designs are shown in Appendix A.

The asphalt concrete placed at the K-ATL came from batches used in construction projects in Kansas. The same contractor (Shilling Construction Co.) working on the construction project was asked to bring material (trucks) to the ATL facility. The test mixes (Mix 3 and Mix 4) were used in highway construction project #70-106 K-7191-01 (on-going at the time of placement) on Interstate 70 west of Topeka (eastbound passing lane between Mile Posts 341.0 and 346.0) by Maple Hill. The first control mix (Mix 1) was used as a 60 mm (2.4 in.) base layer in that project. The second control mix (Mix 2) was used in August 1998 on K-4 in Wabaunsee County, Kansas. Both control mixes had previously been used in Kansas highway projects and their performance appeared to be satisfactory.

The location of the control and test sections and corresponding mixes are shown in Figure 4.1.

4.1.2 Subgrade Soil

The subgrade is the same silty soil originally placed in the K-ATL pits and used during past experiments. When originally placed, it was compacted to 90% of the laboratory Maximum Dry Density (MDD) and the top 46 cm (18 in.) were compacted to 95% of the MDD [1]. Density was monitored with a nuclear density gage. After several hundred load applications during previous tests, the subgrade was deemed to be even better compacted.

4.1.3 Base Layer and Compaction

All four sections were placed on a 23 cm (9 in.)-thick granular base of 19 mm (3/4 in.) nominal maximum size crushed limestone (AB-3) with about 15% passing through a No. 200 sieve. The experiments previously conducted in the middle pit (ATL-Exp #5 and #6) consisted of asphalt pavement directly on soil without any aggregate base layer [2]. Also when removing the concrete slabs of ATL-Exp #4 (the last test conducted in the north pit [2]) most of the aggregate base used for that test was lifted or disturbed. It was therefore necessary to add AB-3 to the north pit and place a new layer of AB-3 to the middle pit. The material used was analyzed at KDOT soil lab. Soil test results are given in Appendix B.

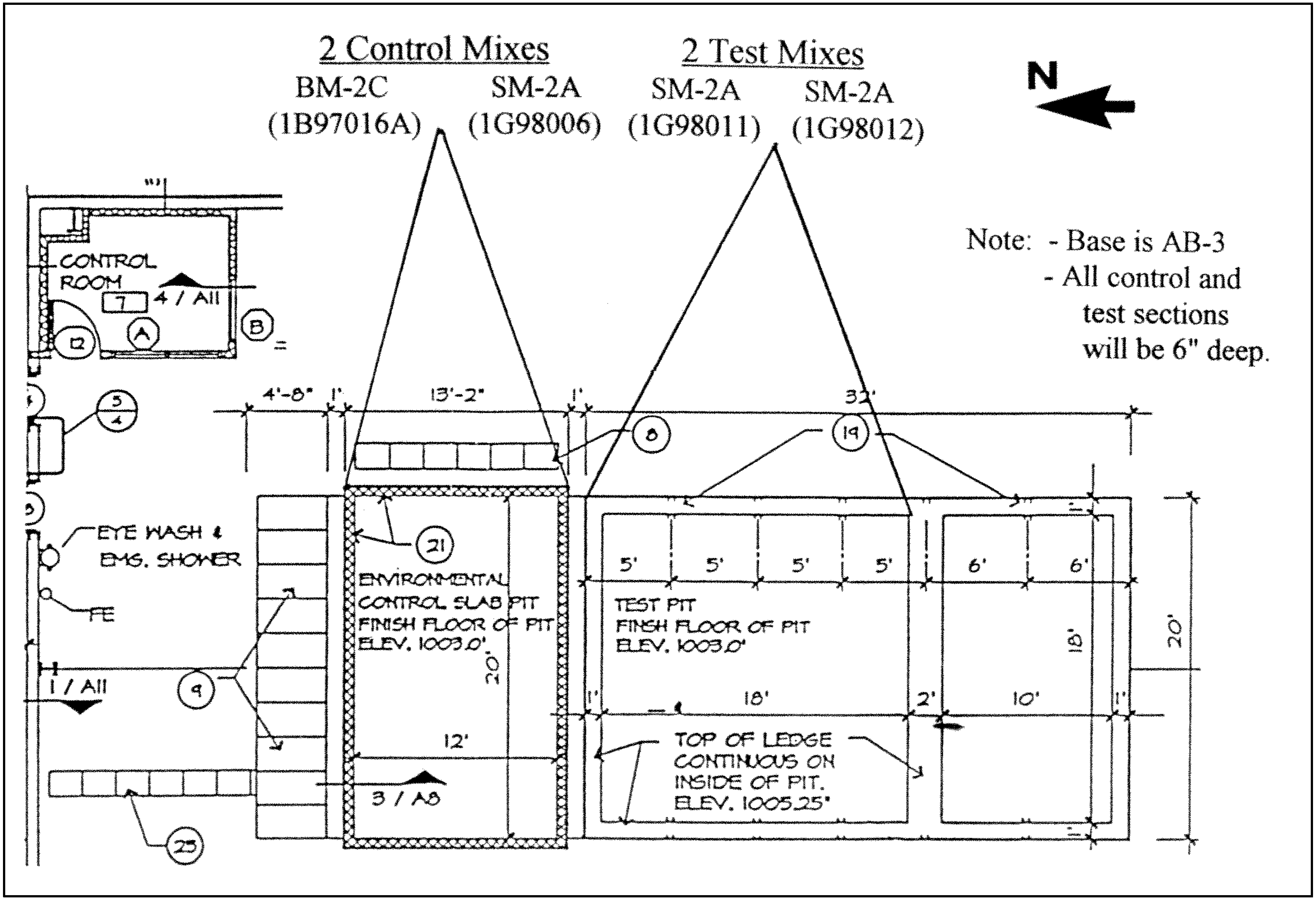


Figure 4.1 Location of Control and Test Sections at the K-ATL and Corresponding Mix Types.

Figure 4.2 Roller Soil Compaction for ATL-Exp #7

The aggregate base was compacted by a construction contractor using a baby sheep's-foot roller as shown in Figure 4.2. Compaction was verified using a nuclear density gage. Corners and edges along the pit walls were compacted using a pneumatic jumping Wacker-type plate which was also used to compact the base before the strain gages were placed. The Wacker plate compaction is shown in Figure 4.3.

4.1.4 Pavement Placement

All pavement sections were 152 mm (6 in.) thick and were placed in two lifts of about 76 mm (3 in.) each. Only the test sections (placed in the middle pit) were instrumented for strain and pressure measurements. Other monitoring tests such as rutting profiles and nuclear densities were performed on all four sections.

Figure 4.3 Plate Soil Compaction for ATL-Exp #7

The control sections were placed first, and a few weeks later the test sections were constructed. Construction took place in September and October 1998. Mix 1 was the first to become available during the corresponding field construction project and was therefore placed first in the north pit as the north lane. Then a full-depth straight cut was made longitudinally with a pavement circular saw to obtain a 1.8 m (6 ft) wide lane and make room for the second control section (Mix 2).   Figure 4.4 (photo taken facing West) shows Mix 1 in place, at the right of the picture, and the cut edge and aggregate base ready for Mix 2. Timber form-work was placed parallel to the wheel rolling direction against the long sides of the pit wall as shown at the left of the picture. Such form-work was later removed after asphalt was placed to allow for a 50 mm (2 in.) gap between the slabs and the side walls of the pit. The other three sections were placed when the corresponding mixes became available from the highway construction project. They were constructed sequentially starting with Mix 2 in the second (south) lane of the north pit, then Mix 3 as the north lane of the middle pit, and finally Mix 4 as the south lane of the middle pit.

Figure 4.4 Construction of Control Sections in the North Pit of the K-ATL

Figure 4.5 Placement of Asphalt Concrete Specimen in Middle Pit of K-ATL

Figure 4.5 shows Mix 3 being placed at its intended location (photo taken facing West). No form-work was needed for these sections since the lanes were 2.44 m (8 ft)-wide each and the width of the middle pit is 6.1 m (20 ft). Therefore the outer edges of these slabs were kept free since there was about a 0.61 m (2 ft) distance between the edges of the pavement and the side walls of the pit.

4.2 Loading Conditions

Loading consists of rolling wheel passes of a dual tandem axle of 150 kN (34 kips). The centerline of the tandem axle corresponds to the location of the line separating the two mixes placed side-by-side in each of the two pits. The experiment met the estimated maximum number of passes for both the control sections and test sections, which was 80,000 repetitions. A fixed wheel pass (zero lateral wander) was followed and two-pass cycles (two-way traffic) were applied throughout the tests. Tire pressure was 621 kPa (90 psi).

The control sections (Mixes 1 and 2) were loaded first up to about 20,000 load repetitions. Then, the test sections (Mixes 3 and 4) were loaded until that same number of cycles was applied. After that, each pair of the control sections and test sections were loaded in turn, 20,000 repetitions at a time. This loading sequence was determined in consultation with the project monitor and with the members of the Technical Committee for reasons explained below in Section 4.3.

As requested by the K-TRAN project ([3], p.7 and 14, Task 6), after the first 10,000 repetitions of the 150 kN (34 kips) K-ATL tandem axle on the test sections (Mixes 3 and 4), different axle configurations and wheel loads were applied. The following variations were applied:

1. 160 kN (36 kip) tandem axle
2. 150 kN (34 kip) tandem axle
3. 145 kN (32.5 kip) tandem axle
4. 100 kN (22 kip) single axle
5. 90 kN (20 kip) single axle
6. 80 kN (18 kip) single axle

During the application of these cycles, both strain and pressure measurements were taken simultaneously at each of the eight strain gages locations (as discussed in Section 4.4) one location at a time. At each of the gage and corresponding pressure cell locations, about 10 cycles were run first to ensure that stability of the data acquisition system is reached, then 25 additional complete cycles (50 load repetitions) were applied and digitally recorded.

This task needed about 3,400 load repetitions after which testing resumed with the normal 150 kN (34 kips) tandem axle selected to complete the 20,000 repetitions on these test sections, and all subsequent load cycles for the rest of this experiment.

4.3 Heat Application and Temperature Setting

Heat was applied to the surface of the pavement specimens using infrared radiant heaters projected towards the centerline of the wheel paths for the test sections as well as for the control sections. All heating occurred from the surface. Surface temperature values were periodically checked using a hand-held thermometer (Raytek Model ST6).

4.3.1 Heat Application Procedure

During the application of the tandem axle loads, the surface of the pavement was heated to 50°C (122°F). For the purpose of uniformity and consistency, it was desirable to have all load cycles applied under the same temperature conditions. Maintaining the surface temperature at 50°C (122°F) was easily accomplished by setting the radiant heater control units to this value. These are monitored by built-in infrared sensors reading temperature right of the pavement surface. However, it is more difficult to achieve constant subsurface temperatures. For instance, if the radiant heaters were kept on running all the time, including evenings and weekends, the temperature at the bottom of the pavement–originally at room temperature–will keep rising until it eventually (maybe after a few days) becomes almost constant throughout the entire slab depth. This would be slightly less than the surface temperature. At this stage, the subbase would be getting warmer too. Moreover, it is much more difficult to predict and monitor heat dissipation through the soil and pit walls. On the other hand, heaters must be removed to measure profiles, densities, etc.

Therefore, the operation of the radiant heaters needed to be controlled more closely such that, to the best possible extent, the temperature "gradient" between the surface and mid-depth of the pavement is maintained more-or-less constant. The first two weeks of testing were spent on experimentation with temperature application alone to study the thermal response of the slabs and heat transfer/dissipation characteristics of the pavement. This resulted in a heating/loading strategy that was followed throughout the rest of the experiment, as presented below.

4.3.2 Heating/Loading Combination

In addition to achieving consistency of the loading and environmental conditions throughout the experiment, it was also important to use the heating time efficiently so that the application of load repetitions does not get delayed because of the temperature cycling. The optimum strategy found was as follows:

1. The surface heaters are turned on using an automatic timer, around 4:00 AM and sometimes earlier (on Mondays following a weekend or after a

maintenance shutdown). The temperature controllers, regulated by surface infrared sensors, are always set to 50°C (122°F). By 8:00 AM, surface temperature would normally reach this value and load application begins.

2. Temperature is monitored through the slab thickness by reading and recording the embedded thermocouples, especially those in the middle layer. During heat and load application, temperatures are digitally recorded every 30 minutes.

3. When the temperature at mid-depth of the pavement slab reaches 39°C (102°F) the radiant heaters are turned off manually. Heat will still propagate down through the slab even when the heating source is off because the surface temperature will remain around 50°C (122°F) for a while. When the mid-depth temperature goes down to 36.5°C (98°F) the surface heaters are turned on again manually. Some judgement calls here are necessary to prevent overshooting and undershooting. In general, when load cycles are applied, mid-depth temperature is maintained around 37.75 ± 1.25°C (100°F ± 2°F) and the temperature differential between the surface and mid-depth remains no less than 11°C (20°F), otherwise the testing machine is stopped until favorable temperature gradient is restored.

4. Around 5:00 PM, the ATL testing machine will be stopped for the day. Heaters are turned off and the automatic timer is set for early morning of the next working day.

Following this strategy, 10,000 repetitions could be applied in three to four days and testing was possible any day of the week. Most importantly, load cycles were consistently applied only when the temperature differential between the surface and mid-depth is around 11°C (20°F). That ensured that loading was always under the same temperature conditions at any given time during the test.

No chiller or refrigeration was used. The only “cooling” occurred overnight or when the heat source was turned off allowing removal of heat by natural convection. The lowest temperature ever reached was the room temperature of the lab which is kept around 21°C (70°F).

4.3.3 Effect of Loading Time Sequence

In following the load/heat application described above, the following potential problem concerning the pavement behavior was raised: Posing for a few days between load/thermal applications may have an effect on the fatigue properties of the asphalt concrete pavement. Switching from one pit to the other can give the sections that are not being tested a chance to “rest” and consequently to “heal” from damage and plastic deformation caused by high temperature and load cycles. This may result in strengthening of the material that otherwise would not take place if the sections were tested continuously without rest.

This phenomenon was not to be investigated in depth during this experiment. However, consistency of the test/rest sequence and the load/heat application procedure can ensure that all sections are treated the same. For this reason when the facility was closed during the University winter break all sections had reached exactly 20,000 load repetitions. On the other hand, sections tested side-by-side in the same pit have been exposed to the same conditions and therefore, for the purpose of comparison, “resting/healing” will not be considered a parameter.

4.4 Sensor Installation and Data Acquisition

Several sensors were placed in the test sections to monitor pavement behavior. In addition to measurements obtained from these sensors, FWD tests were conducted at the beginning of the experiment, and nuclear density measurements and surface profiles were recorded periodically.

4.4.1 Instrumentation and Sensor Placement

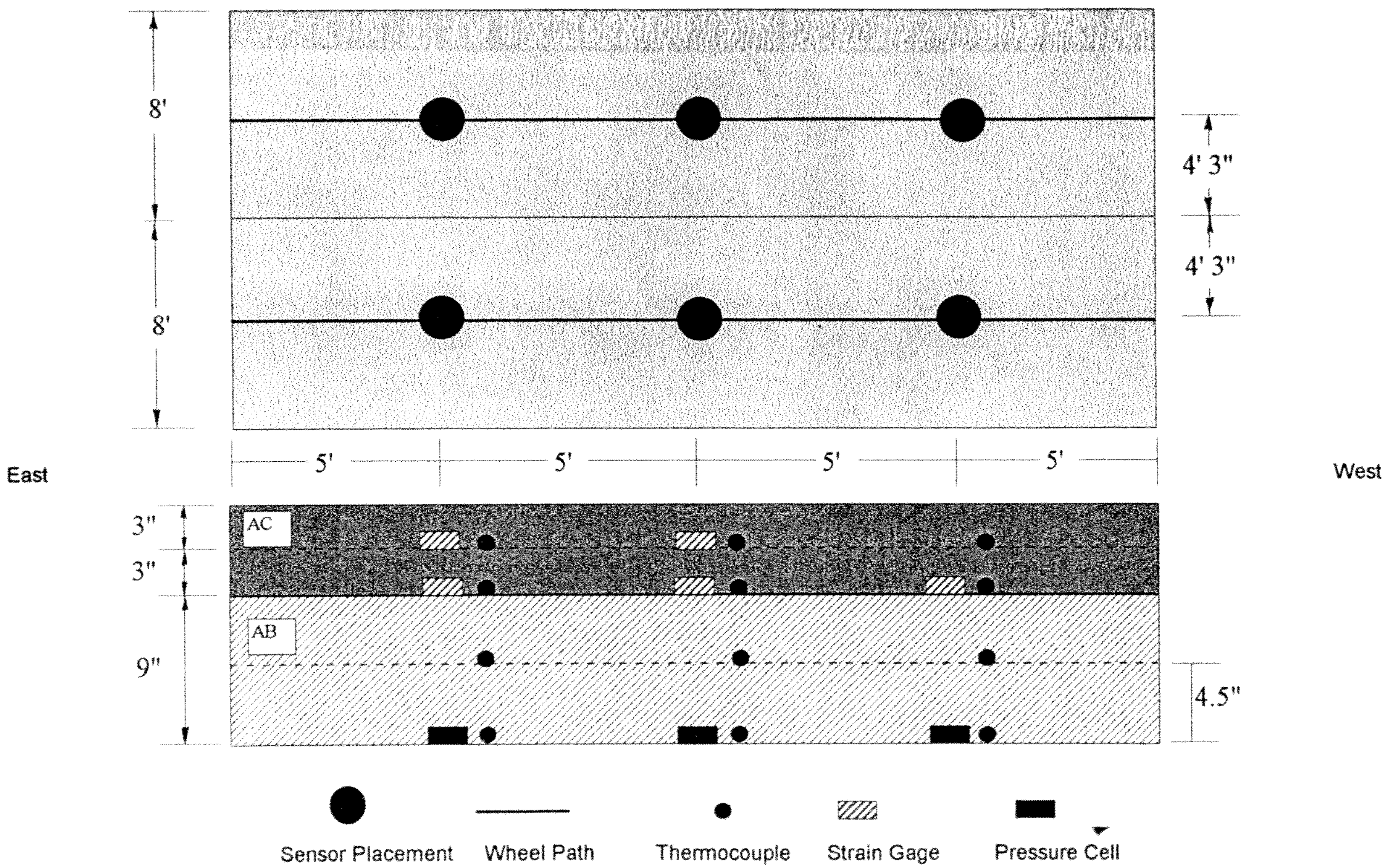
To compare the performance of the different pavement slabs the following instrumentation was used (in the *test sections* only):

1. Dynamic Soil Pressure Cells (Geokon 3500),
2. Strain Gauges (Dynatest PAST-2AC), and
3. Thermocouples (fabricated in-house at the K-ATL).

These particular types of sensors were successfully used at the K-ATL in previous projects and have shown good performance and acceptable results [2]. In particular, data from similar Geokon pressure cells and Dynatest strain gauges (same models) were measured and digitally recorded by the K-ATL personnel during the FY-98 Accelerated Testing project (ATL-Exp #5 and 6). Also, thermocouple data were read and digitally recorded during FY-97 project (ATL-Exp #3 and 4).

As in the case of the previous experiments, these sensors were installed according to the manufacturer’s guidelines and following procedures recommended by the MnRoad research program [6,7]. Response traces similar to those reported by other experimental researchers [8,9] and shown in Figures 2.8 and 2.9 were obtained at the K-ATL.

The layout and location of the different sensors on the plan of the *test sections* and through the depth are shown in Figure 4.6.



Note: The strain gages 3" below the surface in the AC are only on the North Side.

Figure 4.6 Location of Sensors on Plan and Through Section Depth

The only instrumentation that was placed in the *control sections* is two sets of thermocouples–three sensors in each set–placed at the centerline of Mix 2 (south half) of the north pit. The first set (three) was placed below the pavement, on top of the subbase, and the other set (also three) at mid-thickness of the pavement. The layout and depth of these thermocouples are similar to those of the test sections (see Figure 4.4) except that only the south lane had temperature sensors. These were used in monitoring heat application and temperature gradient, as explained in Section 4.3.

4.4.1.1 Soil Pressure Cells

Six soil pressure cells, Model 3500 Dynamic Series with Ashkroft K1 Transducers (from Geokon), were placed as indicated in Figure 4.6. On the plan, this is along the centerline of each wheel (pair of tires), at the quarter-span points. The centerline of the wheel paths for the north and south lanes are symmetrically located at 1280 mm (51 in.) from the middle of the pit. Three pressure cells were therefore placed on each wheel path, at about 1.5 m (5 ft) from the east and west ends.

The Geokon pressure cells are constructed from two circular flat plates of 230 mm (9 in.)-diameter welded together around their periphery. The plates are separated by a thin film of liquid which is connected through a tube to the pressure transducer. The transducer is connected to the data acquisition system by a conductor cable

Figure 4.7 Geokon Pressure Cell with Pressure Transducer and Conductor Cable

that is sealed into the transducer housing. It utilizes a bonded foil resistance strain gaged diaphragm that converts changes in pressure in a hydraulic flat-jack into a usable electrical signal. One of the cells used is pictured in Figure 4.7.
The pressure cells were installed according to the manufacturer's guidelines and following the procedures recommended by the MnRoad research program. They were placed on top of the compacted subgrade soil, below the AB-3 aggregate base layer. This corresponds to about 390 mm (15 in.) below the surface of the pavement. The connecting cables were placed in PVC pipes for protection during the following base construction and compaction. The location of the installed pressure cells is depicted in Figure 4.8.

Figure 4.8 Location of Installed Pressure Cells

4.4.1.2 Strain Gauges

Eight strain gauges (Dynatest Model PAST-2AC) were placed as indicated in Figure 4.6, along the centerline of the wheel paths. This line is the same line along which the pressure cells were placed. Three gauges were installed at the bottom of the asphalt concrete layer below each of the two test sections, right on top of the AB-3 base. A small amount of cold asphalt mix patching material was placed on top of these gages to protect them during hot asphalt paving. This is shown in Figure 4.9. Two additional strain gauges were installed at about mid-depth; i.e., at the interface between the two asphalt lifts, in the north section only (see Figure 4.10).

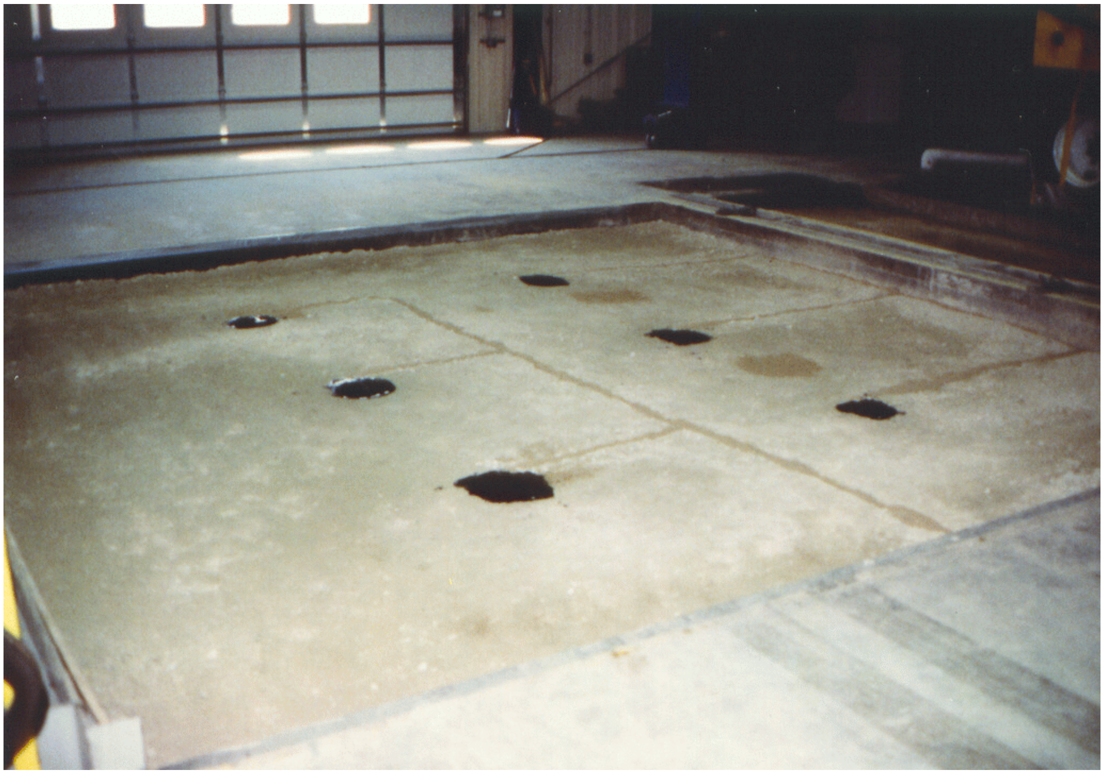


Figure 4.9 An Asphalt Mix Cover Was Used for Protection of Gages

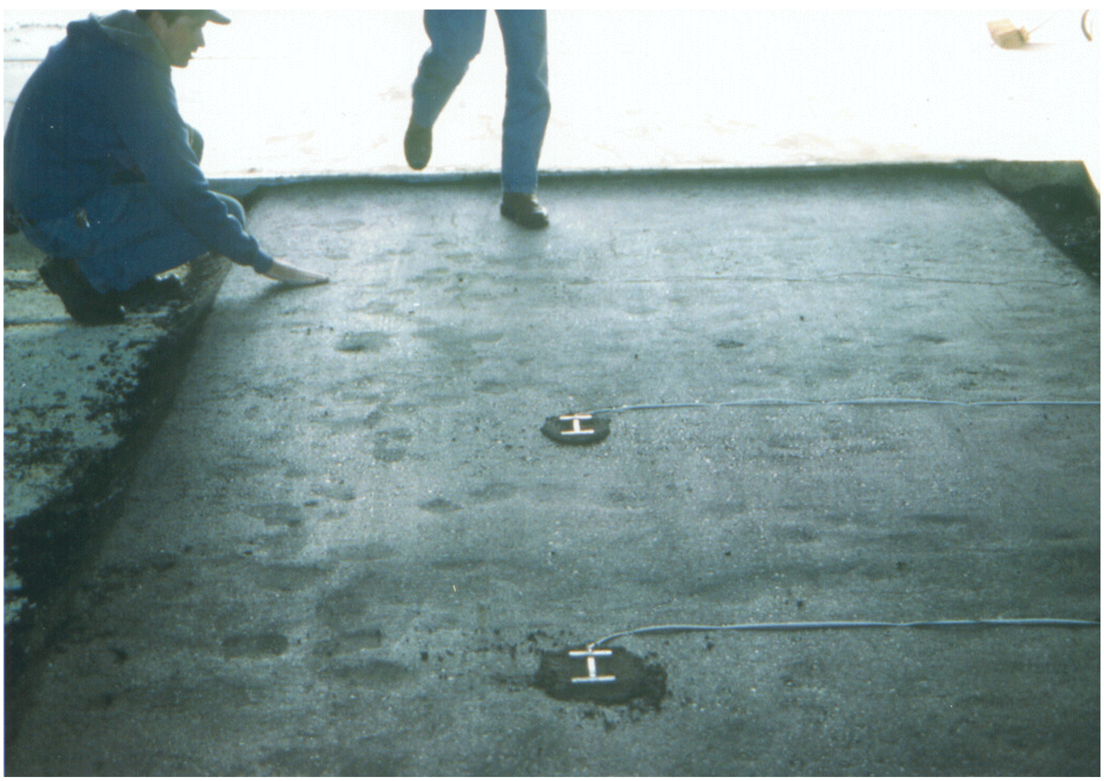


Figure 4.10 Installed Strain Gages at Mid-Depth of Slab

The gauges (often designated as H-gauges) consist of electrical resistors embedded within a strip of glass-fiber reinforced epoxy supported at each end of the strip on transverse stainless steel anchors forming an H-shape. The gauges are installed to measure horizontal tensile strain measurements under the wheel passage. The orientation of the gauges was parallel to the direction of traffic and thus only longitudinal strains were measured. Horizontal strains in asphalt pavement provide the means for comparing the in-situ results to those of analytical models. The data are often useful to study the current failure criteria used in mechanistic-empirical pavement design procedures.

Due to manufacturing complexity, the resistance of these strain gauges is not constant, but rather varies from one gauge to the other between 120 and 127 Ohms. For this reason, commercial ready-to-use strain indicators could not be used for signal conditioning. Special provisions had to be made for electric circuit bridge completion and signal amplification.

4.4.1.3 Thermocouples

Thermocouples are temperature sensors embedded between the pavement layers. They were placed in the two test sections in the middle pit in four vertical layers corresponding to four different vertical depths through the pavement structure and base. Six sensors were installed in each layer corresponding to the horizontal location of the strain and pressure sensors. The top layer is the mid-depth of the asphalt layer. The second layer down was at the interface between the asphalt layer and the base layer. The next two layers are at mid-depth and at the bottom of the base, respectively. A total of 24 thermocouples were installed. The location of these thermocouples is depicted in Figure 4.6.

This arrangement specifically permits having one thermocouple placed in the vicinity of each of the strain gauges. These sensors read the temperature in the neighborhood of the strain gages embedded in the pavement layer. From past experience, these might be needed if temperature compensation is necessary. Even though the strain gauges are supposed to have a self temperature compensation feature, it was thought that these thermocouples would be handy in case of abnormal instability or unexpected malfunction that might be attributed to excessive temperature sensitivity (manufacturer's recommendation).

All thermocouples were read and recorded periodically. The top layer of thermocouples was particularly observed to ensure that the necessary temperature gradient between the surface of the pavement and the pavement mid-depth was within the specified range as outlined in Section 4.3.2. This gradient had to be maintained during the wheel load applications.

4.4.2 Data Acquisition System

Data were collected using the existing data acquisition system developed at the K-ATL through previous research contracts. The hardware consists of several terminal blocks on a number of corresponding SCXII modules mounted on instrumentation chassis. Data acquisition boards are installed in PC computers with Pentium processors. The software consist of the LabView package of which the Department of Civil Engineering at KSU maintains a current license for 10 users. All these hardware and software are products of National Instruments, Inc.

Additional boards, software updates, and computer upgrades are regularly acquired to enhance the data acquisition system. In order to read and record strain, pressure, and temperature data simultaneously, two separate subsystems, each connected to a different computer, were necessary. Modifications to the previously developed computer programs (or VI's, standing for Virtual Instruments) were made as part of both this and the K-TRAN project.

A brief summary of the data acquisition hardware and software configuration for the strain and pressure data acquisition is given in Bhuvanagiri *et al.* [4]. A detailed description of the strain data acquisition system and its development procedure are given by Melhem [10]. The other systems follow the same format and procedure with minor modifications. The final results are given in this report in Appendix C.

For each of the (a) pressure, (b) strain, and (c) temperature data acquisition systems, Appendix C gives the following:

1. A schematic representation the data acquisition hardware setup,
2. The graphical source code of the corresponding software (VI), and
3. The corresponding Graphical User Interface.

4.5 Performance Monitoring Plan

The instrumentation and data acquisition described above (in Section 4) were mainly intended to collect data that can be used elsewhere to perform a detailed analysis of the pavement behavior under the successive axle load repetitions. Data collection was done only for the two test sections (Mixes 3 and 4).

The purpose of the activity described in this section was to monitor the performance of the pavement sections being tested. This was conducted on the test sections as well as the control sections. The performance monitoring consists of the following tasks:

1. Nuclear Density Measurements on Asphalt Surface
2. Transverse Profile Measurements with Face Dipstick
3. Transverse Profile Measurements with Transverse Rut Measuring Device

4. Longitudinal Profile Measurements with Face Dipstick
5. Deflection measurements by FWD

Except for Task 5 (deflection measurements by FWD) all the other tasks listed above were performed at the beginning and after every 10,000 load applications, for both the test sections and control sections. Task 3 was necessary to obtain a more precise transverse profile of the surface rutting. A detailed description of Tasks 1 through 5 is presented below.

4.5.1 Nuclear Density Measurements

Density measurements were taken periodically after each 10,000 repetitions using a nuclear density gage. Measurements were made at 1.52 m, 3.05 m, and 4.57 m (5 ft, 10 ft, and 15 ft) along the external wheel paths of the dual tandem axle. Each of the test sections and control sections therefore has three locations along the line corresponding to the external tire of the pair rolling on it. Three one-minute readings were taken at each location. Variation of density values versus the number load applications can give an indication of the compaction or distress due to wheel traffic.

4.5.2 Transverse Profile Measurements with Face Dipstick

Profile measurements were taken periodically after each 10,000 repetitions using the Face Dipstick apparatus. Transverse profile curves were computed and plotted at every 1.52 m (5 ft) across the wheel paths. Therefore, each of the test sections and control sections has transverse profiles at three locations along the slabs: one location at mid-span, and two locations at the quarter points.

From past experience, transverse profiles generated this way do not show a good description of the rut since readings are taken every 30 cm (12 in.) and much of the details of the deformation shape are missed. However, this will be done at the request of the K-TRAN project [3].

4.5.3 Transverse Profile Measurements with Rut Measuring Device

When studying rutting of asphalt pavement, in order to obtain accurate transverse profiles, a better device needs to be used rather than relying on the Face dipstick apparatus. The dipstick gives readings every 30 cm (12 in.), and unless several passes are made, many of the heaves and valleys will be missed. Readings at much smaller intervals along the width of the pavement section are needed, such as every 13 mm (1/2 in.) or 6.5 mm (1/4 in.). For this purpose, a special surface rut measuring device was developed.

<u>Transverse Rut Measuring Device</u>

The mechanical parts of this device were fabricated in-house at the K-ATL. They consist of a 3.66 m (12 ft)-long aluminum square tube mounted on two end-brackets with 4 screws each for level adjustment. A sliding mechanism, to which a digital transducer is attached, traverses the tube to measure surface variation, rutting and to obtain accurate and correct measurements of the surface profile. Recording digital data electronically helps eliminate human error. For this reason a Logic-Basic (Model BG4820) electronic digital indicator and associated laptop computer were acquired with funds from this project. The indicator interfaces directly with the computer and serial port through a RS232 connecting cable. It has a 101.6 mm (4.0") measuring range and 0.01 mm (0.0005") accuracy.

Transverse profile measurements were taken periodically after each 10,000 repetitions using the developed rut measuring device. Data was collected and stored electronically so that elevations could be recorded every 13 mm (½ in.). This ensured that all heaves and depressions are recorded and a more accurate surface profile could be constructed. Transverse profile locations are the same as those measured with the dipstick (Section 4.5.2).

4.5.4 Longitudinal Profile Measurements with Face Dipstick

Measurements were taken along the external wheel paths of the dual tandem axle. As the load repetitions are incrementally applied, surface profiles along the line corresponding to the external tire of the pair rolling were constructed. This was done for each of the test sections and control sections. Taking measurements on the wheel path (rather than on the centerline of the lane) will give a better indication of the change in the profile, if any, due to the application of the load cycles. Moreover, measuring the surface elevation under any of the tire lines is more significant than at the center line of the wheel (pair of tires). This could be done on either tire path. The selection of the external tire in particular was done mainly for consistency.

Attempts were made to compute the International Roughness Index (IRI) values using the computer software RoadRuf, made available by the University of Michigan. The software uses recorded values for the longitudinal profiles to compute the IRI. However, the procedure used in the software is based on an extensive length of the profile measurements and is not appropriate for data collected over a 6.1 m (20 ft)-long travel.

4.5.5 Deflection Measurements by FWD

Falling Weight Deflectometer (FWD) tests were conducted on all sections (test sections and control sections) but only at three intervals during the experiment. These were as follows:

a. At the start, before any load cycles are applied,

b. At midway, or after about 40,000 cycles have been applied, and
c. At the end of the test, or at about 80,000 cycles

FWD tests were performed by the KDOT crew with a Dynatest 8000 FWD in both traffic directions (East to West, and West to East). A comparison of the responses computed from the FWD back-calculated layer moduli and the measured responses has been reported by Bhuvanagiri *et al.* [4].

4.6 Other Tasks and Responsibilities

The other tasks performed in this project are:

1. Test sections and scheduling (placement by Shilling Construction under KDOT supervision.)
2. Scheduling of coring and FWD tests (coring and tests done by KDOT personnel)
3. Bulk sample collection
4. Trenching transverse cuts at the maximum rut locations (two test sections only)
5. Saw cutting materials-lab fatigue-test bulk samples

These tasks and the monitoring plan described in Section 4.5 were performed as delineated in Table 4.1.

Table 4.1 Task Distribution and Responsibilities

Activity	Responsibility Distribution		
	K-TRAN: KSU 98-2	FHWA-KS-99-7	KDOT
1. Literature Search	°		
2. Instrument order and installation	°		
3. LabView and strain module interface buildup	°		
4. Response monitoring reading (gages)	°		
5. Pavement section design	input		° [1]
6. Superpave mixture design	input		° [1]
7. Construction of the test sections and scheduling	input	°	super-vision
8. Quality control including in-situ Nuclear density tests for the as-built sections and subsequent coring	input	°	° [1]
9. Bulk sample collection		°	
10. Load applications and performance monitoring scheduling		°	
11. FWD tests			° [2]
12. Transverse profile measurements & reporting		°	
13. Longitudinal profile measurements, IRI computation & reporting		°	
14. Fabrication of laboratory fatigue test samples (from bulk samples)	°		help
15. Saw cutting laboratory fatigue test samples (from one test section)		°	
16. Analytical and numerical studies	°		input
17. Reporting of the *KSU 98-2* project	°		review

[1]Glenn Fager
[2]Albert Oyerly

5.0 TEST RESULTS AND PAVEMENT PERFORMANCE

This chapter presents a summary of the test results, pavement performance, and conclusions of this experiment. Load and heat application followed the procedure described in Sections 4.2 and 4.3. The data were collected from the embedded instrumentation using the electronic data acquisition system as outlined in Section 4.4. The performance monitoring plan presented in Section 4.5 has been executed as planned.

The summary of the testing activity and experiment monitoring is shown in Tables 5.1 and 5.2. Table 5.1 pertains to the North pit with the control sections (Mixes 1 and 2). Table 5.2 pertains to the South pit (middle pit of the Lab) with the test sections (Mixes 3 and 4) which had the instrumentation embedded. The dates shown in these tables are the days when the corresponding number of load applications (2^{nd} column) have been achieved and, for the rest of the columns, the days when the respective activities have been performed.

As mentioned earlier (Section 4.2), each pair of the control sections and test sections were loaded in turn, 20,000 repetitions at a time, starting with the control sections. This required moving the testing machine and radiant heaters back and forth from one pit to the other. Except for deflection measurements by FWD all other sensor readings and monitoring task were performed at the beginning of the experiment and after every 10,000 load applications.

It can be noted that Table 5.2 has an additional column (3^{rd} column) which shows the sensor data collection that does not exist in Table 5.1; the control pit was not instrumented. Sensor data include measurements of strain gauges, pressure cells, and temperatures (thermocouples). It can also be noted that sensor data were recorded towards the completion of each set of 10,000 load repetitions. These were measured under the rolling wheel loads while the last few hundred cycles in the corresponding set of loads are applied. This was normally done the same day the specified number of repetitions was achieved; however, surface profiles and nuclear density measurements were performed after load cycles were completed, with no loading or heating being applied. These were performed the same day or sometimes one or two days later.

Table 5.1 Executed Monitoring Plan for North (Control) Section

Date Completed	Number of Repetitions	Transverse Profile	Longitudinal Profile	Static Profile	Nuclear Density	FWD
	0	11/18/98	11/18/98	11/20/98	11/18/98	11/10/98
12/3/98	10k	12/4/98	12/4/98	12/4/98	12/4/98	
12/9/98	20k	12/10/98	12/9/98	12/18/98	12/16/98	
1/6/99	30k	1/6/99	1/6/99	1/6/99	1/6/99	
1/11/99	40k	1/12/99	1/12/99	1/12/99	1/12/99	1/28/99
2/2/99	50k	2/2/99	2/2/99	2/3/99	2/3/99	
2/8/99	60k	2/9/99	2/9/99	2/8/99	2/10/99	
2/23/99	70k	2/23/99	2/23/99	2/23/99	2/23/99	
2/26/99	80k	2/26/99	2/26/99	2/26/99	3/1/99	3/29/99

Table 5.2 Executed Monitoring Plan for Test Sections (South Pit)

Date Completed	Number of Repetitions	Sensor Data	Transverse Profile	Longitudinal Profile	Static Profile	Nuclear Density	FWD
	0	11/12/98	11/18/98	11/18/98	12/19/98	11/18/98	11/10/98
12/16/98	10k	12/16/98	12/16/98	12/16/98	12/17/98	12/16/98	
12/18/98	Task 6	12/18/98					
12/23/98	20k	12/23/98	1/5/99	1/5/99	1/5/99	1/6/99	
1/15/99	30k	1/15/99	1/19/99	1/19/99	1/19/99	1/19/99	
1/22/99	40k	1/22/99	1/22/99	1/22/99	1/22/99	1/22/99	1/28/99
2/12/99	50k	2/12/99	2/15/99	2/15/99	2/15/99	2/15/99	
2/18/99	60k	2/18/99	2/18/99	2/18/99	2/19/99	2/18/99	
3/3/99	70k	3/3/99	3/4/99	3/4/99	3/4/99	3/4/99	
3/9/99	80k	3/9/99	3/9/99	3/9/99	3/10/99	3/10/99	3/29/99

5.1 Vertical Soil Pressure

As discussed in Section 4.4.1.1, six pressure transducers were placed on top of the compacted subgrade soil, below the AB-3 aggregate base layer, at about 390 mm (15 in.) below the surface of the pavement. These are identified in Figure 5.1 as cell p1 through p6, along with the corresponding transducer serial number (PT-464xx) and channel number (Ch.x) used in the NIDAQ data acquisition system.

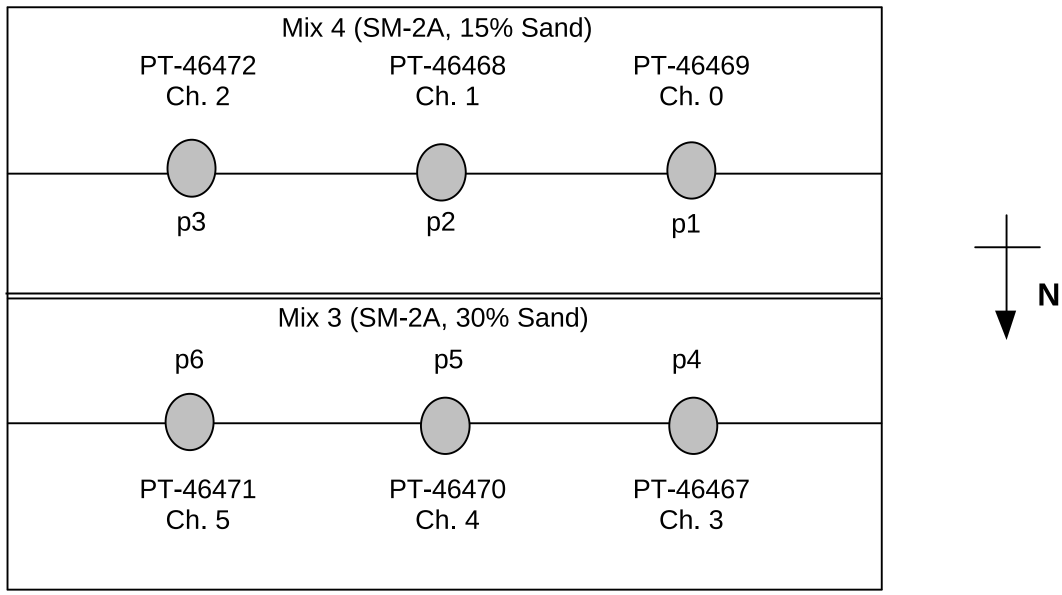


Figure 5.1 Pressure Cells Numbering and Location

Soil pressure traces induced by the passage of the truck tandem axle were digitally recorded. These traces, also seen on the computer screen as signals from the sensors, were transmitted to the data acquisition system. As discussed earlier and indicated in Table 5.2, these measurements were made towards the end of the application of each 10,000 load repetitions while the wheel axles were kept rolling. After the data acquisition system had warmed up, pressure signals would stabilize, noises would be eliminated, and displayed pressure traces from all six gauges would appear more regular and more consistent. At this time 25 complete cycles are recorded consecutively for each gauge, one gauge at a time. Recording starts for the first cycle when the wheel carriage is heading from east to west (west bound), followed by the reversed rolling direction of this cycle (east bound). Subsequent cycles are recorded in the same fashion immediately afterward. This procedure and sequence was used at all times for all recorded pressure and strain sensor data.

Representative traces for the first of such group of cycles (i.e., two wheel passes) is shown in Figure 5.2. These are depicted for the pressure transducers placed at midspan of each specimen (sensor p2 in Mix 4, SM-2A with 15% sand; and sensor p5 in Mix 3, SM-2A with 30% sand). Even though, measurements were recorded every 10,000 load repetitions, for the sake of demonstration, traces are shown at every 20,000 repetitions. Also only the first of each 25 consecutive cycles is plotted.

It can be noted that each truck pass produces two consecutive peaks corresponding to the passage of each of the two axles of the tandem. For any particular curve, the two passes are separated by about 3.5 seconds of zero stress which correspond to the time between two consecutive truck passes. The graphs show the first peak which would be due to the front axle (heading west), immediately followed by the second axle, then after about 3.5 seconds a third peak from the second axle on its way back (heading east), and finally a forth peak from the front axle return. The time period between consecutive peaks of the front axle (first and forth peaks) is about 6.5 seconds. This is half of a complete two-way cycle that takes between 12 and 13 seconds.

The four peak values of each first cycle (such as those shown in Figure 5.2) were averaged at increments of 10,000 load repetitions. Referring to Figure 5.1, each of the south and north lanes has three pressure cells designated p1, p2, p3, and p4, p5, p6, respectively. The variation of the peak pressure with the number of load repetitions is displayed in Figure 5.3 for (a) Mix 4, SM-2A with 15% river sand (south lane), and (b) Mix 3, SM-2A with 30% river sand (north lane). Once again, these values are based on the first of the 25 consecutive cycles recorded at any particular stage for a certain transducer.

(a) Sensor p2 in Mix 4 (b) Sensor p5 in Mix 3

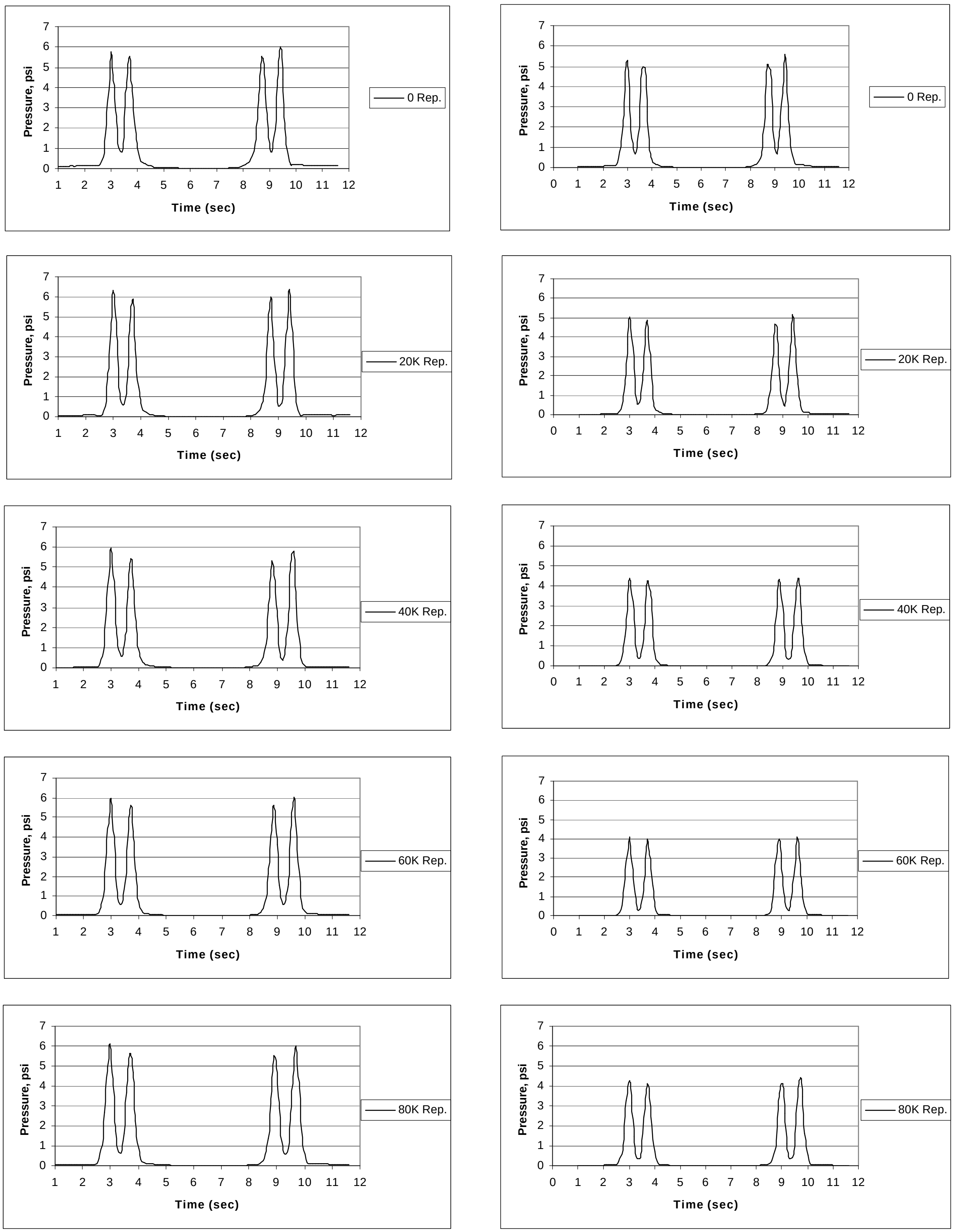
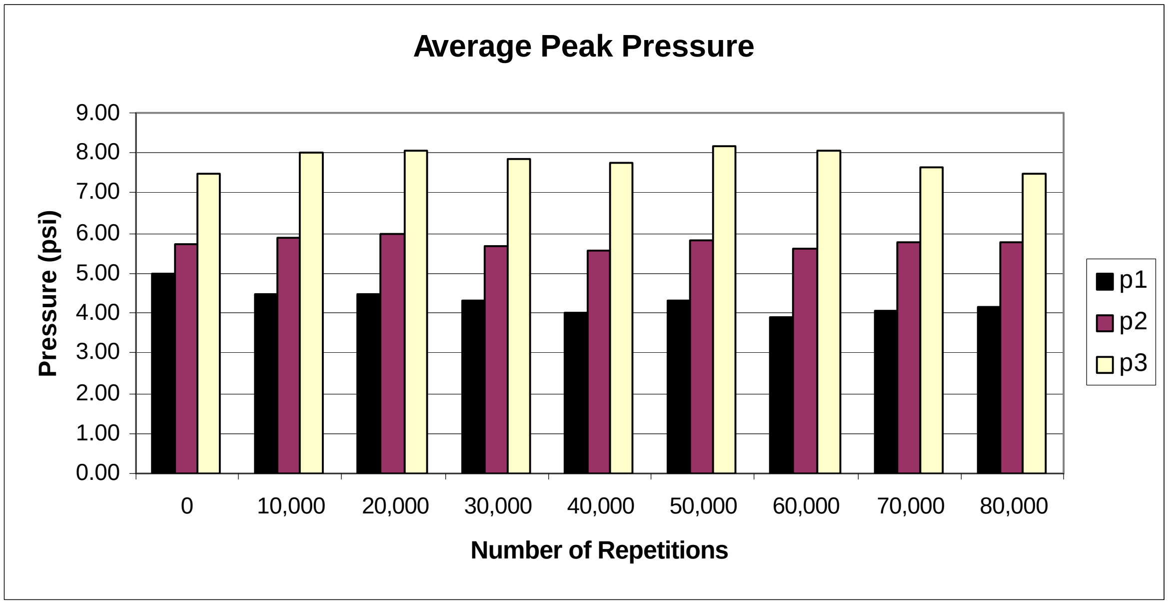
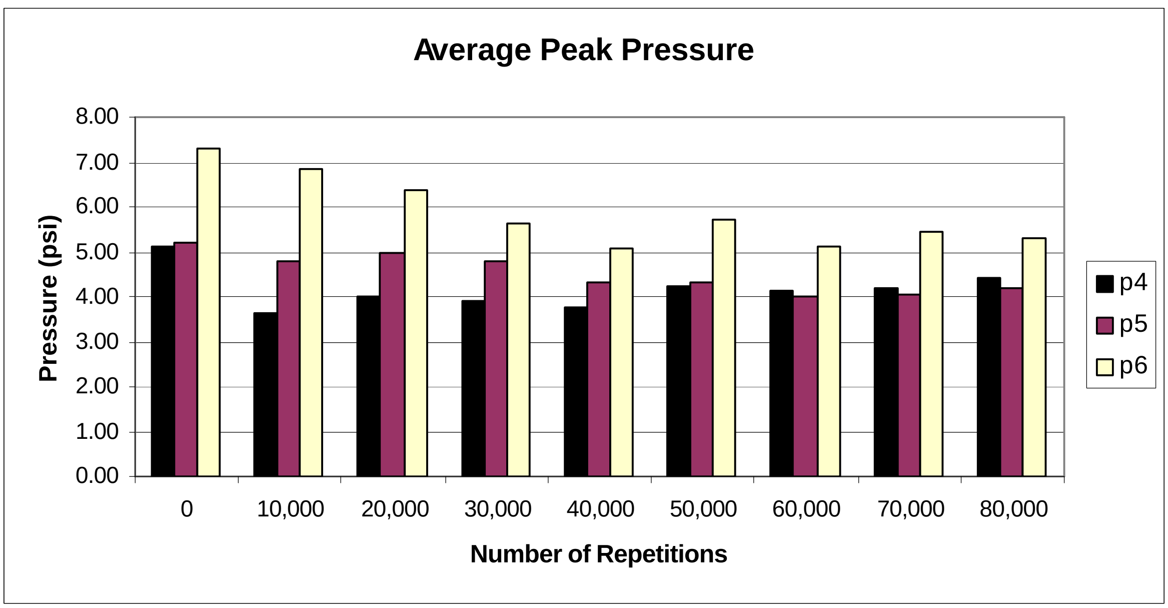


Figure 5.2 Representative Pressure Traces from Cells Located at Mid-span



(a) Mix 4 (SM-2A, 15% Sand)



(b) Mix 3 (SM-2A, 30% Sand)

Figure 5.3 Variation of Peak Pressure with Number of Load Repetitions

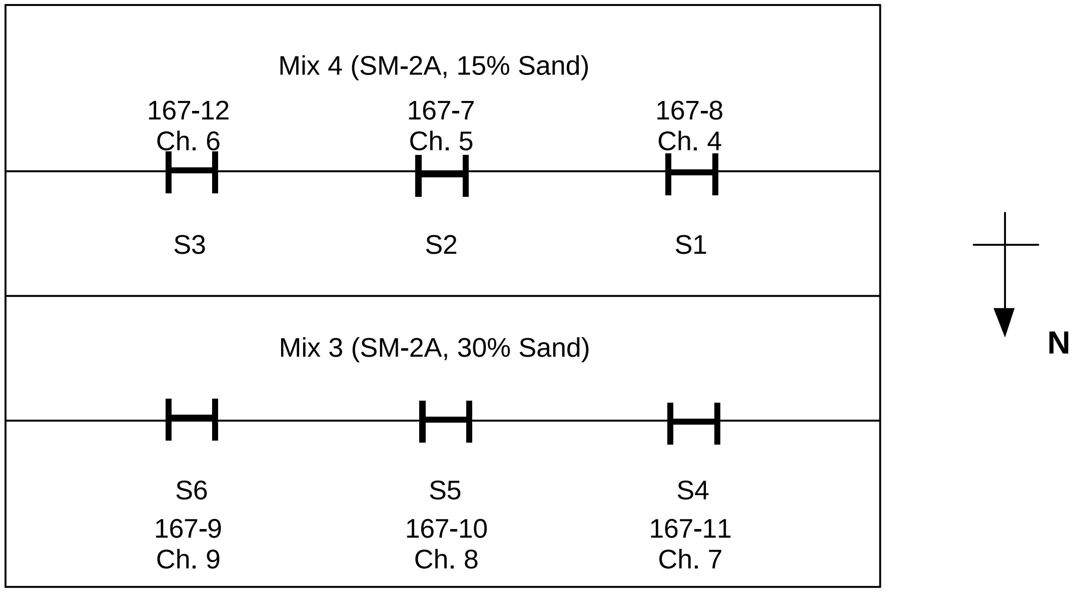
5.2 Horizontal Tensile Strains

As in the case of pressure cells, strain traces were digitally recorded under the passage of the truck tandem axle. A different computer connected to a second National Instrument data acquisition (NIDAQ) system was used to record strains. The two computers and respective NIDAQ's were run simultaneously such that at each location strain and stresses would be recorded under the same truck passage. The strain traces were displayed on the computer screen as signals from the gauges were transmitted to the data acquisition system. Signals from the strain gauges had significantly more noise than those from all six pressure cells.

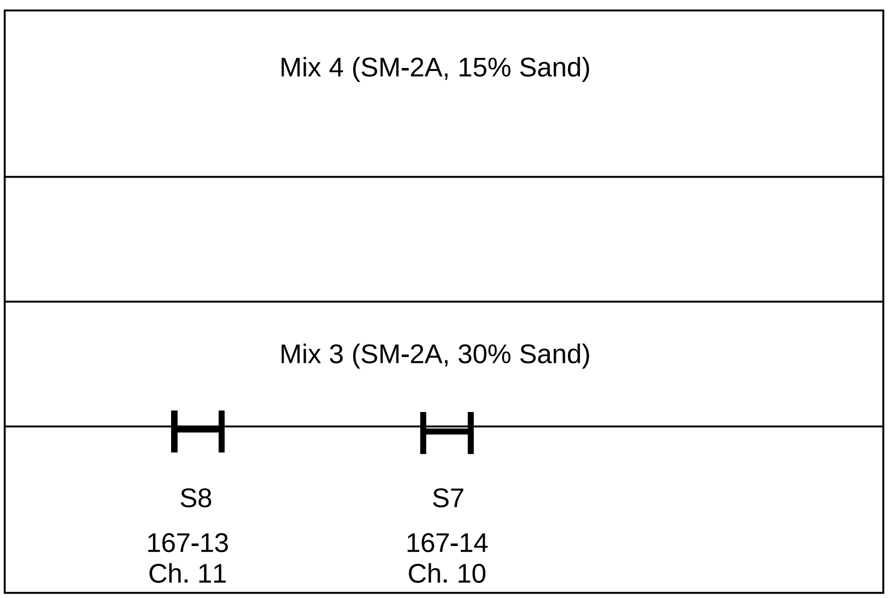
The location of the eight strain gauges was discussed in Section 4.4.1.2. These are identified in Figure 5.4 as gauges s1 through s8, along with the corresponding transducer serial number (167-xx) and channel number (Ch.x) used in the NIDAQ data acquisition system. Note that s1 through s6 were placed below the Asphalt Concrete (AC) layer (Figure 5.4 (a)) while s7 and s8 were placed at mid-depth of the AC in the north lane only (Figure 5.4 (b)). Referring to both Figures 5.1 and 5.4, it should be noted that pressure cells p5 and p6 were each recorded twice, once with strain gauges s5 and s6**,** and again with gauges s7 and s8**.** The reason for this was to obtain simultaneous strain and pressure measurements under the same truck passage at each of the designated locations (referring to Figure 4.8, it can be seen that p5, s5, s7, and p6, s6, s8 correspond to the same location in the plan).

As described in Section 5.1 for the case of the pressure cells, 25 complete cycles were recorded consecutively for each strain gauge, one gauge at a time (recording started for the first cycle when the wheel carriage is heading from east to west). Representative traces for the first of such cycles (i.e., two wheel passes) is shown in Figure 5.5. These are depicted for the strain gauges placed at midspan of each specimen (sensor s2 in Mix 4, SM-2A with 15% sand; and sensor s5 in Mix 3, SM-2A with 30% sand). Once again, even though measurements were recorded every 10,000 load repetitions, for the sake of demonstration traces are shown at every 20,000 repetitions.

The number of peaks due to the tandem axle, the time interval between consecutive truck passes, and period of zero strain between passes are the same as in the case of the soil pressure. Here, however, a small negative strain (compression) is detected slightly before the front axle of the tandem produces the peak tensile wave, and after the back axle produces the second peak tensile wave. Between the two tensile peaks, a more pronounced compression dip is noted. These phenomena are similar to others' results reported in the literature (as discussed in Chapter 1 and 4) and were consistent at all sensor locations. This stress reversal is normally attributed to the rebound of the pavement slabs due to the truck passage. Lower fibers of the slabs experience tensile strains under the wheel load due to the bending of the slab. In contrast, pressure is always negative (compression) under the slab and no tension is developed due to a truck (or wheel) passage.



(a) At Top of AB-3, 6" Below Surface of Pavement



(b) At Mid-depth of AC, 3" Below Surface of Pavement

Figure 5.4 Strain Gages Numbering and Location

Gage S2 in Mix 4 | Gage S5 in Mix 3

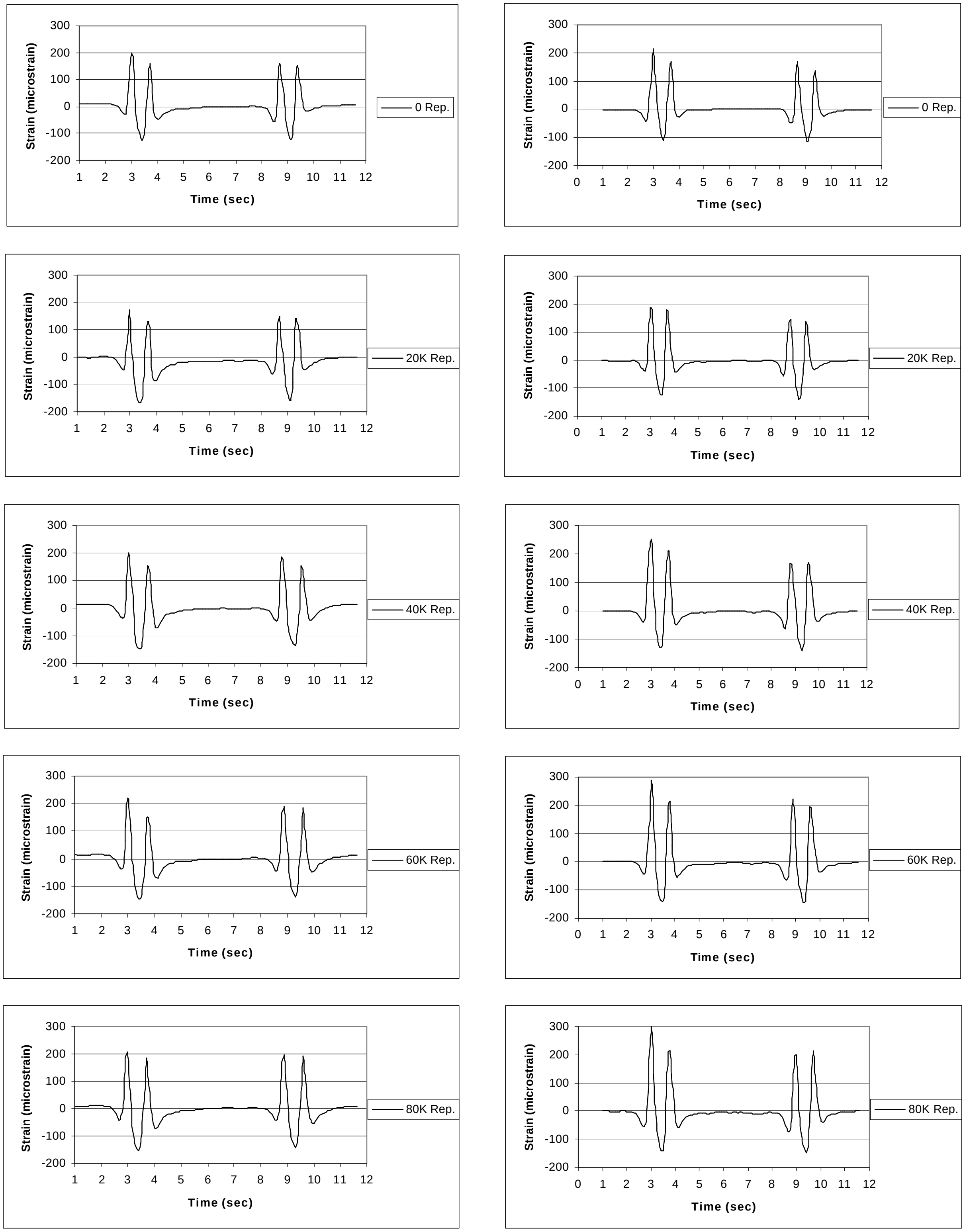


Figure 5.5 Representative Strain Traces from Gages Located at Mid-Span

The four peaks of the first recorded cycle were averaged at increments of 20,000 load repetitions. Referring to Figure 5.4(a), each of the south and north lanes has three strain gauges designated s1, s2, s3, and s4, s5, s6, respectively. The variation of the peak strain with the applied number of load repetitions is displayed in Figure 5.6 for (a) Mix 4, SM-2A with 15% river sand (south lane), and (b) Mix 3, SM-2A with 30% river sand (north lane).

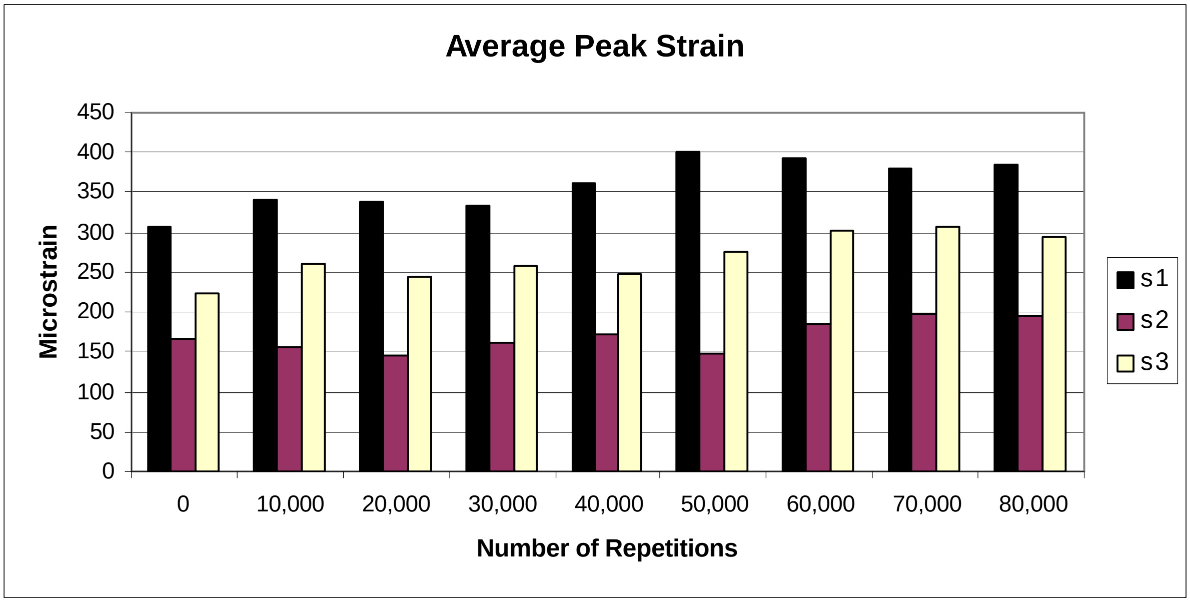
5.3 Pavement Temperature

Temperatures were recorded during the application of the wheel load cycles. These were used to verify the heat application procedure and the heating/loading combination discussed in Sections 4.3.1 and 4.3.2. Temperature logs were electronically maintained each testing day during working hours, including the times when the testing machine was run or when strain and pressure readings were being recorded. All 24 thermocouples, at the different depth and locations (see Figure 4.8), were recorded every 30 minutes, on the average.

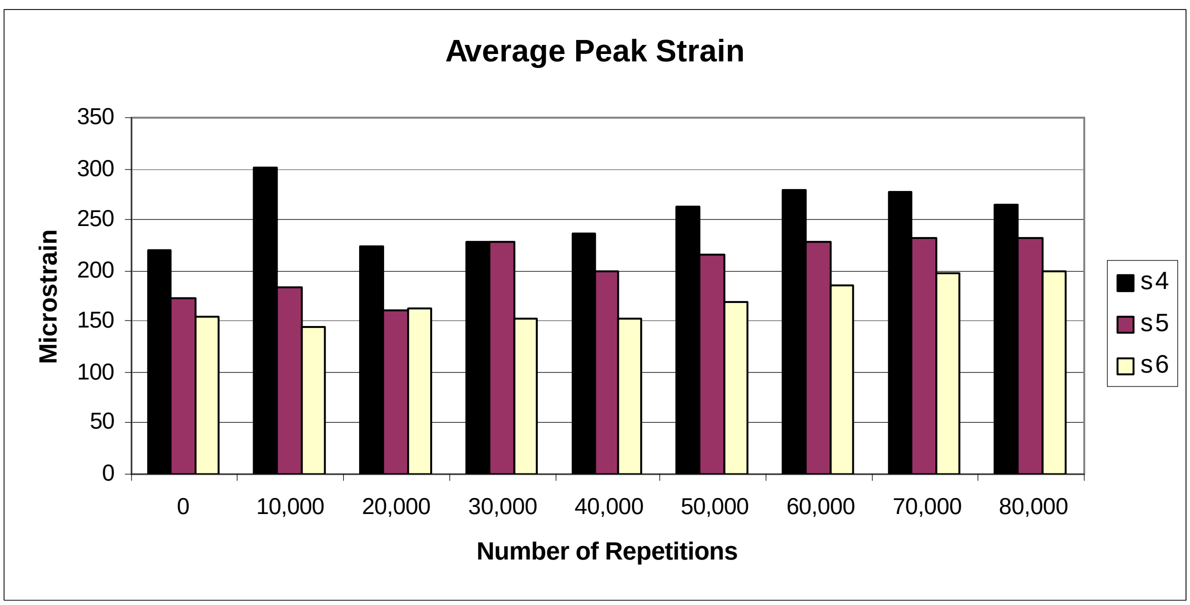
5.4 Asphalt Concrete Density

The (wet) density of the asphalt concrete was measured at the beginning of the test and every 10,000 repetitions thereafter, up to 80,000 for all four slabs. Recalling Figure 4.1, Mixes 1 and 2 were in the north pit (control sections), while Mixes 3 and 4 were in the south pit (test sections). For each of the two pits, measurements were made at three locations on each of the south and north slabs, designated 1, 2, 3 and 4, 5, 6, respectively. These locations were selected at the quarter-span points along the north track of each pair of wheel paths. For the test sections, they correspond longitudinally to the location of the strain gauges embedded under the pavement.

At each location, three one-minute readings of the nuclear gauge were taken and averaged. The variation of the asphalt concrete density with the number of load repetitions applied to the pavement sections is depicted in Figure 5.7. It can be observed that the values do not change significantly except from the initial conditions before any load was applied.



(a) Mix 4 (SM-2A, 15% Sand)



(b) Mix 3 (SM-2A, 30% Sand)

Figure 5.6 Variation of Peak Strains with Number of Load Repetitions

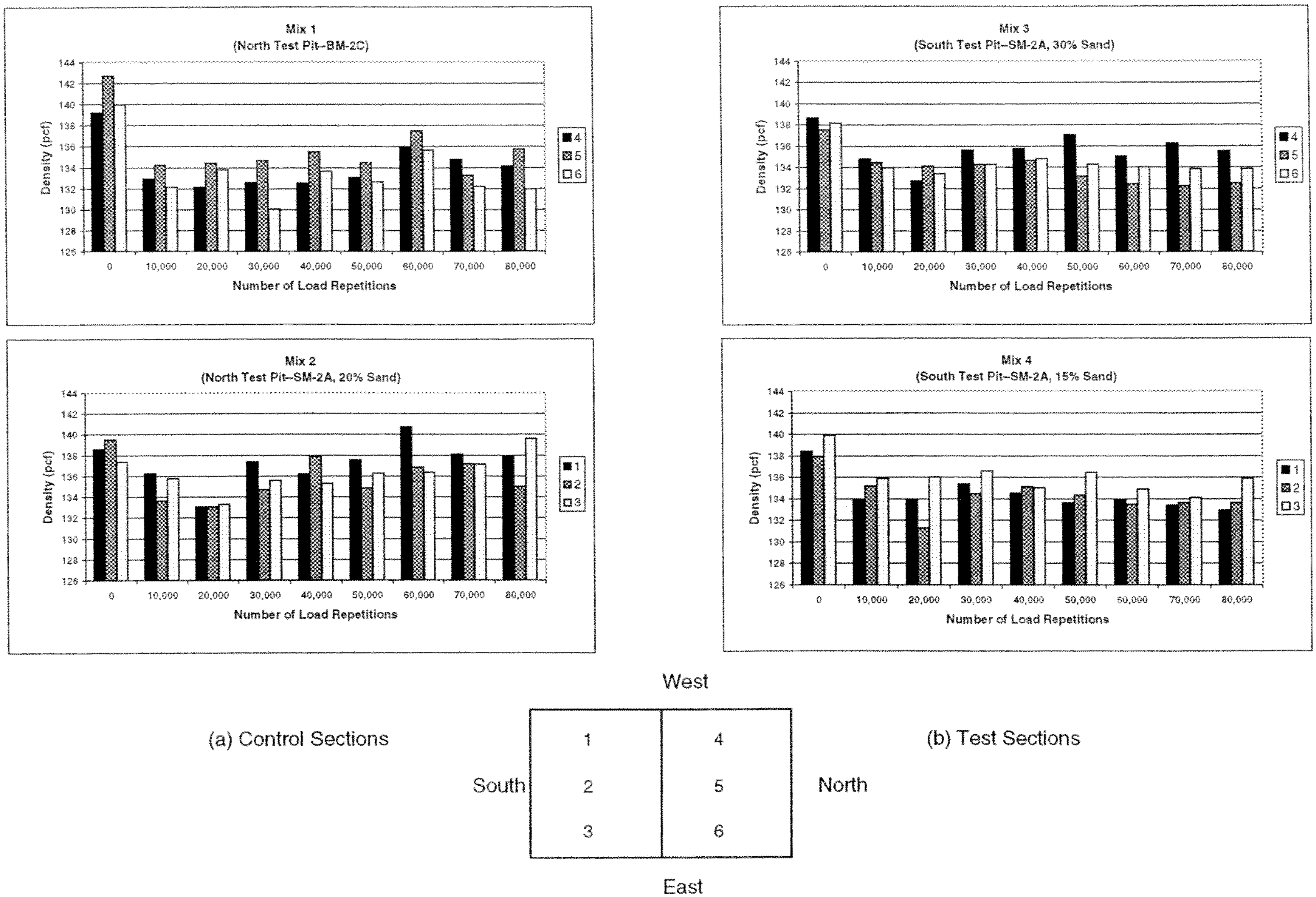


Figure 5.7 Variation of Asphalt Concrete Density with Number of Load Repetitions

5.5 Pavement Surface Rutting

Surface rutting was measured using both a Face Dipstick device and the Transverse Rut Measuring Device developed at the K-ATL and described in Section 4.5.3. Using the Face Dipstick, surface elevations of the pavement are measured at 305 mm (12 in.)-intervals, corresponding to the swiveling feet of the apparatus. Readings were recorded manually as the device was moved along a straight path. A two-way passage on any given path allows corrections to be made such that the elevation of the ending point would correspond to that of the initial point and ensure that the loop is closed correctly. This was most useful to construct the longitudinal profiles.

With the Transverse Rut Measuring Device, a more accurate reading elevation could be measured and electronically recorded every 13 mm (1/2 in.). This allowed plotting of a more precise and more accurate surface profile that depicts the progression of asphalt rutting under the fixed wheel paths.

5.5.1 Longitudinal Profiles

Longitudinal profiles were constructed using readings from the Face Dipstick device. As indicated in Tables 5.1 and 5.2, longitudinal profiles were constructed (for both the control sections and test sections) at the beginning of the tests and after each 10,000 load applications, as well as at the end of the tests. These were measured along a line spanning the entire length of the slabs (6.1 m or 20 ft). Measurements started always at the East heading West and back to the starting point. Longitudinal profiles followed chalk-lines traced at the center of the outer track of any dual's path; for a north lane, that would be the north track, and for a south lane the south track.

The changes in the longitudinal profiles are shown in Figures 5.8 through 5.11, for Mixes 1 through 4, respectively. It should be noted that the first and last 610 mm (2 ft) of the tracks (towards the east and west edges of the pavement sections) are where the wheel carriage gets on and off the pavement slabs onto the lab floor. During testing these regions are subject to the worst impact from the carriage which causes dipping in the longitudinal tracks at the beginning and the end of the path. These were periodically filled with additional asphalt repair material to level up the ramp on and off the lab floor. The profiles measurements could have been taken before or after these ramps were formed, and therefore the variation in the first and last two feet of the longitudinal profile can be disregarded.

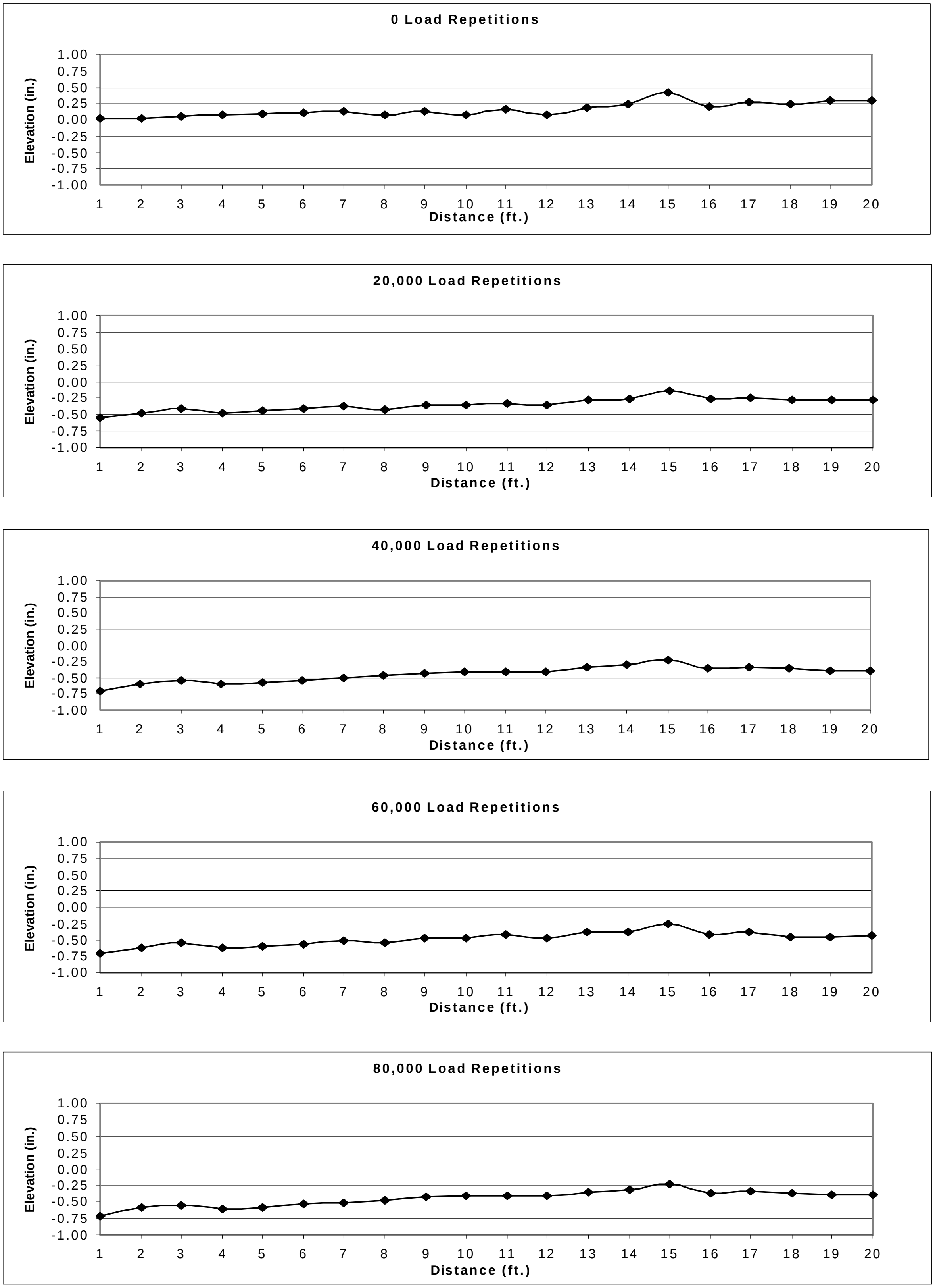


Figure 5.8 Change in Longitudinal Profile with Loading for Mix 1

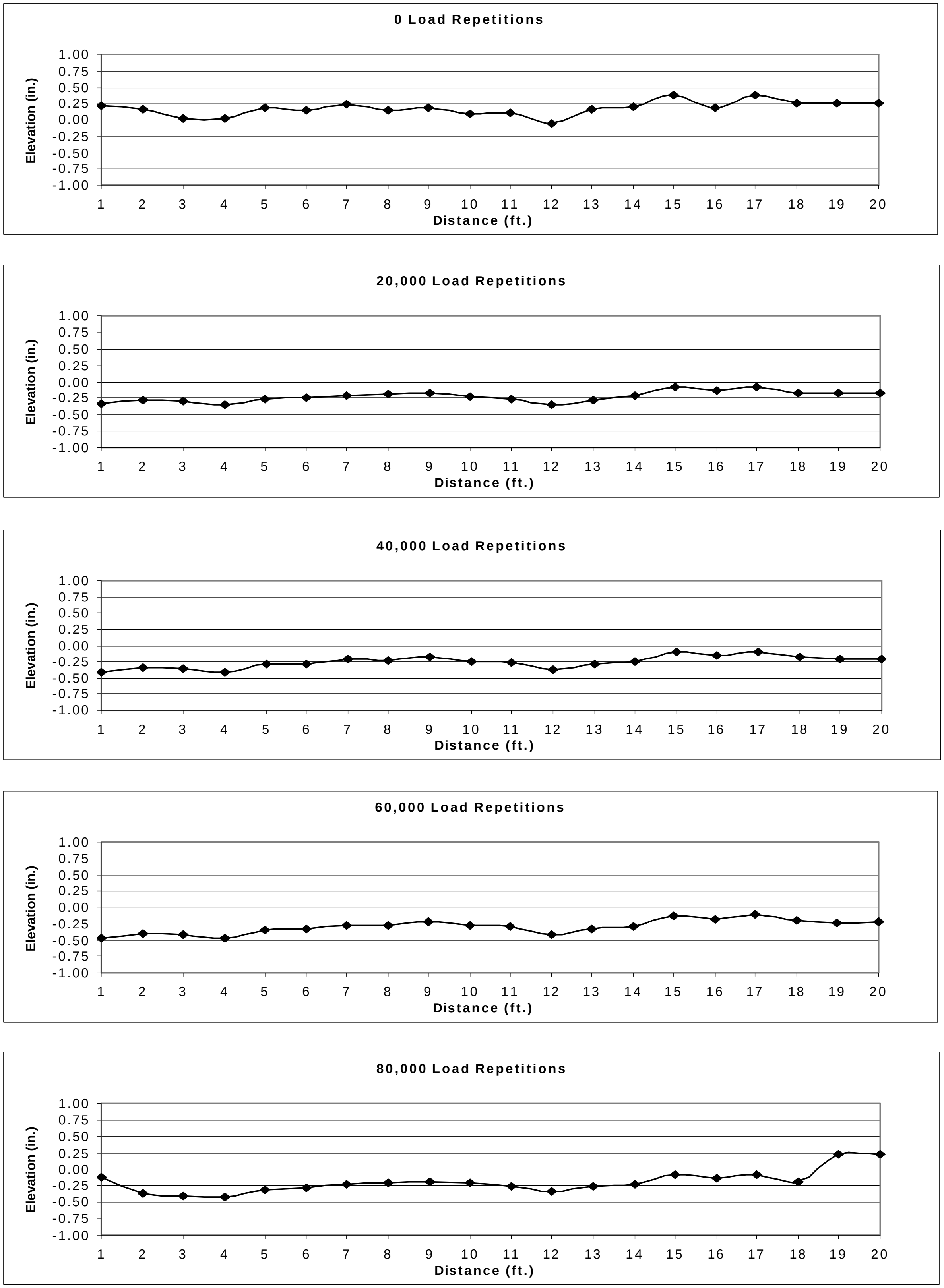


Figure 5.9 Change in Longitudinal Profile with Loading for Mix 2

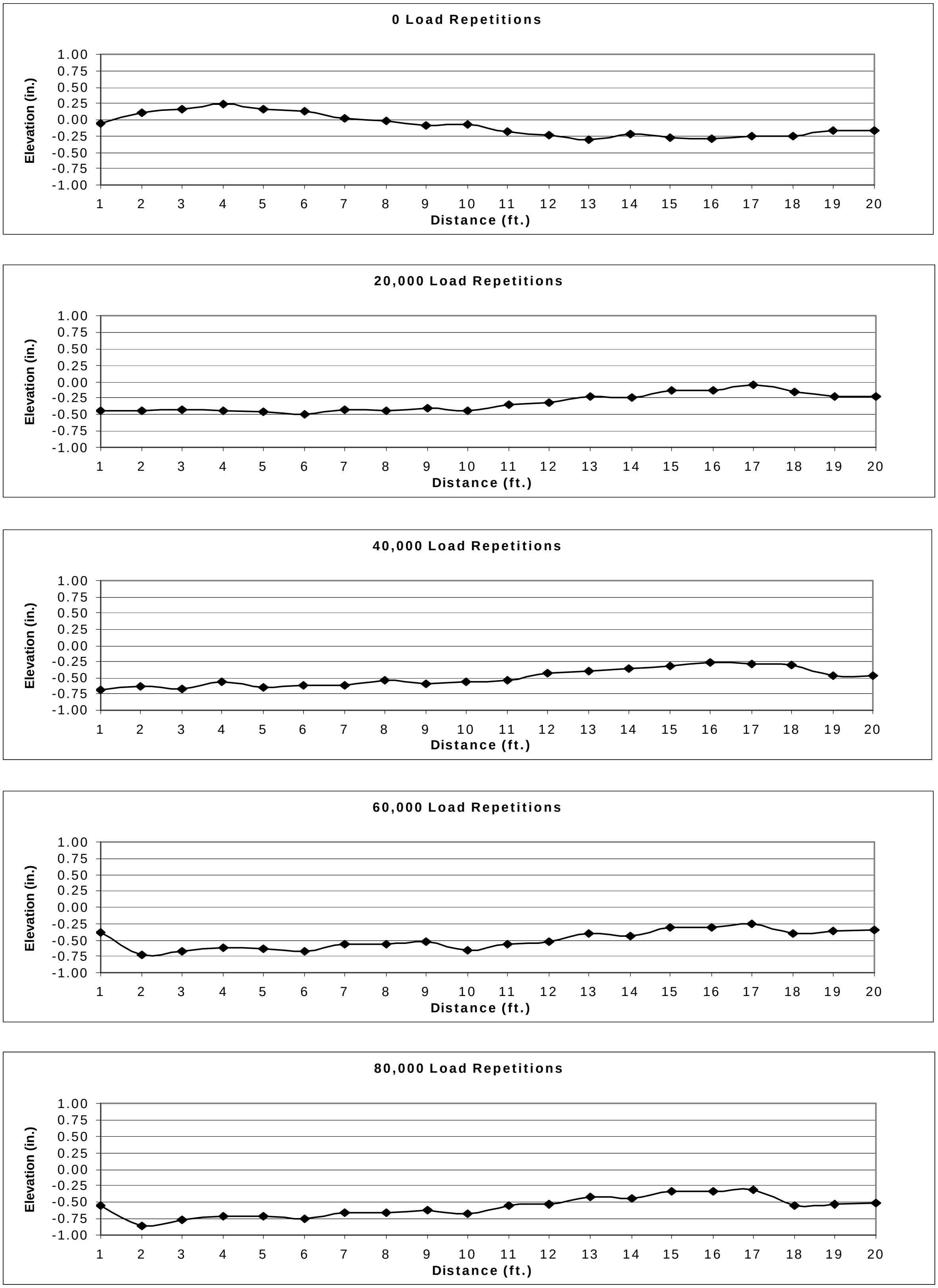


Figure 5.10 Change in Longitudinal Profile with Loading for Mix 3

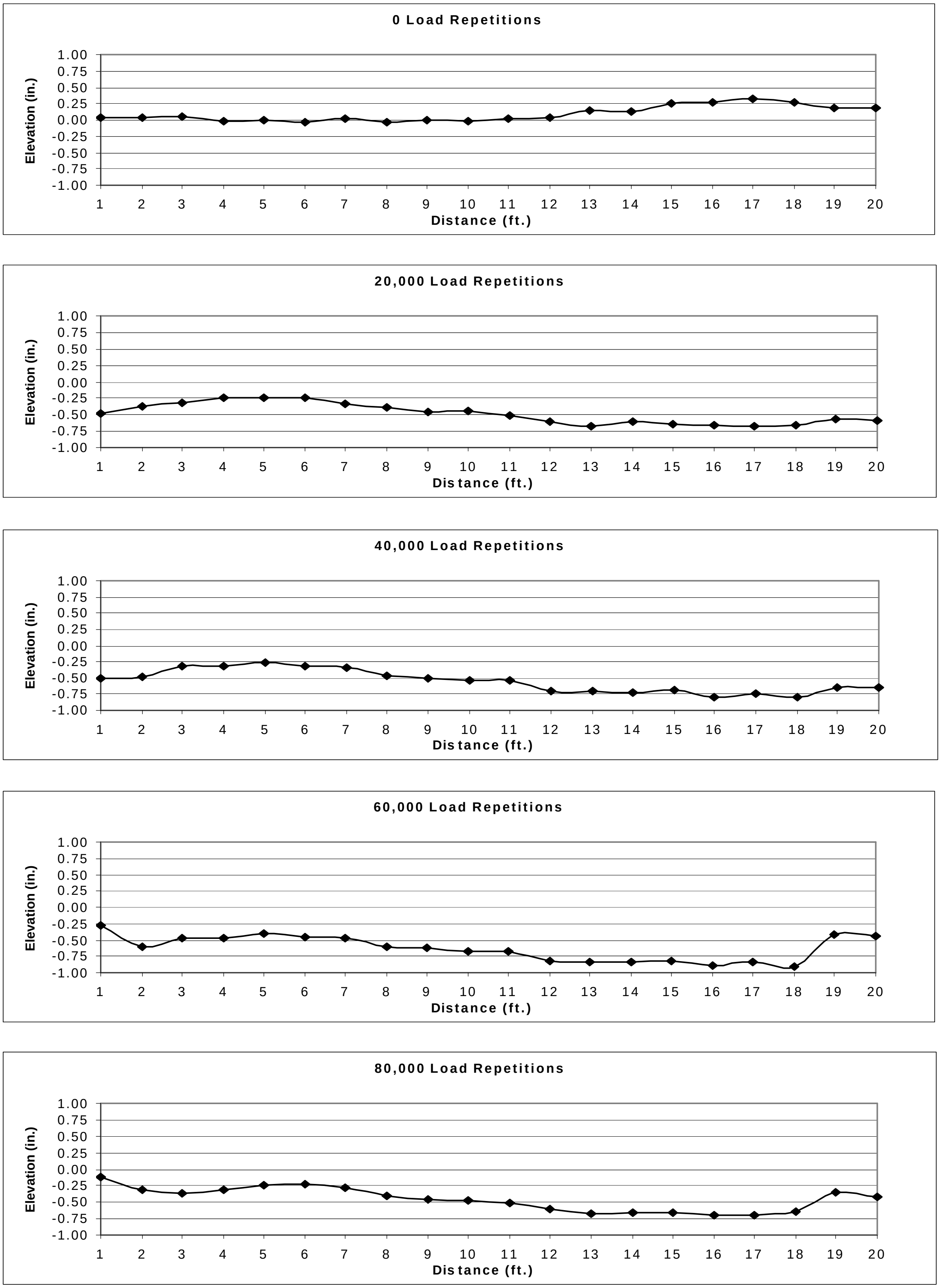


Figure 5.11 Change in Longitudinal Profile with Loading for Mix 4

5.5.2 Transverse Profiles

As indicated in Tables 5.1 and 5.2 transverse profiles were also constructed (for both the control sections and test sections) at the beginning of the tests and after each 10,000 load applications, as well as at the end of the tests. The change in elevation between the different loading stages indicates the progression of rutting, and comparison with the initial profile gives an indication of the total rut depth.

The physical definition of rutting is the longitudinal depressions in the wheel paths accompanied by upheavals to the sides [11]. The K-ATL single or tandem axles have two wheels per axle, and each wheel has a pair of tires. When asphalt concrete material is displaced (by plastic deformation) from under the wheels to the sides of the wheel tracks the deepest valleys are at the centerline of the tire tracks and heaves would form outside and between the dual tracks of any given wheel. As shown in Figures 5.12 through 5.15 the highest heave is between the two tire tracks.

<u>Evaluation of Rutting</u>

In this experiment, rutting is taken as the difference between the lowest point on a profile (usually at, or close to, the centerline of an individual tire track) and an imaginary straight edge resting on the test lane surface and spanning an individual tire track. This method of rut measurement is similar to the one used by White and Hua [5]. There are certainly other ways of quantifying ruts, but this one is followed here and throughout this study for comparison purpose. Rutting defined by different methods can be easily obtained by measuring directly off the constructed profile curves.

As indicated earlier, two apparatuses were used to measure the pavement surface elevation every 10,000 load repetitions for all four sections. Rutting computations were based on the profiles constructed using the Transverse Rutting Measurement Device. The device length is 3.66 m (12 ft; measuring range is 267 cm or 105 inches), therefore, covering the width of both wheel paths of the tandem axle. Therefore each two adjacent sections were measured at once: Mixes 1 and 2 (control sections) side-by-side in the north pit, and Mixes 3 and 4 (test sections) side-by-side in the south pit. The covered width is beyond most of the heaves that are formed along the outside edges of the wheel paths.

Measuring always started on the south side of the south lane, going North across a pair of adjacent pavement section, to the north side of the north lane. Anchor screws were fixed in the pavement to ensure that the rutting measurement device base plates were always installed at the same location every time measurements are taken. These screws, and consequently the resulting profiles, were positioned at mid-span of the slabs (labeled “Middle Profiles”) and 1.52 m (5 ft) from the east and west ends (labeled “East Profiles” and “West Profiles,” respectively).

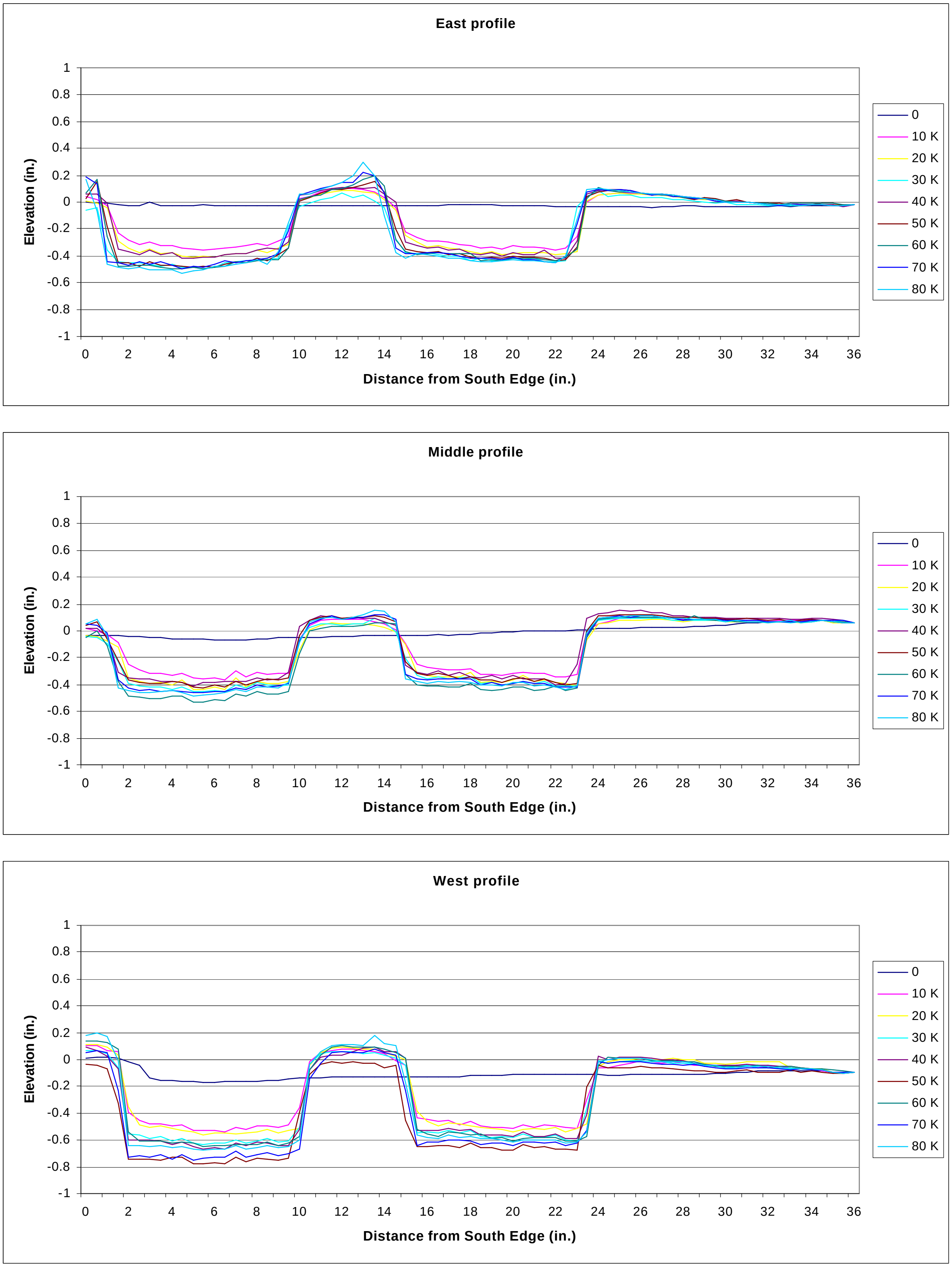
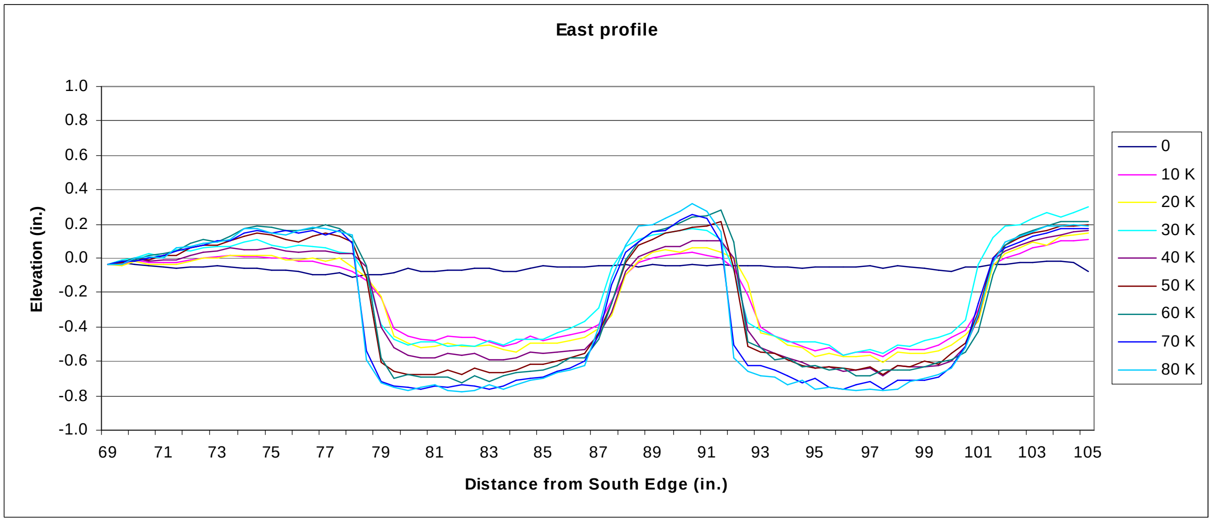
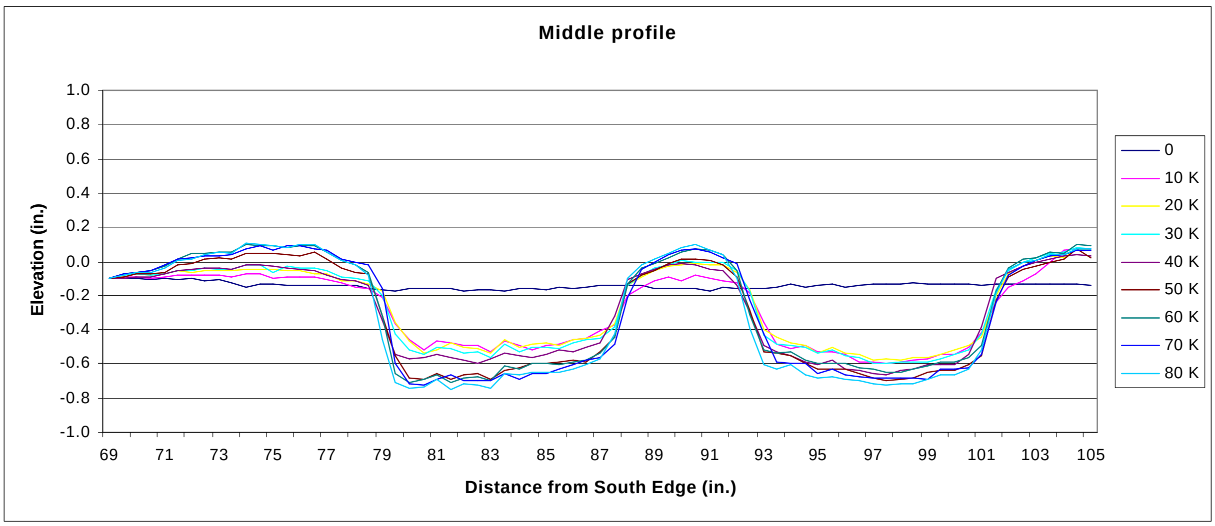


Figure 5.12 Transverse Profile and Progression of Rutting for Mix 2





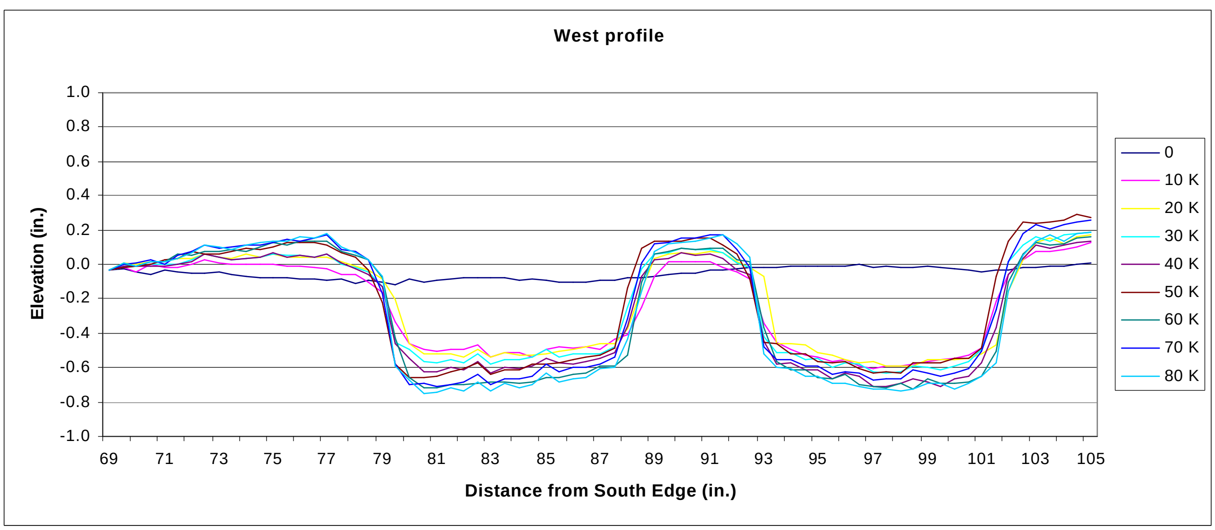


Figure 5.13 Transverse Profile and Progression of Rutting for Mix 1

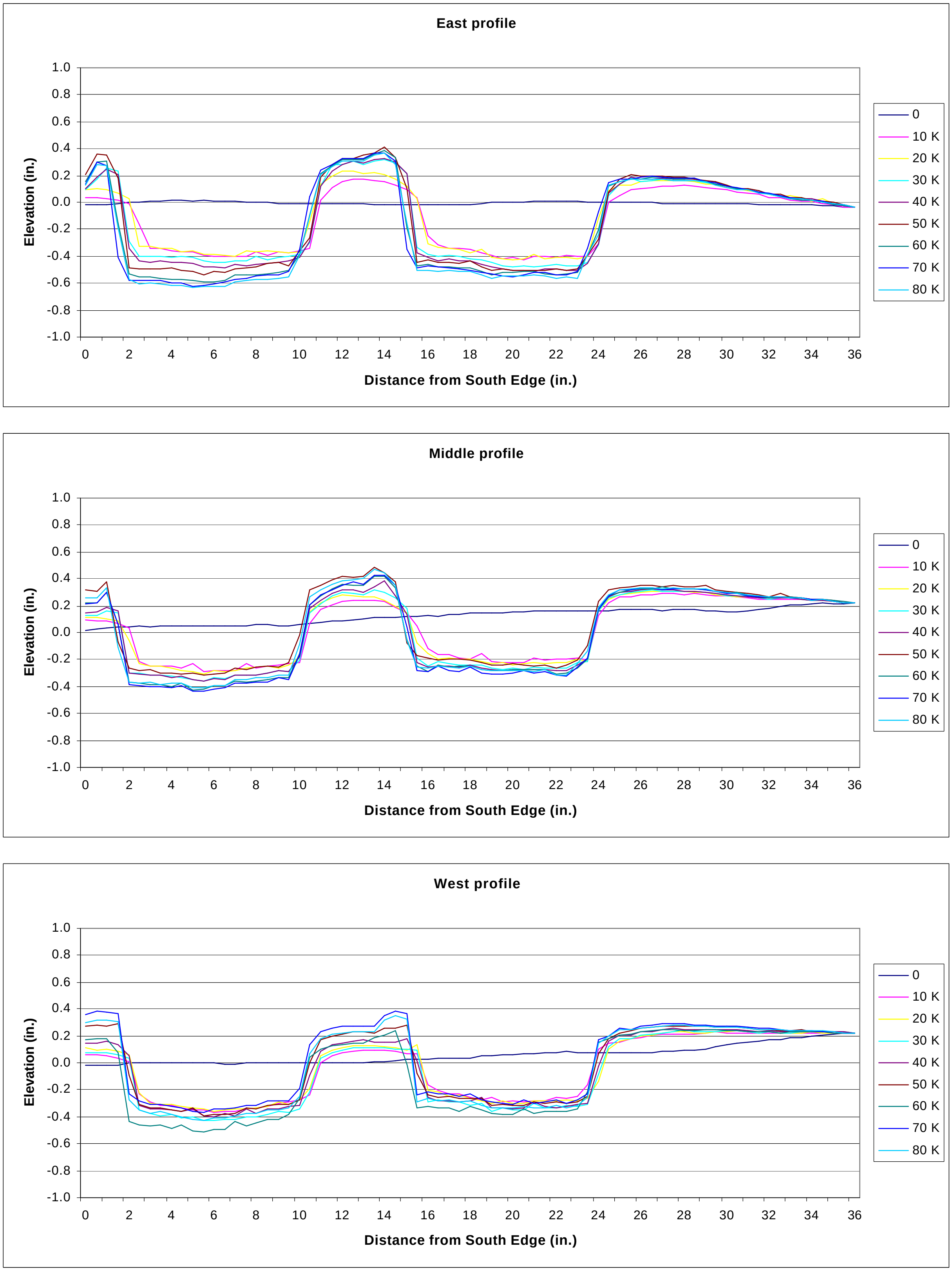
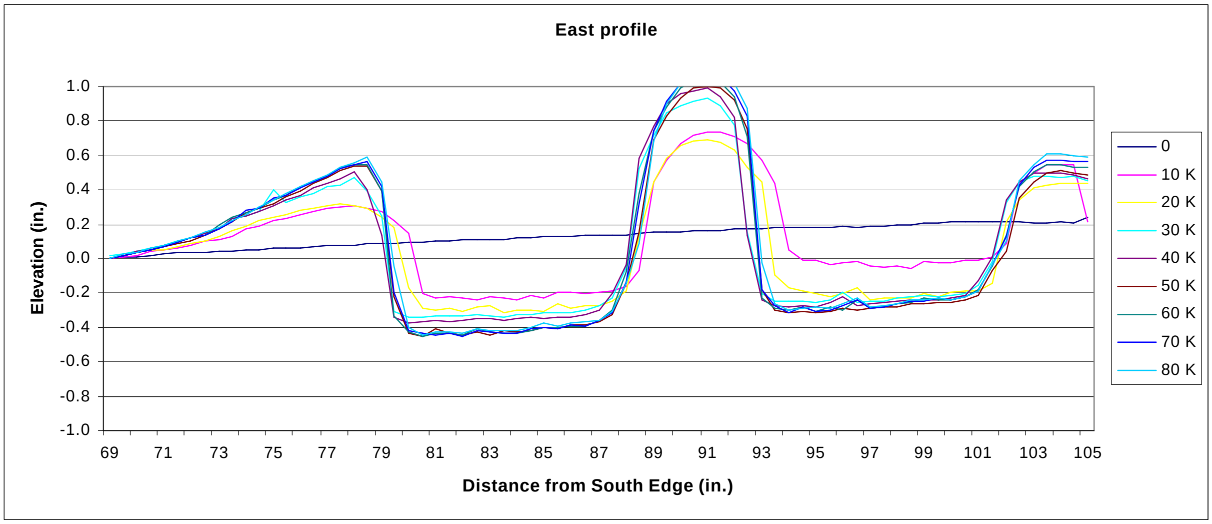
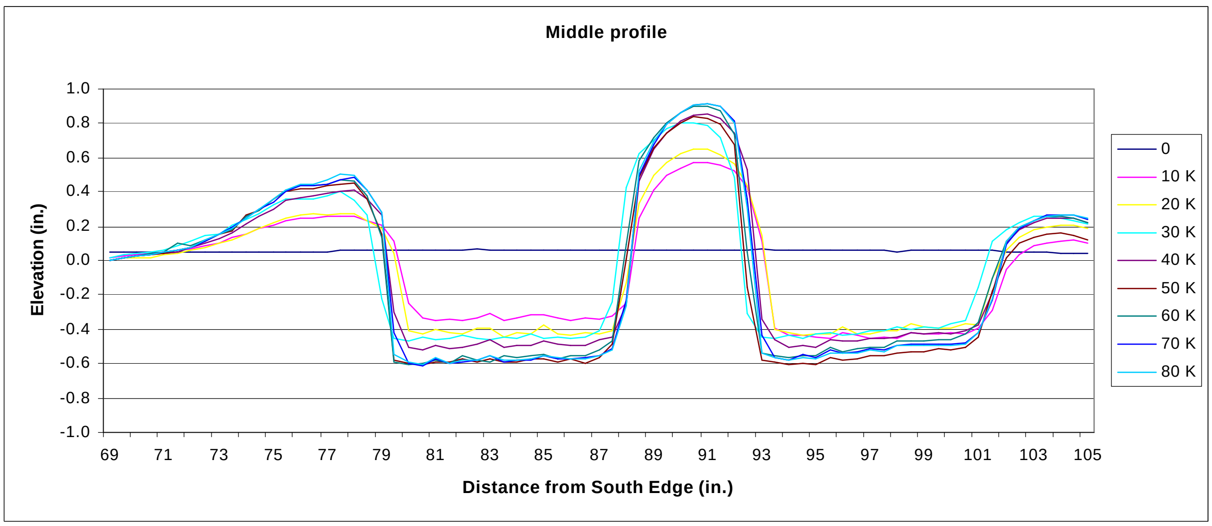


Figure 5.14 Transverse Profile and Progression of Rutting for Mix 4





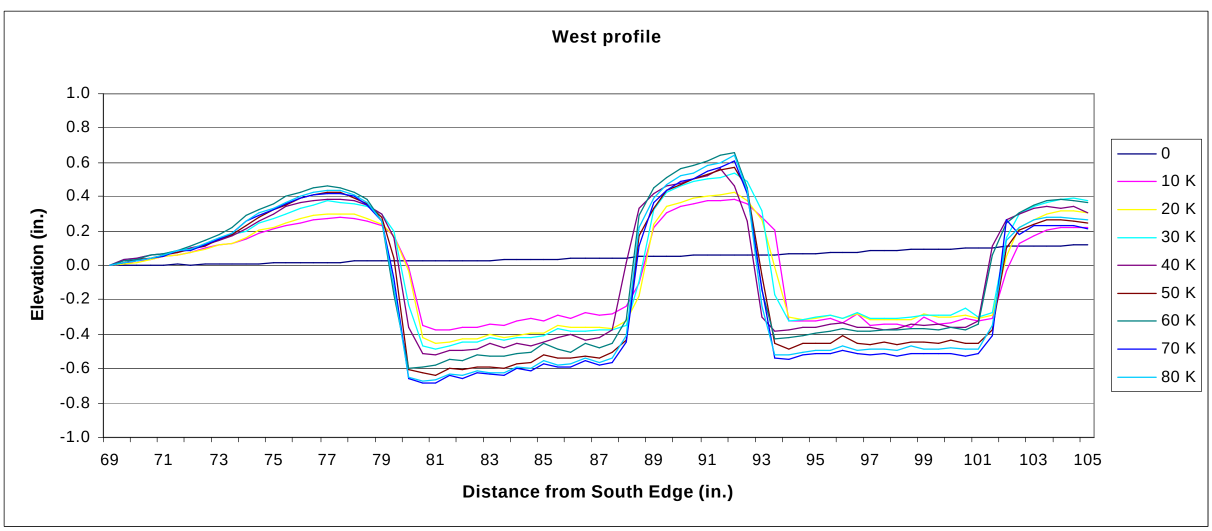


Figure 5.15 Transverse Profile and Progression of Rutting for Mix 3

The surface profiles constructed at the start of the experiment and after each 10,000 load applications are shown in Figures 5.12 through 5.15 for the four sections tested in this experiment. This gives an indication of the progression of rutting in each section relative to the number of load passes applied. In each figure, three graphs are presented showing the east, middle, and west profiles, respectively. Since the passage of the truck normally does not have much affect on the portions away from the wheel path, detailed profile curves were constructed only for the main portion of the wheel path. This gives a width coverage of 91 cm (36 in.) for each wheel. Noting that Mixes 1 and 2, and 3 and 4 were tested in pairs, so too were the measurement of their surface profiles, as graphed in Figures 5.12 and 5.13. This is why Mix 2 is reported before Mix 1, since Mix 2 was in the south lane and Mix 1 was in the north lane and measuring started from the south edge. For this reason the distance from the south edge is shown as 25 mm to 915 mm (1 to 36 in.) in Figure 5.12 and 1.75 m to 2.67 m (69 to 105 in.) in Figure 5.13. This is also the case for Mixes 4 and 3 in Figures 5.14 and 5.15.

The magnitude of the rut depths (as defined above) in each of the east, middle and west profiles for Mixes 1 though 4 are presented in Tables 5.3 through 5.6, respectively. The rut marks along the wheel paths for the test sections (middle pit) can be seen in Figure 5.16, with Mix 3 on the left of the picture and Mix 4 on the right.

Figure 5.16 Wheel Marks on the Test Sections at the end of 80,000 Load Applications of the ATL 36 Kip-Tandem Axle.

Table 5.3 Rutting Depths (in.) for North Pit, North Wheel Path (BM-2C)--Mix 1

No. of Reps.	East Profile			Middle Profile			West Profile		
	South Tire	North Tire	Avg.	South Tire	North Tire	Avg.	South Tire	North Tire	Avg.
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10,000	0.52	0.63	0.58	0.41	0.58	0.50	0.55	0.67	0.61
20,000	0.56	0.69	0.63	0.51	0.59	0.55	0.58	0.70	0.64
30,000	0.64	0.76	0.70	0.54	0.64	0.59	0.64	0.78	0.71
40,000	0.67	0.80	0.74	0.59	0.64	0.62	0.69	0.81	0.75
50,000	0.86	0.87	0.87	0.68	0.73	0.71	0.78	0.85	0.82
60,000	0.96	0.94	0.95	0.78	0.74	0.76	0.84	0.85	0.85
70,000	0.98	0.98	0.98	0.80	0.76	0.78	0.85	0.88	0.87
80,000	1.02	1.02	1.02	0.84	0.81	0.83	0.91	0.91	0.91

Table 5.4 Rutting Depths (in.) for North Pit, South Wheel Path (SM-2A, 20% Sand)--Mix 2

No. of Reps.	East Profile			Middle Profile			West Profile		
	South Tire	North Tire	Avg.	South Tire	North Tire	Avg.	South Tire	North Tire	Avg.
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10,000	0.42	0.43	0.43	0.41	0.43	0.42	0.61	0.55	0.58
20,000	0.45	0.48	0.47	0.44	0.48	0.46	0.64	0.60	0.62
30,000	0.50	0.50	0.50	0.48	0.51	0.50	0.68	0.64	0.66
40,000	0.50	0.50	0.50	0.48	0.52	0.50	0.75	0.65	0.70
50,000	0.64	0.54	0.59	0.51	0.54	0.53	0.76	0.65	0.71
60,000	0.68	0.58	0.63	0.55	0.55	0.55	0.77	0.66	0.72
70,000	0.70	0.60	0.65	0.55	0.55	0.55	0.82	0.68	0.75
80,000	0.74	0.64	0.69	0.61	0.58	0.60	0.83	0.73	0.78

Table 5.5 Rutting Depths (in.) for Middle Pit, North Wheel Path (SM-2A, 30% Sand)--Mix 3

No. of Reps.	East Profile			Middle Profile			West Profile		
	South Tire	North Tire	Avg.	South Tire	North Tire	Avg.	South Tire	North Tire	Avg.
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10,000	0.72	0.74	0.73	0.78	0.78	0.78	0.70	0.68	0.69
20,000	0.80	0.82	0.81	0.92	0.88	0.90	0.81	0.70	0.76
30,000	1.00	0.95	0.98	1.07	0.98	1.03	0.93	0.76	0.85
40,000	1.08	1.02	1.05	1.10	1.10	1.10	0.99	0.83	0.91
50,000	1.16	1.08	1.12	1.24	1.15	1.20	1.12	0.92	1.02
60,000	1.18	1.10	1.14	1.29	1.18	1.24	1.15	0.96	1.06
70,000	1.22	1.13	1.18	1.31	1.21	1.26	1.18	1.00	1.09
80,000	1.24	1.21	1.23	1.32	1.22	1.27	1.21	1.06	1.14

Table 5.6 Rutting Depths (in.) for Middle Pit, South Wheel Path (SM-2A, 15% Sand)--Mix 4

No. of Reps.	East Profile			Middle Profile			West Profile		
	South Tire	North Tire	Avg.	South Tire	North Tire	Avg.	South Tire	North Tire	Avg.
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10,000	0.50	0.58	0.54	0.43	0.48	0.46	0.44	0.41	0.43
20,000	0.56	0.64	0.60	0.49	0.52	0.51	0.49	0.46	0.48
30,000	0.71	0.73	0.72	0.62	0.59	0.61	0.51	0.51	0.51
40,000	0.76	0.77	0.77	0.62	0.64	0.63	0.57	0.55	0.56
50,000	0.90	0.83	0.87	0.72	0.69	0.71	0.70	0.60	0.65
60,000	0.93	0.85	0.89	0.77	0.69	0.73	0.70	0.63	0.67
70,000	0.96	0.88	0.92	0.79	0.71	0.75	0.76	0.63	0.70
80,000	0.97	0.88	0.93	0.90	0.74	0.82	0.78	0.69	0.74

5.6 Cores and Trenches

A number of cores were drilled in the wheel path and away from the wheel path at the end of the experiment. Coring was performed by KDOT personnel. The diameter of the cores were 102 mm (4 in.) and were drilled through the full depth of the pavement. The cores taken from the test sections, as well as a number of beam specimens for fatigue tests, were cut from these pavement sections, and given to the principal investigators of the K-TRAN Project for further experimental and analytical studies. Cores taken from the control sections were given to KDOT engineers for further analysis.

A full-depth transverse trench was saw-cut through the width of the test sections in the middle pit to have a visual observation of the asphalt concrete layer. About 51 mm (2 in.) of the aggregate base material was also removed to expose the separation line between the bottom of the pavement layer and the top of the AB-3 base. A close-up view of SM-2A sections is shown in Figure 5.17 for Mix 4 (15% sand) and in Figure 5.18 for Mix 3 (30% sand). No evident indication was found of any consolidation or compaction of the subgrade soil or aggregate base layer below the pavement.

Figure 5.17 Side Wall of Cut Trench in SM-2A Test Section with 15% Sand

Figure 5.18 Side Wall of Cut Trench in SM-2A Test Section with 30% Sand

5.7 Summary and Conclusions

The experiment met the estimated maximum number of passes for each of the control sections and test sections, which is 80,000 repetitions. A fixed wheel pass (zero lateral wander) was followed and two-pass cycles (two-way traffic) were applied throughout the tests. Loading consisted of rolling wheel passes of a dual tandem axle of 150 kN (34 kips). Tire pressure was 620 kPa (90 psi). In general, load cycles were applied when the surface temperature of the pavement was around 50°C (122°F) while mid-depth temperature was maintained around 37.8 ± 2.2°C (100 ± 4°F). Consequently, the temperature gradient between the surface and mid-depth of the pavement remains always no less than -6.7°C (20°F).

Rutting was measured every 10,000 load repetitions. The rutting at the terminal stage (at the end of 80,000 repetitions) is summarized in Table 5.7. Values are shown for each of the four mixes at the west, middle, and east transverse profile locations. The last column in Table 5.7 gives the average of the final rutting for each mix.

Table 5.7 Summary of Rutting (in.)

	West	Middle	East	Average
Control Sections:				
- Mix 1 (BM-2C)	0.91	0.83	1.02	0.92
- Mix 2 (SM-2C, 20% Sand)	0.78	0.60	0.69	0.69
Test Sections:				
- Mix 3 (SM-2C, 30% Sand)	1.14	1.27	1.23	1.21
- Mix 4 (SM-2C, 15% Sand)	0.74	0.82	0.93	0.83

By comparing the final rutting (average from the three locations), it can be noted that, except for the mix with 30% sand, Superpave mixes show less rutting than the Marshall mix. The best performing mix of all four sections is Mix 2, indicating that 20% ratio is the optimum sand content in these Superpave mixes. On the other hand, 30% ratio is the worst sand content and resulted in the most rutting (unacceptable, more than one inch).

When comparing each of the pair of sections tested side-by-side, the following may be concluded:

- The best performing Superpave mix (Mix 2) shows a final rutting of 75% of the adjacent BM-2C mix (Mix 1), a typical common Marshall mix used in Kansas.

- The worst performing Superpave mix (Mix 3) shows a final rutting of about 1.5 times the corresponding mix (Mix 4), which suggests that 30% sand is excessive and not recommended.

Looking at the four sections all together, it can be concluded that:

- When adequately designed, Superpave mixes perform better than Marshall mixes.

- The optimum sand content is 20%, which results in about an 18 mm (0.7 in.) rut.

- For a ratio of sand 5% less than the optimum (i.e., 15%) rutting is increased by about 20%. Performance is not as good, but is still better than the Marshall mix.

- For a ratio of sand 10% more than the optimum (i.e., 30%) rutting is increased by about 75%. Performance is very poor, and rut is significantly worse than even the conventional Marshall mix.

It should be noted that actual service life of similar pavements on the highway will be much longer than the one experienced in the accelerated testing environment. The frequency of occurrence of high axle-loads being applied exactly on the same path and at the rate of 10 repetitions per minute (600 repetitions per hour) is higher than normal traffic conditions. Even on heavy traffic highways, chances are slim that the same type of load axles will hit the exact same spots on the wheel path so frequently. On the other hand, it has been established that the axle of a testing machine (such as that of the K-ATL moving at a speed of 5-7 mph) produces much more damage than those of trucks running at 60 or 70 mph. This is mainly due to the fact that the tires of the slower axles are in contact with the surface at any certain spot along the path much longer than tires of a running truck. These are all characteristics of accelerated pavement testing.

Accelerated pavement testing can give a very good performance assessment when two pavement mixes or pavement types are compared side-by-side. The relative behavior is a good qualitative indication of pavement performance. It gives a general evaluation of how well an alternate design works when compared to a typical design.

Data collected from longitudinal tensile strains below the pavement, soil pressure in the subgrade, asphalt wet densities, material testing, surface elevations and longitudinal profile curves have been collected, properly classified, and documented. Initial analysis of this data did not show a significant trend or pattern for the variation of these parameters as load cycles are applied, or theoretically, damage is indued. However, such data can be used in further research and more detailed analysis. It is made available to future analytical studies and is suitable for comparison with results from numerical modeling and computational methods. For instance, a comparison of the responses computed from the FWD back-calculated layer moduli and the measured responses has been reported by Bhuvanagiri *et al.* [10]. Also they reported attempts to correlate the variation in the longitudinal tensile strains and the vertical compressive stress to possible changes in the AC layer moduli and the modulus of the aggregate base.

The rutting observed in this experiment agree with most of the remarks made by the surrogate study and reported in Bhuvanagiri *et al.* [10]. For instance, the statement that “the north section (Mix 3) had a large shear flow of the AC layer material and most of the rutting happened due to this phenomenon” is true. Also, it is correct to indicate that “it appears that the Superpave mixture containing a large amount of river sand was susceptible to plastic shear flow indicating a lack of stability.”

Another conclusion made by Bhuvanagiri *et al.* [10] is that “most of the rutting on the south section (Mix 4) was due to consolidation of the AC and/or other layers since little flow of AC material was evident.” This is not totally true since plastic flow in this section is also quite significant. Consolidation of the AC layer may have taken place, but the observation of the layers’ profiles on the walls of the trenches (such as Figures 5.17 and 5-18) cut in the test sections indicates that no consolidation, compaction, nor settlement of the soil/aggregate base beneath the pavement has occurred in neither Mix 3 nor Mix 4.

However, the visual inspection of the cores in all four sections led to a general observation of a reduction in the thickness of the asphalt concrete layer between the core taken off the wheel paths and those taken from within the wheel paths. This reduction generally corresponds to the degree of rutting observed at the surface of the pavement.

APPENDIX A

SUPERPAVE MIX DESIGNS

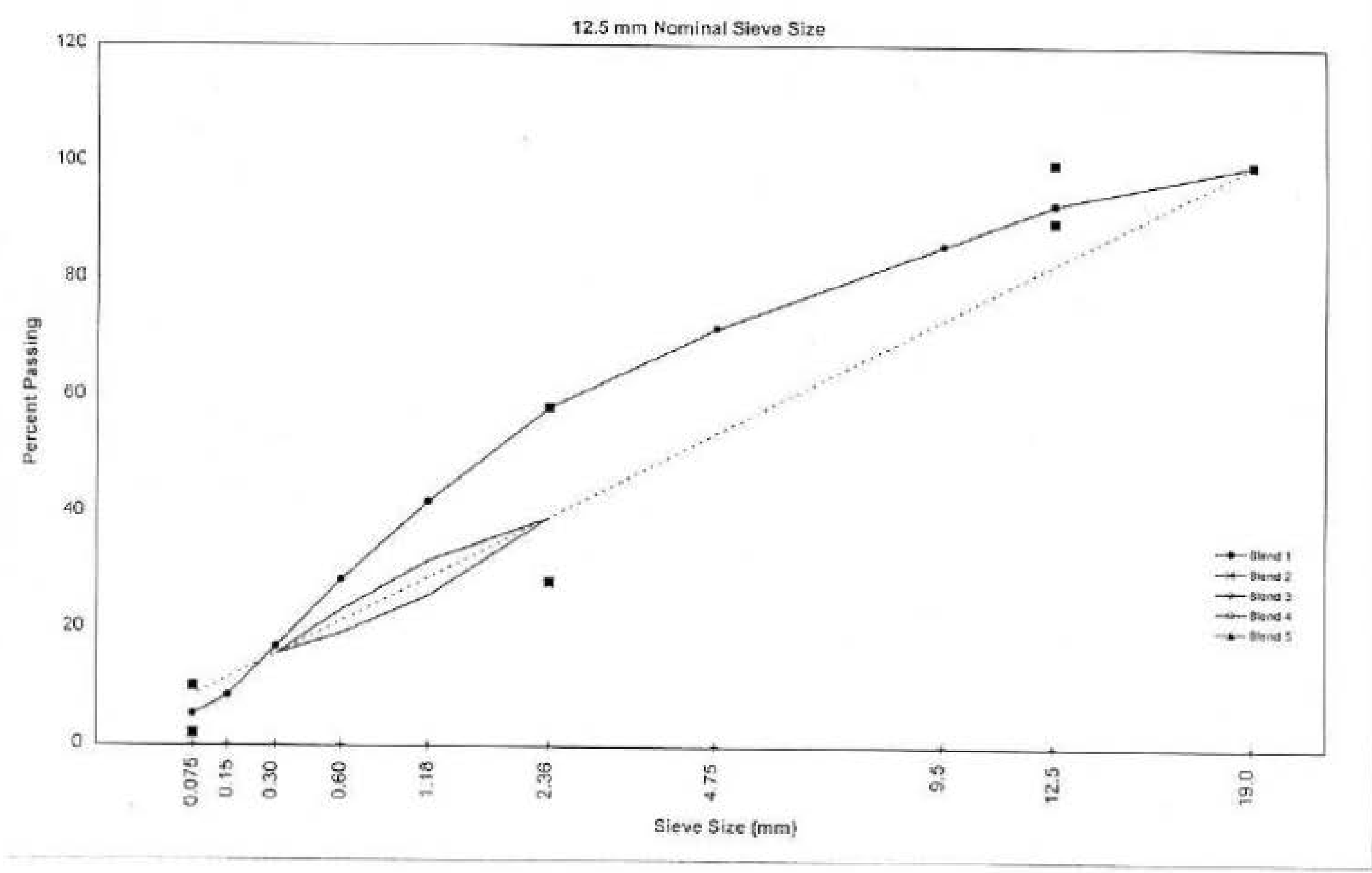
20% Sand + 4" + 8 ft-wide, No instrumentation, North Pit.

Aggregate Gradation Trials

SM-2A

Project Name: ATL CONTROL MIS
Technician: GLENN FAGER
Date: 8/28/96

Filename: PINE1251
Description: C
Nominal Sieve Size: 12.5 mm



Aggregate Gradation Trials

Project Name: ATL CONTROL MIS
Technician: GLENN FAGER
Date: 8/28/98

Filename: PINE1251
Description:
Nominal Sieve Size: 12.5 mm

Sieve Size	Blend 1	Blend 2	Blend 3	Blend 4	Blend 5
19.00	100.0				
12.50	93.0				
9.50	85.9				
4.75	71.6				
2.36	58.0				
1.18	41.8				
0.60	28.3				
0.30	16.7				
0.150	8.3				
0.075	5.2				

						Specs.
Gsb						
Gsa						
% Absorption						
Sand Equiv.						40% min.
%Flat and Elongated Particles						---
%Fine Ag. Ang.						---% min
%Course Agg. Ang. (1 or more)						55% min
%Course Agg. Ang. (2 or more)						---% min
Va (assumed)	4.0	4.0	4.0	4.0	4.0	
Pb (assumed)	5.0	5.0	5.0	5.0	5.0	
Gse (est.)						
Ws						
Vba (est.)						
Vbe (est.)	0.102	0.102	0.102	0.102	0.102	
Pbi (est.)						

Absorption Multiplier	
Gb	
Traffic (million ESAL's)	
Depth from Surface (mm)	

Dwy Control Mix

KANSAS DEPARTMENT OF TRANSPORTATION
SUPERPAVE (LEVEL 1) RESULTS

Lab #: 1G98006
ntract #: 597136071
. roject: 99 K-6733-01
Mix Designation: SM-2A
Spec.: QCQA
Asp.Source & Gr.: COASTAL PG 58-28
Traffic (ESAL'S): .3 - 1

Design Gyrations: 76
Final Gyrations: 117
County: WABAUNSEE
Field Off.: EMPORIA
Contractor: SHILLING CONST. CO.
Producer: SHILLING CONST.
Date Rec./Rep.: 7/07/98 : 7/09/98

Metric Conv.	37.5 mm 1 1/2	25 mm 1	19 mm 3/4	12.5 mm 1/2	9.5 mm 3/8	4.75 mm 4	2.36 mm 8	1.18 mm 16	600 um 30	300 um 50	150 um 100	75 um 200
Job Mix Spec. Band			0	0 10	10 min		42 61	68 max	77 max	84 max		90.0 98.0
Job Mix Sing.Pt.												
Superpave Grad.			0	7	14	28	43	58	72	83		95.0

Test Data			
Range Tested (% AC)	Increment (% AC)	Superpave Mixing Temperature Range(C)	Superpave Compaction Temperature Range(C)
6.00 to 6.80	0.2666	144 to 150	133 to 138

Operating Range for Hot Mix Plant 133 to 150 (C)

	EVALUATION OF TEST RESULTS					RECOMMEND
Asph Cont. %	6.00	6.20	6.50	6.80		6.20
Air Voids (4.00)						3.90
VFA(>=65% <=78%)						73.20
VMA (Min. 14%)						14.60
Density (KG/M3) (Peak +/- 0.5%)						2329
TSR (Min. 80%)						83.75

Values at Recommended Asphalt Content

Filler/Binder Ratio: 1.10
Nom. Max. Agg Size: 12.5
Max.Sp.Gr.: 2.399
Additive:
Sand Equivalent: 84
Theo.Max.Density: 2399

ield Engineer (2)
istrict Engineer
ureau of Construction & Maintenance
ureau of Materials & Research (2)
a. rials & Research Center (1)
. Metro Materials (1)
roducer
ile

District Materials Engineer

KANSAS DEPARTMENT OF TRANSPORTATION
SUPERPAVE (LEVEL I) RESULTS

Lab # 16960S2
Contract #
Project: 99K6733-01
Mix Designation: SM-2A
Special Provisions: QC/QA
Asphalt Source & Grade: Neste PG 58-28
Traffic (ESAL'S) 1.0

Design Gyrations: 76
Final Gyrations: 117
County: Wabaunsee
Field Engineer:
Contractor: Shilling Construction Co, Inc.
Producer: Shilling Construction Co, Inc.
Date Rec./Rep.:

	37.5 mm 1 1/2 in	25 mm 1 in	19 mm 3/4 in	12.5 mm 1/2 in	9.5 mm 3/8 in	4.75 mm #4	2.36 mm #8	1.18 mm #16	600 mm #30	300 mm #50	150 mm #1 00	75 mm #200
Job Mix Spec Band			0	0-10	10 min		42-61	68max	77max	84max		90-98
Job Mix Sing. Point												
Superpave Gradation				7	14	28	43	58	72	83		95

Test Data

Range Tested (%AC)	Increment (%AC)	Superpave Mixing Temperature Range (C)	Superpave Compaction Temperature Range (C)
6.0 to ~~7.1~~ 6.8	0.3	142 - 148	135 - 141

Operating Range for Hot Mix Plant (C) 135 - 148

Evaluation of Test Results

Asphalt Content	6.0	6.2	6.5	6.8	Recommended ~~6.3~~ 6.2
Air Voids (4 +/- 2)	4.4	3.9	3.2	1.5	3.9
VFA (>/= 65%, <80%)	70.5	73.3	78.2	89.6	~~73.4~~ 73.2
VMA (Min. 14%)	14.9	14.6	14.7	14.4	~~14.5~~ 14.6
Density (KG/M3) (Peak +/- 0.5%)	2318	2329	2331	2346	~~2336~~ 2329
TSR (Min. 80%)		84			84

Values at Reccommended Asphalt Content:

Filler/Binder Ratio: ~~1.2~~ 1.1
Nom. Max. Agg. Size.: ~~19.0~~ 12.5
Max. Spec. Grav.: ~~2.407~~ 2.399
Sand Equivalent: 84
Theo. Max. Density: 149.8 2399

Date submitted 8-3-98

District Materials Engineer

Kansas Department of Transportaion

Superpave Asphalt Mixture Design and Analysis

Date: 6/3/98

Project# 99K6733-01

Mix Type: SM-2A

Nominal Maximum Aggregate Size: 19mm
Estimated Single Axle Load's: .3 - 1
Average Design High Temperature: 38 C
Depth from Surface: 50 mm

Mineral Aggregate Consensus Properties	Required	Actual	Method
1) Coarse Aggregate Angularity	NA		KT-31
2) Fine Aggregate Angularity	>40	43.5	KT-50
3) Flat, Elongated Particles	<10%	6%, 8%	KT-59
4) Sand Equivalent	>40	84	KT-55

Gradation

Method KT-2

	Control Points:		Restidted Zone Boundry		Single Points	
	Max.	Min.	Max.	Min	Required	Actual
25mm		0				
19mm	10	0				
12.5mm						77.3
9.5mm						14
4.75mm						28
2.36mm	72	42	60.9	60.9		43
1.18mm			68.4	74.4		58
0.600µm			76.9	80.9		72
0.300µm			84.5	84.5		83
0.150µm						92
0.075µm	98	90				95

Asphalt Mix	Required	Actual	Method
1) Gyratory Initial	7		
2) Gyratory Design	76		
3) Gyratory Maximum	117		
4) Dust (filler/binder ratio)	0.6-1.2	1.2	KT-3
5) Voids in Mineral Aggregate (VMA)	>14	14.5	KT-58
6) Voids Filled with Asphalt (VFA)	65-78%	73.8	KT-58
7) Lottman			
Air Voids	7+-1	6.77	KT-56
Saturation	55-80	56.2	
Tensile Strentgh Ratio	>80%	84	

Aggregate Gradation Trials

Project Name: SM-2A Wab
Technician: DWS
Date: 4/28/98

Filename: SM-2A Wab Trial 1
Description:
Nominal Sieve Size: 12.5 mm

	X Blend 1	Blend 2	Blend 3	Blend 4	Blend 5
Dust	2.0				
SSG-1	20.0				
CS-1	28.0				
CS-2	15.0				
CS-2A	35.0				
	100.00	0.00	0.00	0.00	0.00

Sieve Size	Blend 1	Blend 2	Blend 3	Blend 4	Blend 5	
19.00	100.0	0.0	0.0	0.0	0.0	
12.50	93.0	0.0	0.0	0.0	0.0	90-100
9.50	85.9	0.0	0.0	0.0	0.0	90 max
4.75	71.6	0.0	0.0	0.0	0.0	
2.36	58.0	0.0	0.0	0.0	0.0	39-58
1.18	41.6	0.0	0.0	0.0	0.0	32 min
0.60	28.3	0.0	0.0	0.0	0.0	23 min
0.30	16.7	0.0	0.0	0.0	0.0	16 min
0.150	8.3	0.0	0.0	0.0	0.0	
0.075	5.2	0.0	0.0	0.0	0.0	2-10

	Blend 1	Blend 2	Blend 3	Blend 4	Blend 5	Specs.
Gsb	2.531					
Gsa	2.640					
% Absorption	1.98					
Sand Equiv.						40% min.
%Flat and Elongated Particles						—
%Fine Ag. Ang.						40% min
%Course Agg. Ang. (1 or more)						65% min
%Course Agg. Ang. (2 or more)						—% min
Va (assumed)	4.0	4.0	4.0	4.0	4.0	
Pb (assumed)	5.0	5.0	5.0	5.0	5.0	
Gse (est.)	2.618					
Ws	2.215					
Vba (est.)	0.029					
Vbe (est.)	0.102	0.102	0.102	0.102	0.102	
Pbi (est.)	5.7					

Stockpiles

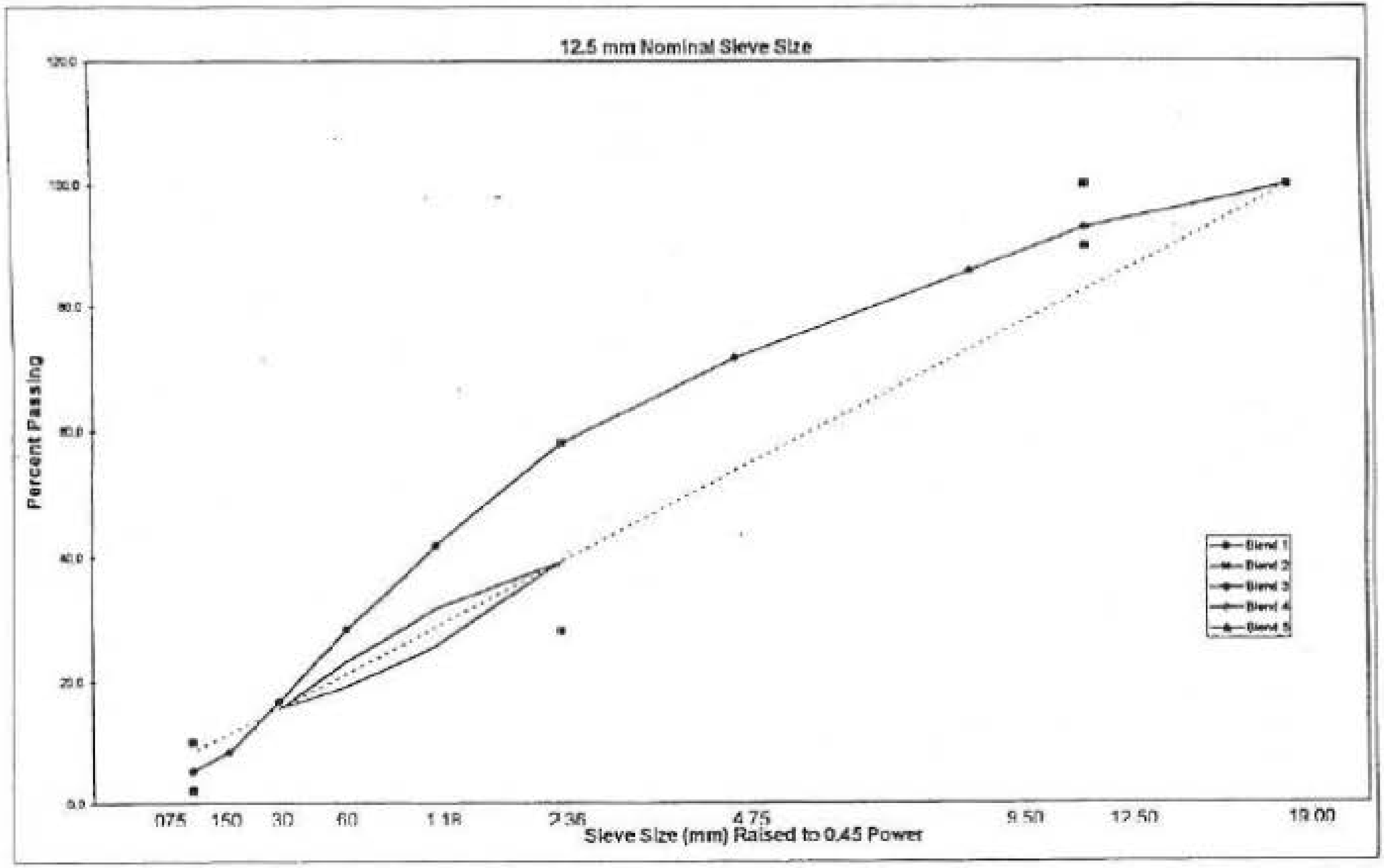
	Dust	SSG-1 (Wamego Wab Pit)			CS-1 (CA-5 Martin-M Zendale)	CS-2 (CS-2 Martin-M Zendale)	CS-2A (Chat Bingham Drag sand)
	100.0	100.0			100.0	100.0	100.0
	100.0	100.0			75.0	100.0	100.0
	100.0	100.0			50.0	99.0	100.0
	100.0	100.0			13.0	73.0	100.0
	100.0	99.0			4.0	52.0	78.0
	100.0	85.0			3.0	37.0	47.0
	99.0	60.0			2.0	29.0	27.0
	92.0	28.0			2.0	23.0	15.0
	73.0	5.0			2.0	19.0	7.0
	58.0	1.0			2.0	16.0	2.5
	2.747	2.602			2.510	2.602	2.470
	2.747	2.609			2.660	2.681	2.620
	4.00	0.44			2.35	2.35	2.30

Absorption Multiplier	0.80
Gb	1.024
Traffic (million ESAL's)	0.9
Depth from Surface (mm)	50.0

Agg. ,ate Gradation Trials

Project Name: SM-2A Wab
Technician: DWS
Date: 4/28/98

Filename: SM-2A Wab Trial 1
Description: 0
Nominal Sieve Size: 12.5 mm



Shilling Const. ID:913-776-5995 JUL 27'98 10:59 No.001 P.06

Mixture Summary Report for Trial Aggregate Blend Analysis

Project Name:	SM-2A Wab Project 1	**N Initial:**	7
Workbook Name:	SM-2A Wab Project 1	**N Design:**	76
Technician:	FES/GFW	**N Max:**	117
Date:	5/20/98	**Nom. Sieve Size:**	12.5 mm
Asphalt Grade:	58-22	**Compaction Temperature:**	148 °C
		Mixture Temperature:	136°C
Design ESAL's (millions):	1 -	**Depth from Surface (mm):**	50
Design Temperature:	38°C	**Mold Size:**	150 mm

Property	Results				Criteria
	B1V6.0	**B1V6.5**	**B1V6.8**	**B1V6.2**	
%AC	6.0	6.5	6.8	6.2	
%Air Voids (V_a)	4.4	3.3	1.5	3.9	4.0 %
%VMA	14.9	14.8	14.3	14.6	14.0 % Min.
%VFA	70.3	77.9	89.7	73.2	65.0 % Min. 78.0 % Max.
Dust/Asphalt Ratio	1.1	1.1	0.8	1.1	0.6-1.2 %
Max. Specific Gravity (G_{mm})	2.398	2.384	2.361	2.399	
Bulk Specific Gravity (G_{mb})	2.318	2.331	2.346	2.329	
%G_{mm} @ N_{ini}	88.3	89.1	91.4	88.7	89.0 % Max.
%G_{mm} @ N_{max}	96.6	97.8	99.3	97.1	98.0 % Max.
Effective Sp. Gravity of Blend (G_{se})	2.623	2.627	2.610	2.632	---
Sp. Gravity of Binder (G_b)	1.024	1.024	1.024	1.024	---
Sp. Gravity of Aggregate (Gs_b)	2.531	2.531	2.531	2.531	---

Summary Report

Project Name: SM-2A W/ab Project 1
Workbook Name: SM-2A W/ab Project 1
Technician: FES/GFW
Date: 5/20/98
Asphalt Grade: 58-22
Compaction Temp: 148°C

N Initial: 7
N Design: 76
N Max: 117
Nom. Sieve Size: 12.5mm
Design Temperature: 38°C
Design ESAL's (millions): 1

Blend	%AC	%Gmm @ N = 7 (corrected)	%Gmm @ N = 76 (corrected)	%Gmm @ N = 117 (corrected)	%Air Voids @ NDesign	%VMA @ NDesign
B1V6.0	6.0	88.3	95.6	96.6	4.4	14.9
B1V6.5	6.5	89.1	96.7	97.8	3.3	14.8
B1V6.8	6.8	91.4	98.5	99.3	1.5	14.3
B1V6.2	6.2	88.7	96.1	97.1	3.9	14.6

Blend	Estimated %AC @ 4% Va	Estimated %Gmm @ N = 7 (89% Max)	Estimated %Gmm @ N = 76	Estimated %Gmm @ N = 117 (98% Max)	Estimated %VMA @ NDesign (14 % Min)	Estimated %VFA @ NDesign (65-78%)
B1V6.0	6.2	88.7	96.0	97.1	14.8	72.9
B1V6.5	6.2	88.4	96.0	97.0	14.9	73.1
B1V6.8	5.8	88.8	96.0	96.8	14.6	72.6
B1V6.2	6.2	88.7	96.0	97.0	14.6	72.6

	B1V6.0	B1V6.5	B1V6.8	B1V6.2
Ag. Bulk Specific Gravity (Gsb):	2.531	2.531	2.531	2.531
Percent Binder by wt. of mix (Pbi):	6.0	6.5	6.8	6.2
Percent Aggregate (Ps):	94.0	93.5	93.2	93.8
Specific Gravity of Binder (Gb):	1.024	1.024	1.024	1.024
Fines (%Passing 0.075mm Sieve):	5.2	5.7	4.8	5.3
Effective Specific Gravity (Gse):	2.623	2.627	2.610	2.632
Effective % Binder (Pbe):	4.7	5.1	5.7	4.7
Dust Proportion (0.6-1.2%):	1.1	1.1	0.8	1.1

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Job# :3004

Shilling [illegible]truction Co, Inc.
555 [illegible]yntz, Suite 260
Manhattan, KS 66502
(785)776-5077
(785)776-4714

Fred Sow[illegible] [illegible]rt.# 1496
Glenn Welsc[illegible] [illegible]rt.# 1517
Barbara Mather Cert.# 1528

KANSAS DEPARTMENT OF TRANSPORTATION

Material	Material Code:	Producer or Pit Name	Legal Description & Official Quality	County
CS-1		**Martin-Marietta**	SE1/4,S33T10S,R09E	Riley
CS-2A	chat drag sand	**Bingham Sand and Gravel**	S22,T29N,R23E	Cherokee
CS-2	screening	**Martin-Marietta**	SE1/4,S33T10S,R09E	Riley
SSG-1	sand	**Wamego Sand**	S33,T12S,R7E	Wabaunsee

APPENDIX B

BASE LAYER SOIL TEST RESULTS

Kansas Department of Transportation

Report of sample of AB-3

Laboratory No. 98-5066

Date Reported. December 15, 1998

Date Received. 11/23/98

Specification No. Sec. 1105 of 1990 Std. Specs. Quantity - - -

Source of material Shilling Const.

Sample from ATL - Middle Pit

Submitted by Glenn A. Fager, Res. Bit. Engr., 2300 VanBuren, Topeka, Ks.

Identification marks AB-3

Project or POV EN2374-99 ACT803

Type of construction Pavm't Surfacing

TEST RESULTS

Sieve Size	2"	1½"	1"	3/4"	1/2"	3/8"	4	8	10	16	30	40	50	80	100	200
Specificed:	0	0-5		5-30			35-60	45-70				60-84				80-92
Actual:	0	0	9	15	30	41	55	64	66	73	77	79	81	83	84	86

		Specified	Actual
Liquid Limit	=	30 max	23
Plastic Limit	=		14
Plasticity Index	=	2-8	9
Max Dry Density =			2,053.0 Kg/m3
Opt. Moisture			10%

cc: L.S. Ingram
Glenn A. Fager
J.J. Brennan
Soil Section
File 1-5

Reported by: Marie Hunt for

Title James J. Brennan, Soils Engineer

Rev. 3-76

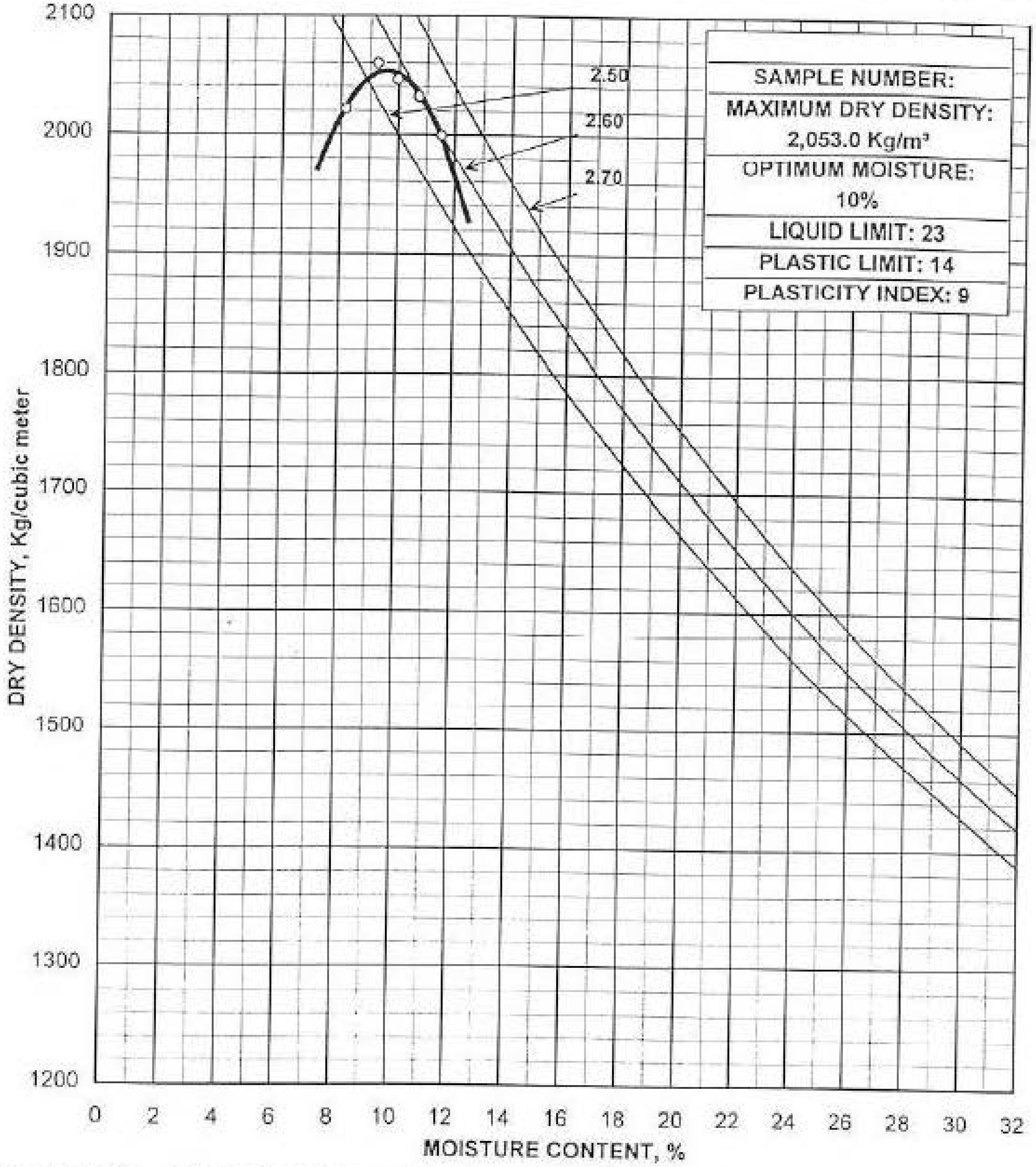
D.O.T. Form 623

KANSAS DEPARTMENT OF TRANSPORTATION

REPORT OF SOIL COMPACTION TESTS

SUBMITTED BY Glenn A Fager, Res. Bit. Engr. ADDRESS ______ LAB. NO 98-5066

PROJECT EN-2374-99 ACT803 COUNTY ______ DATE 12-9-98



TEST METHOD AASHTO T99-93, Method A

REMARKS ______

L. S. Ingram, P.E.
Chief, Bureau of Materials and Research
BY ______
James J. Brennan, Soils Engineer

D.O.T. Form No. 638

APPENDIX C

DATA ACQUISITION SYSTEMS' SETUP

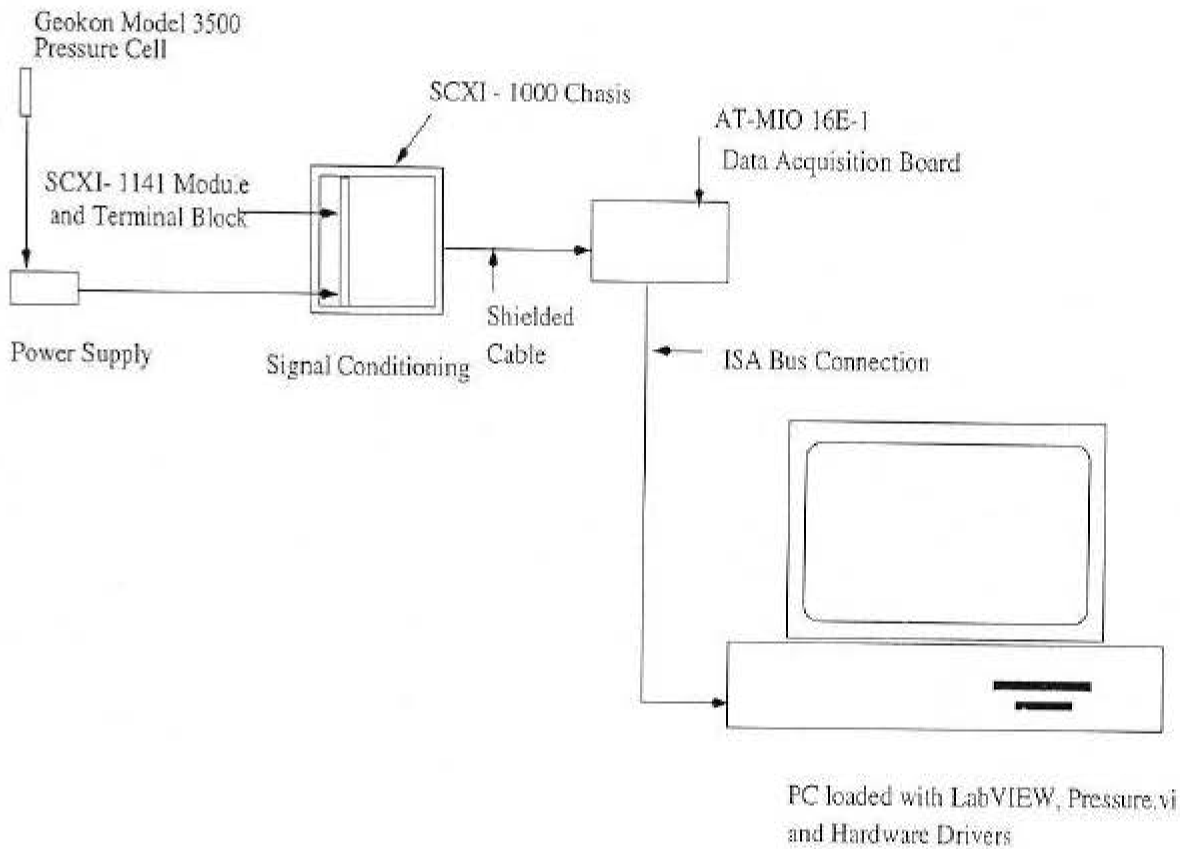


Figure 7: Schematic Representation of Pressure Data Acquisition System

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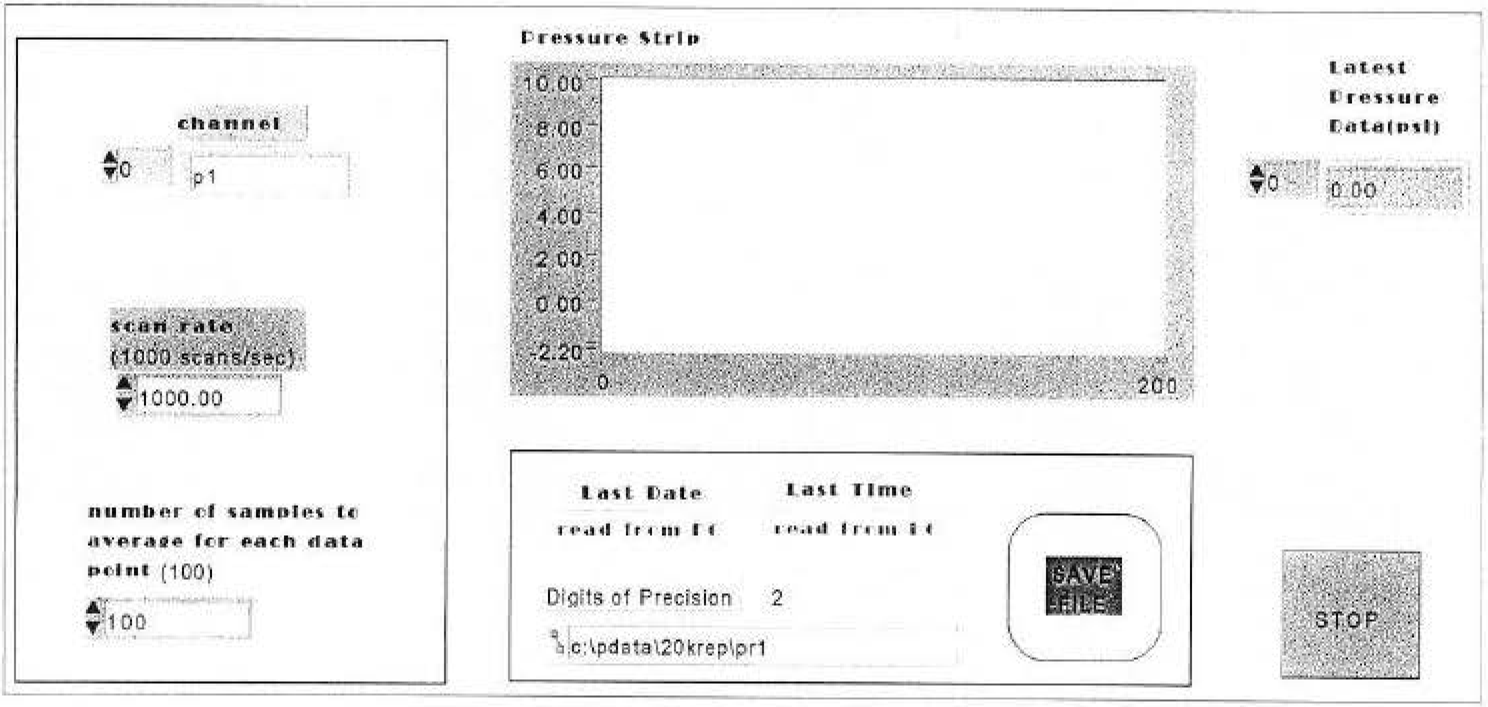

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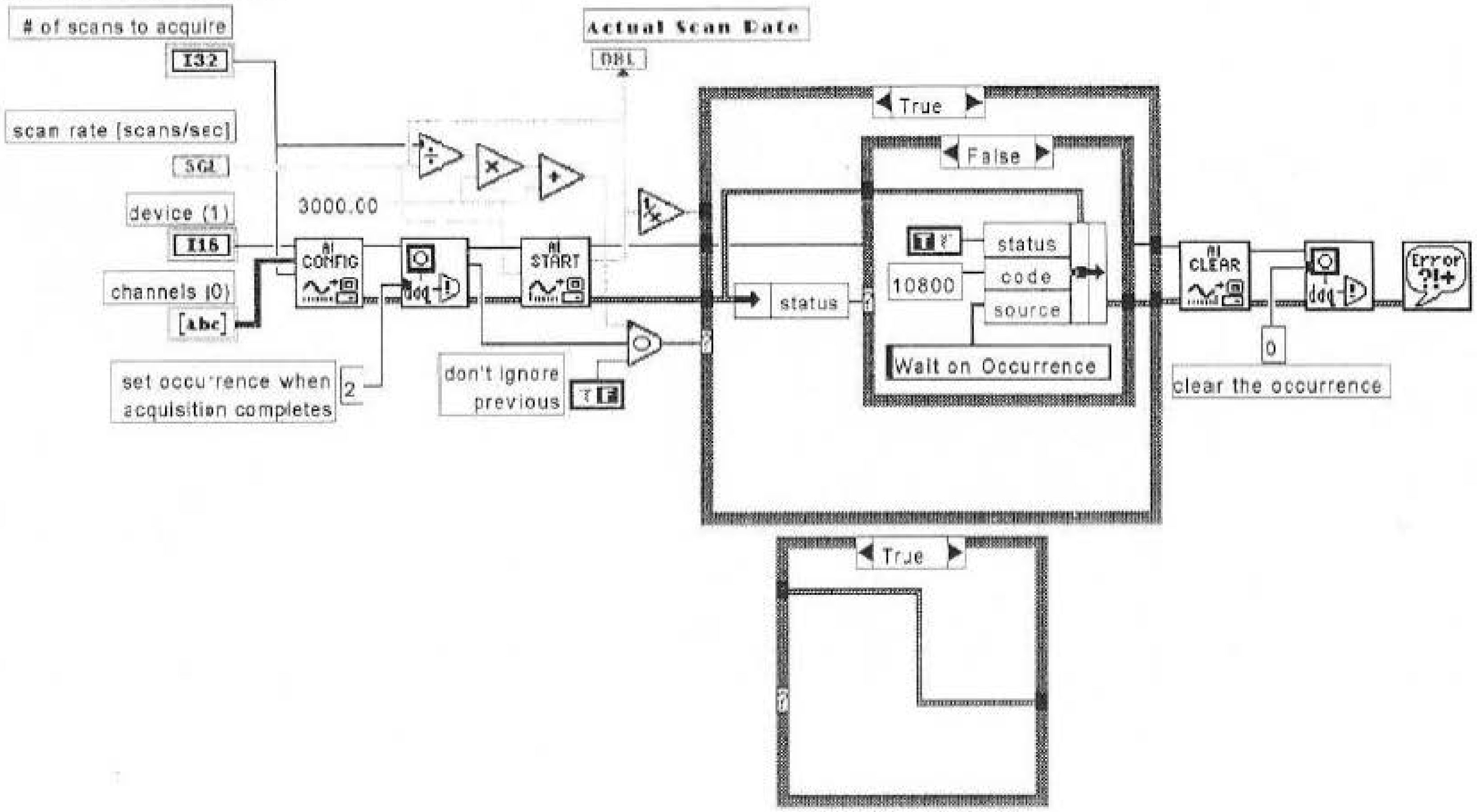

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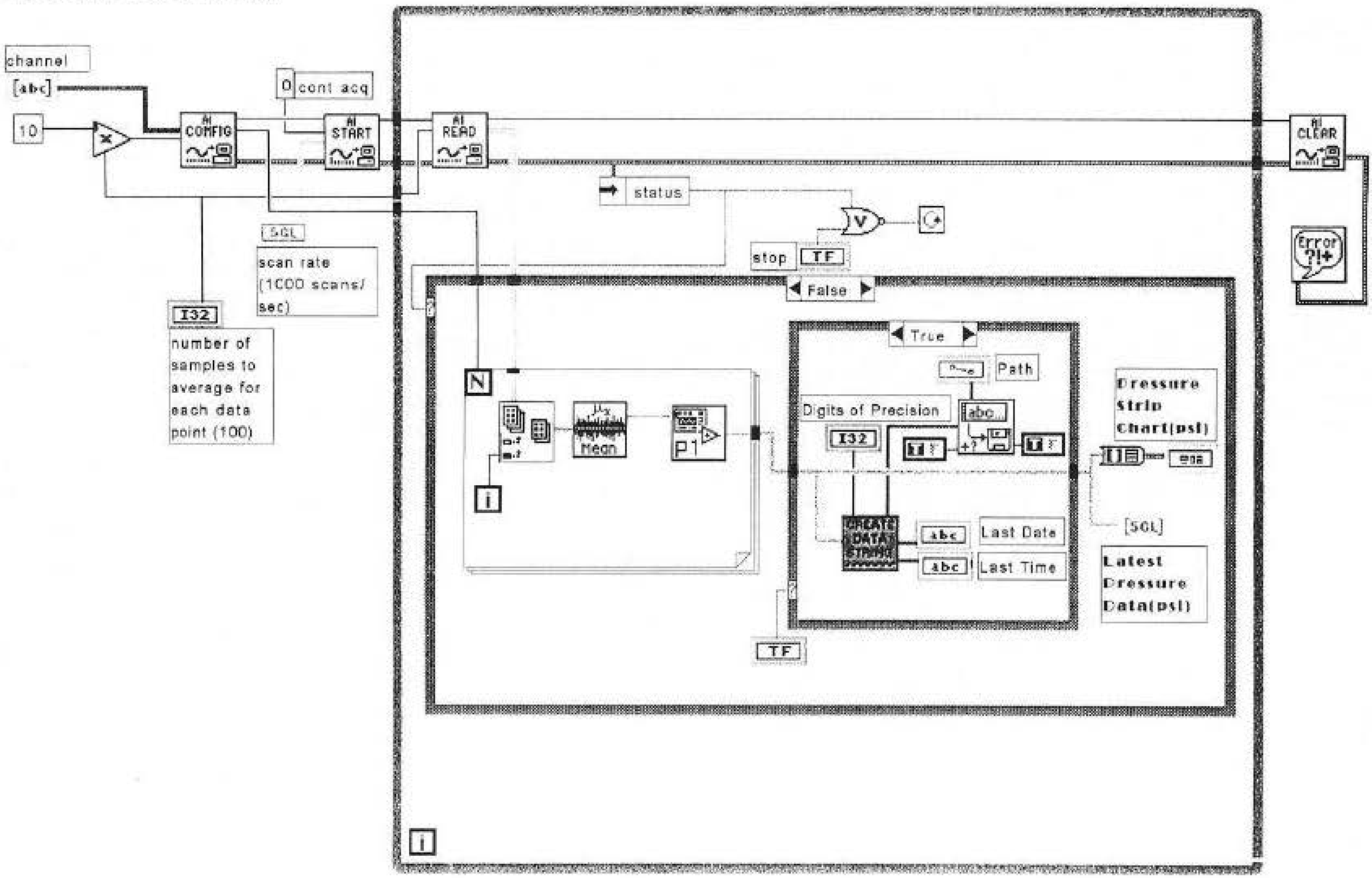

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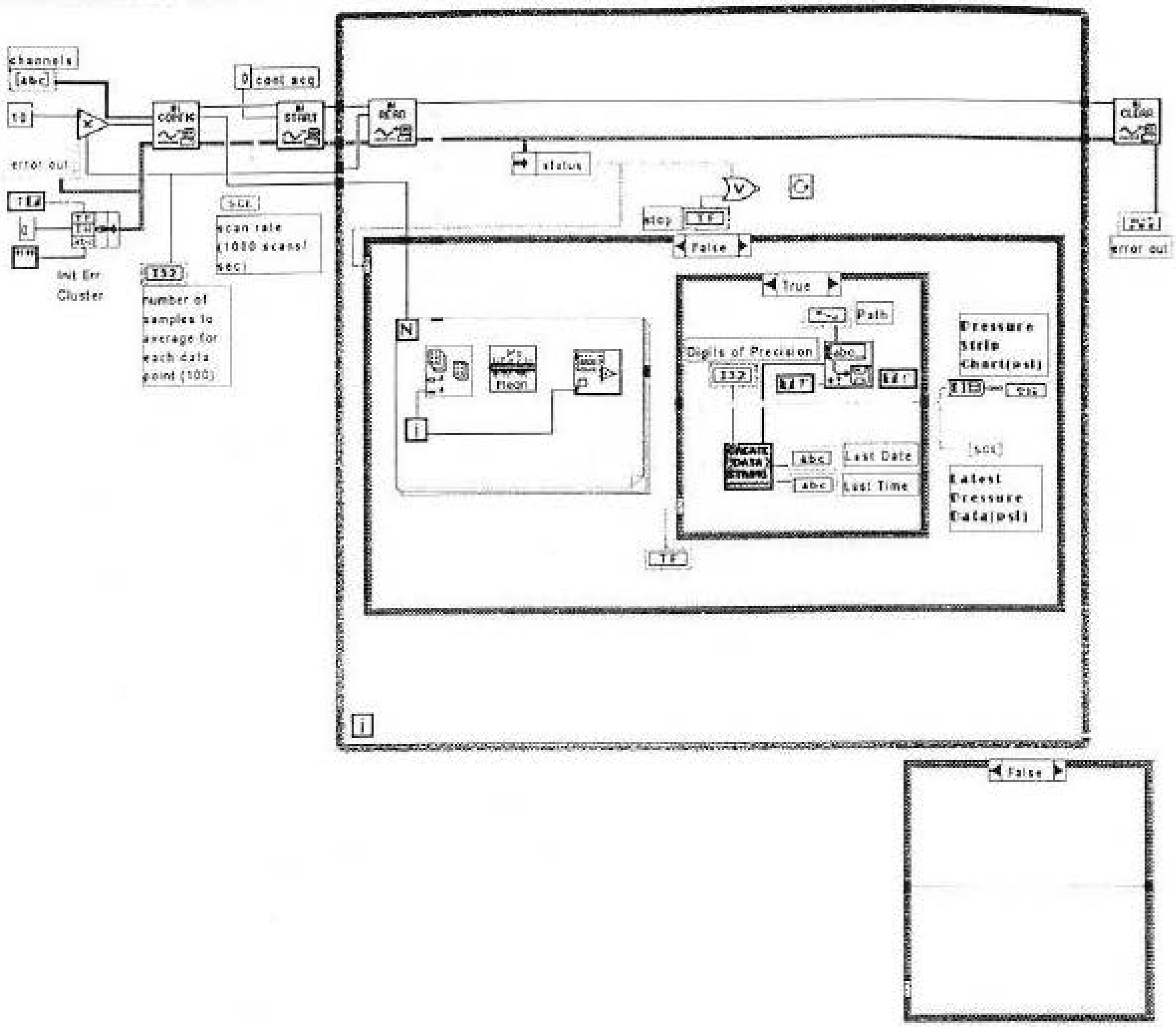

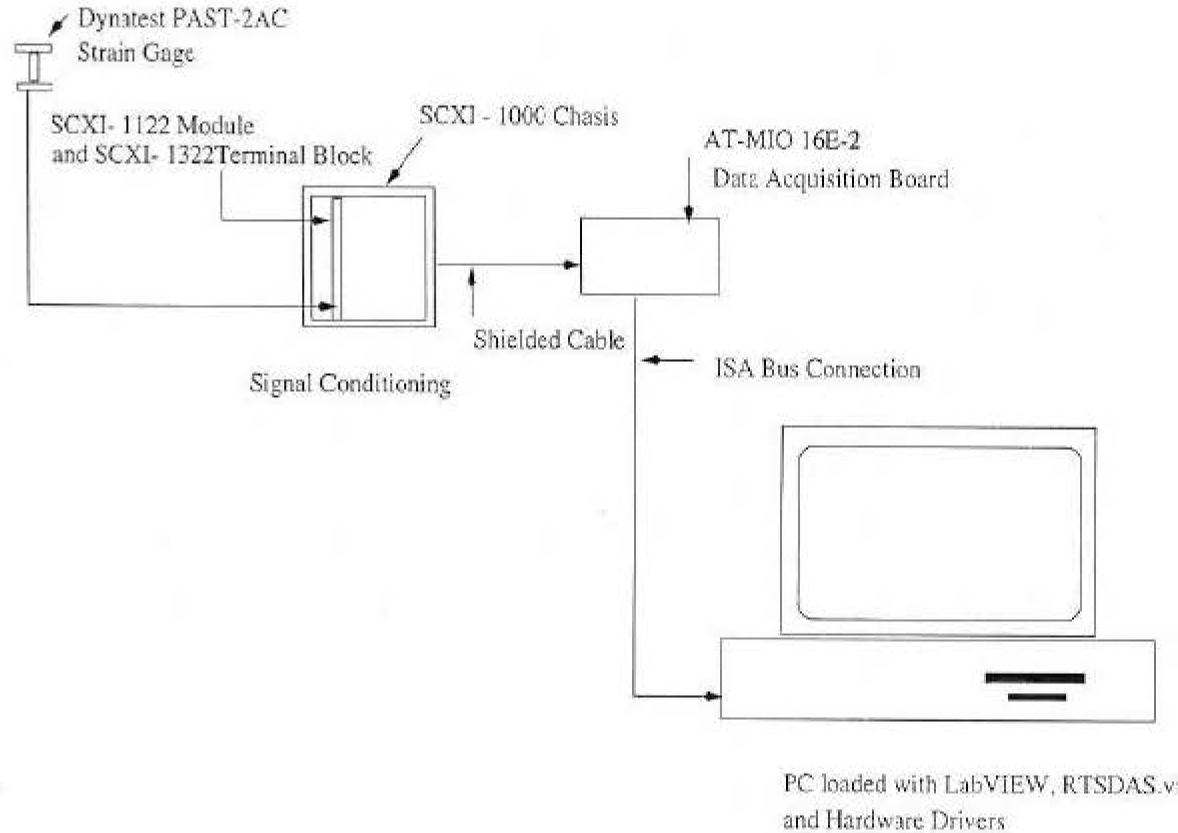

Figure 6: Schematic Representation of Strain Data Acquisition System

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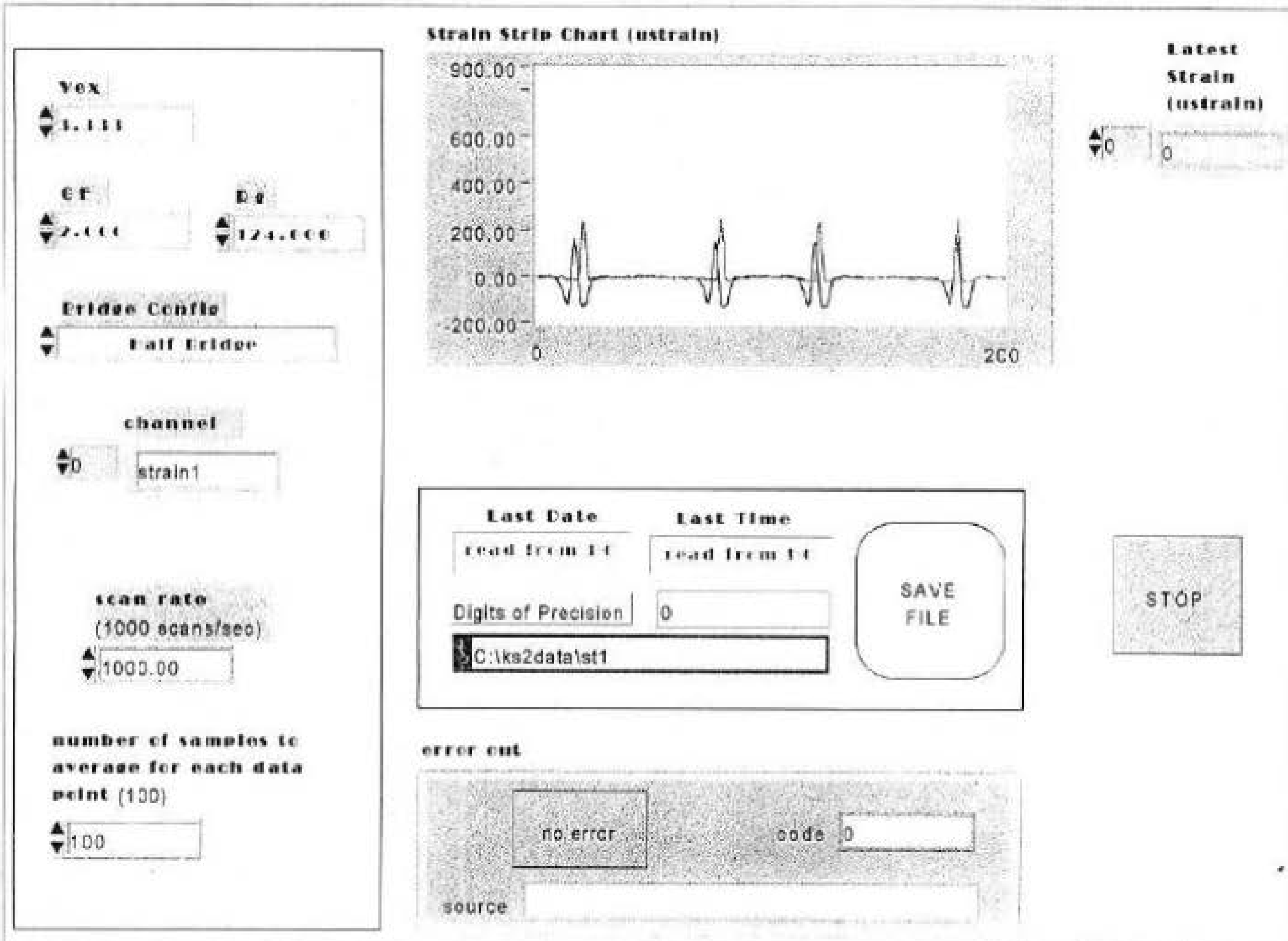

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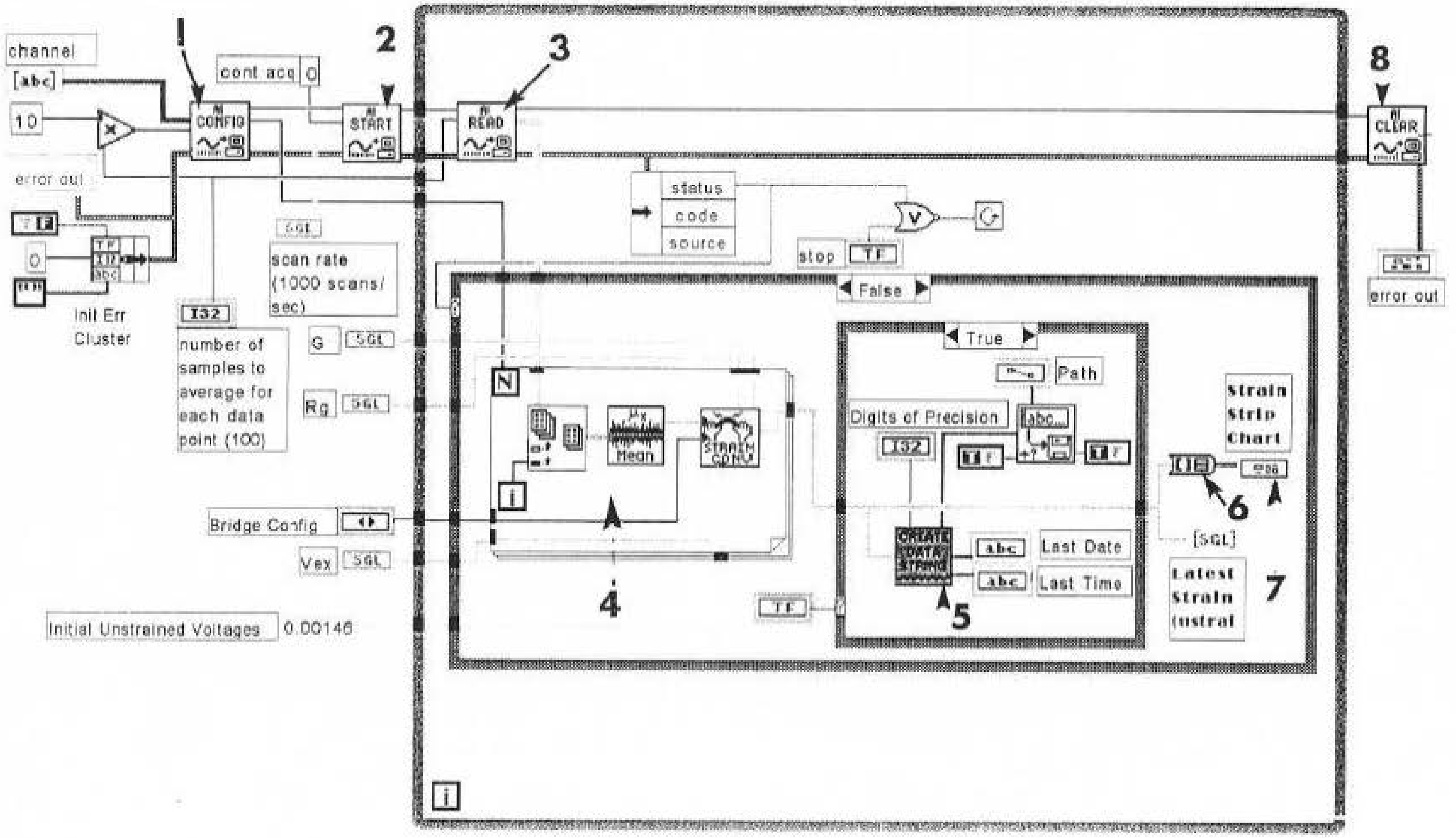

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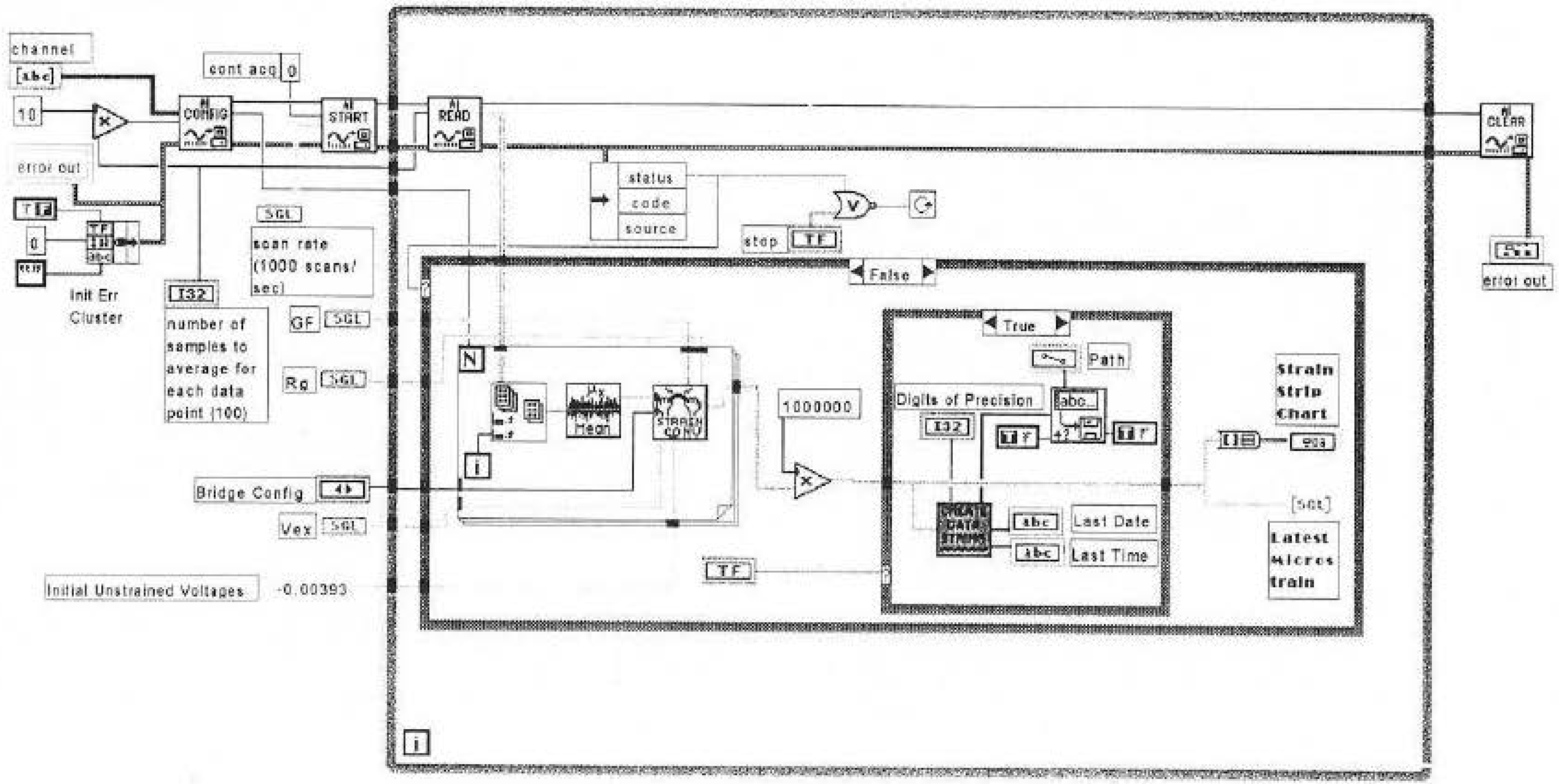

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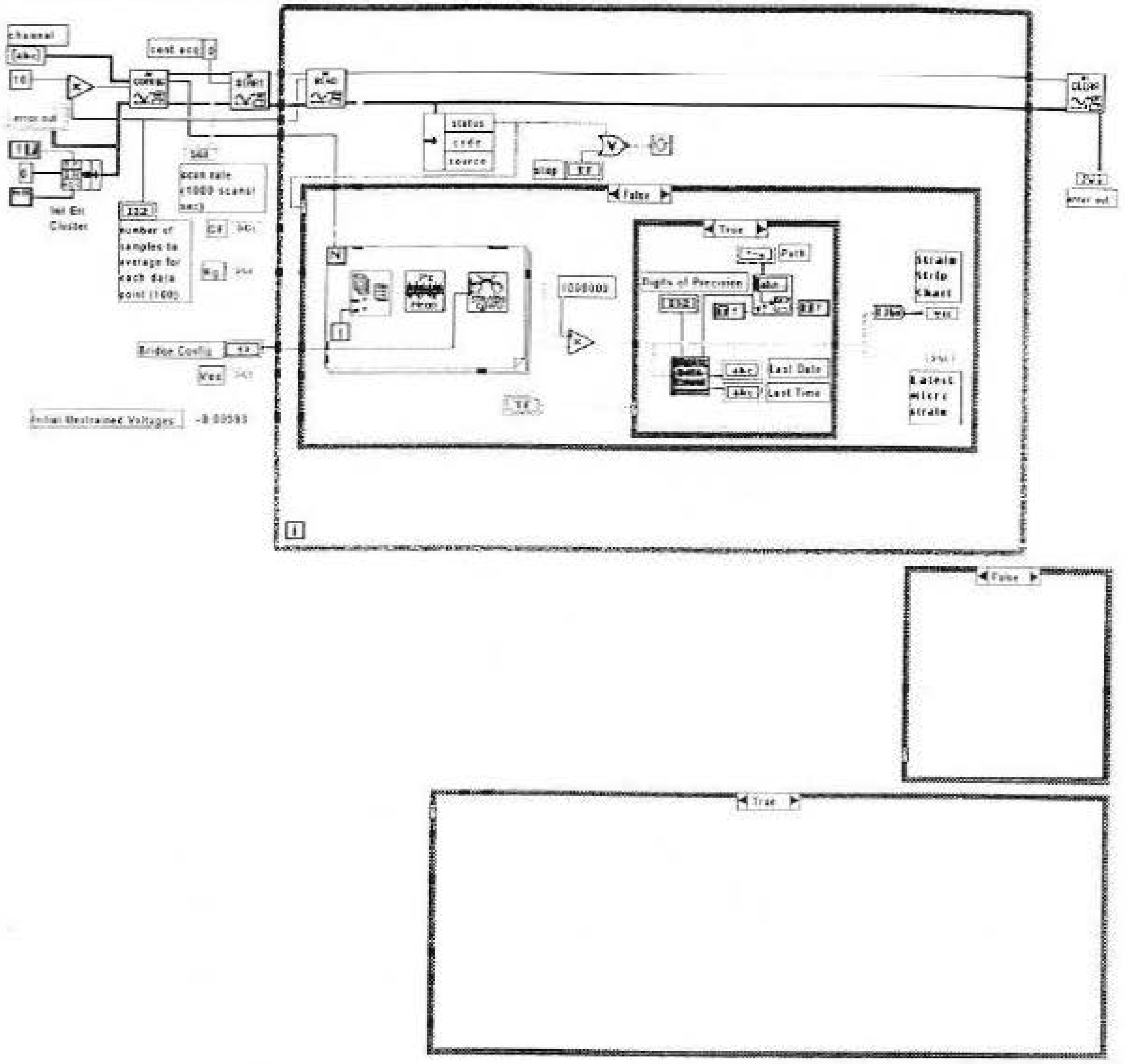

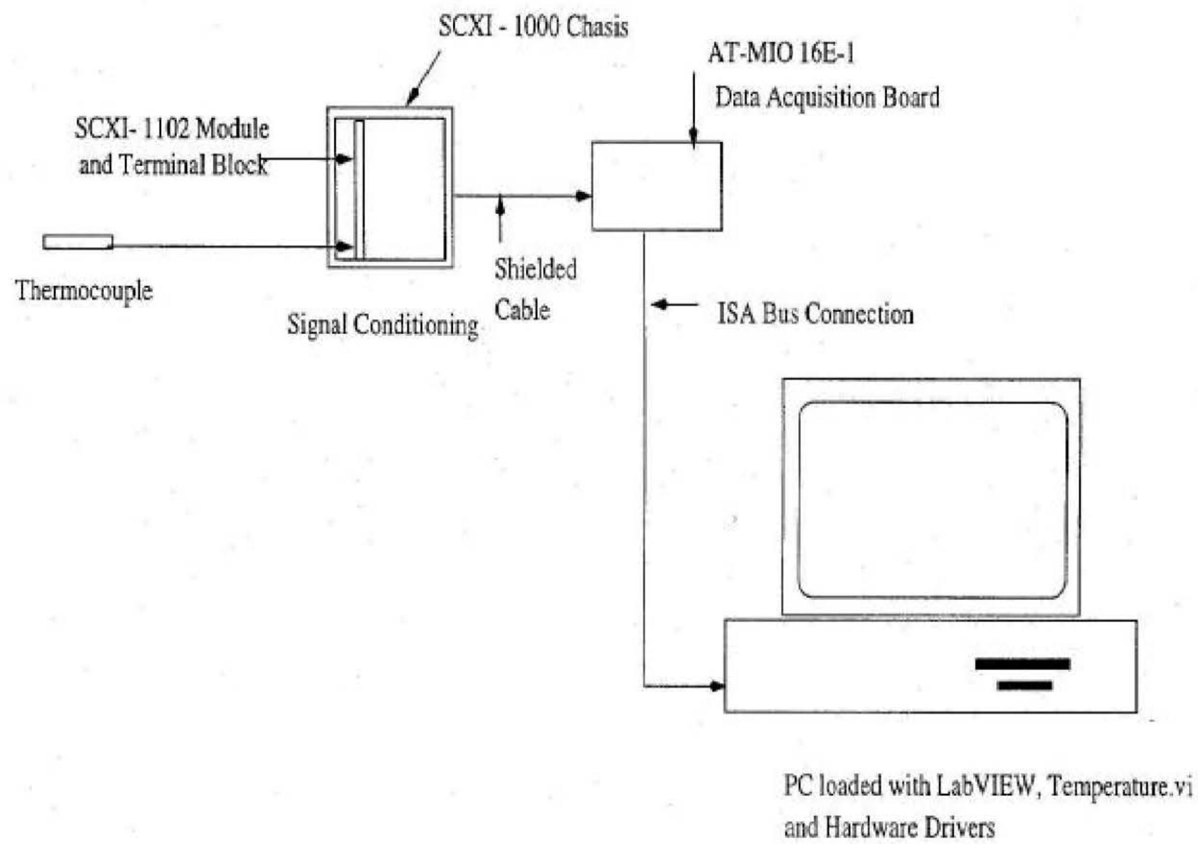

Figure 5: Schematic Representation of Temperature Data Acquisition System

Temp

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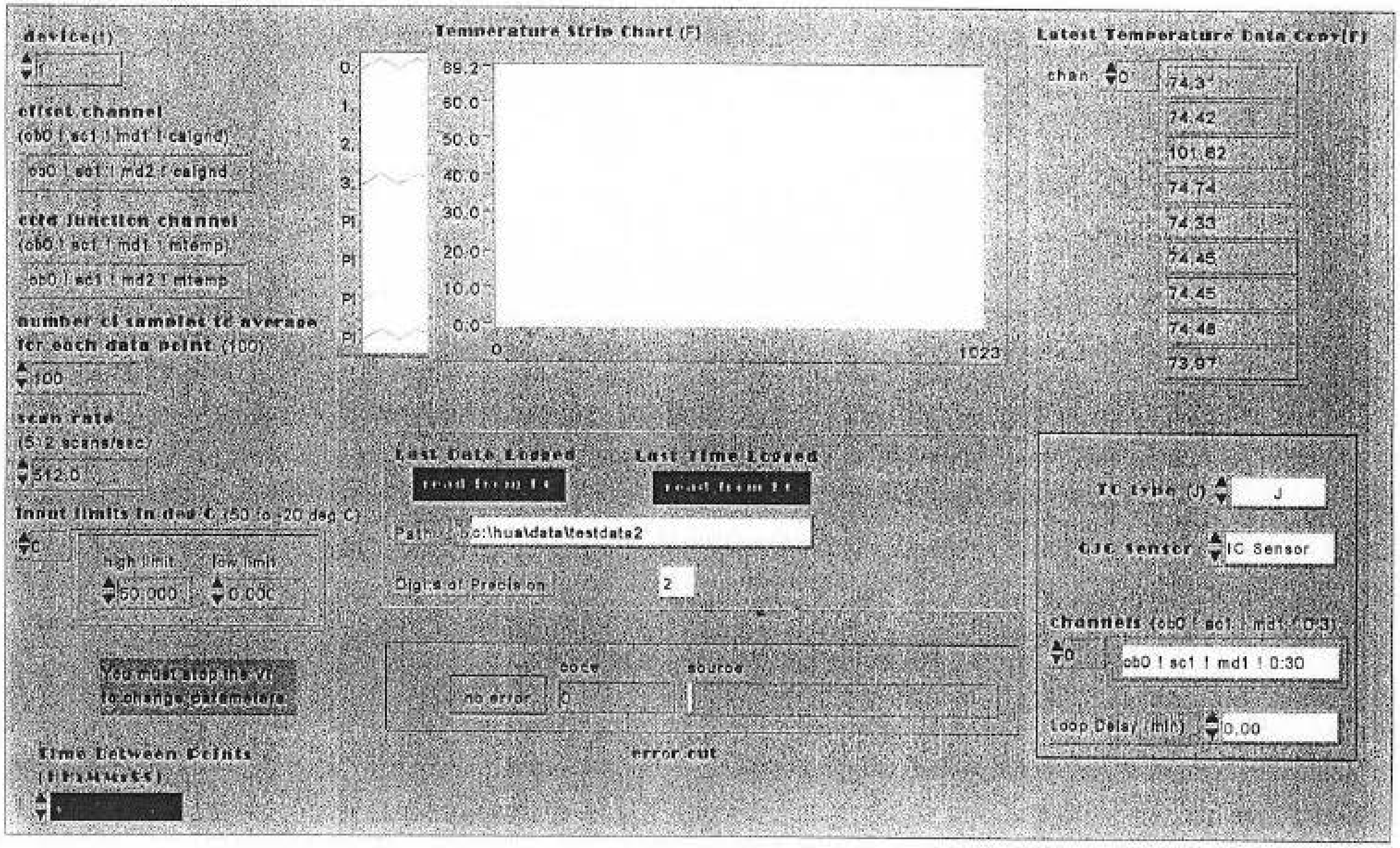
Page 1



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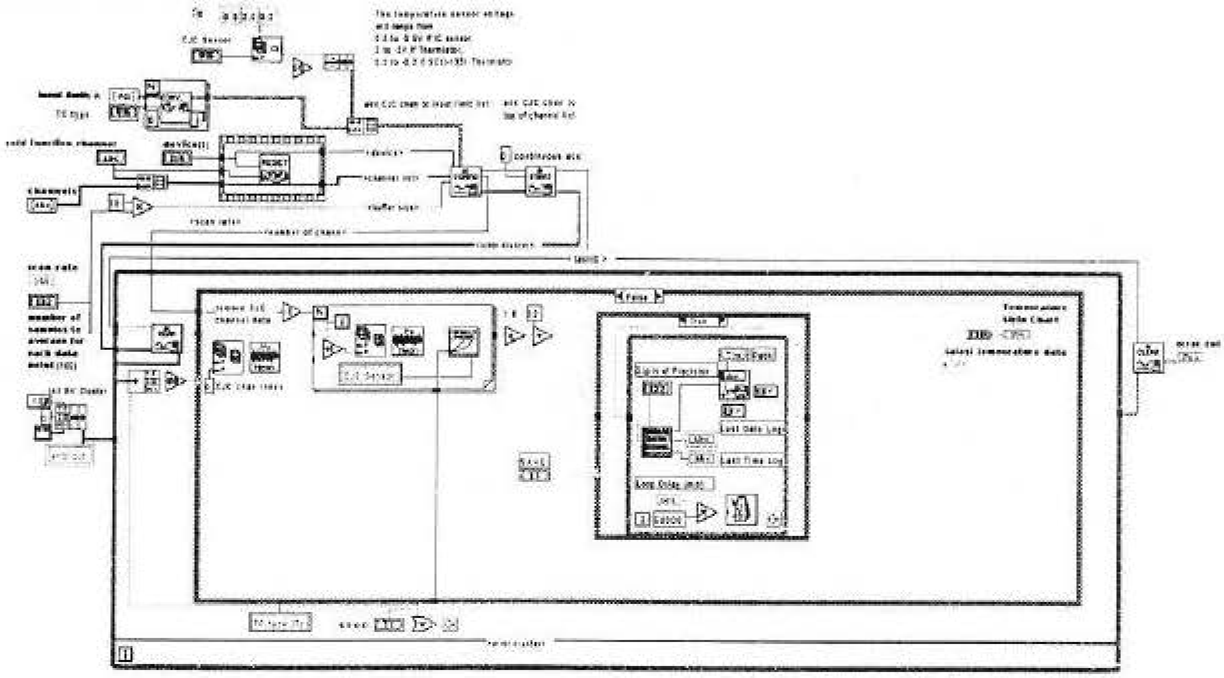

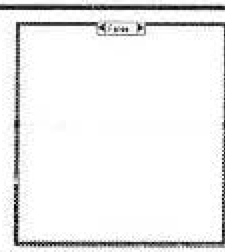

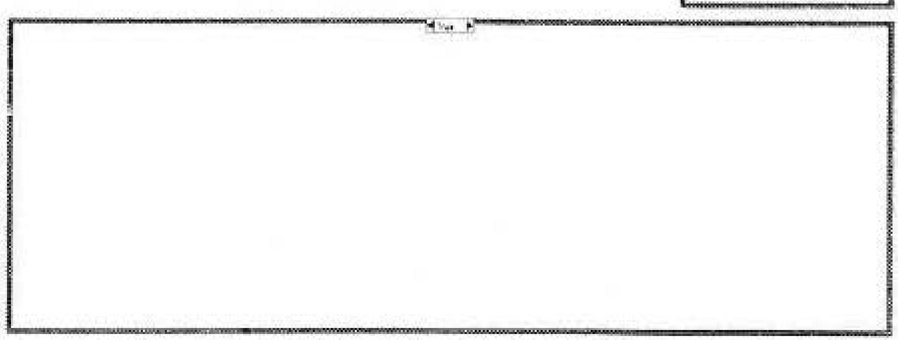

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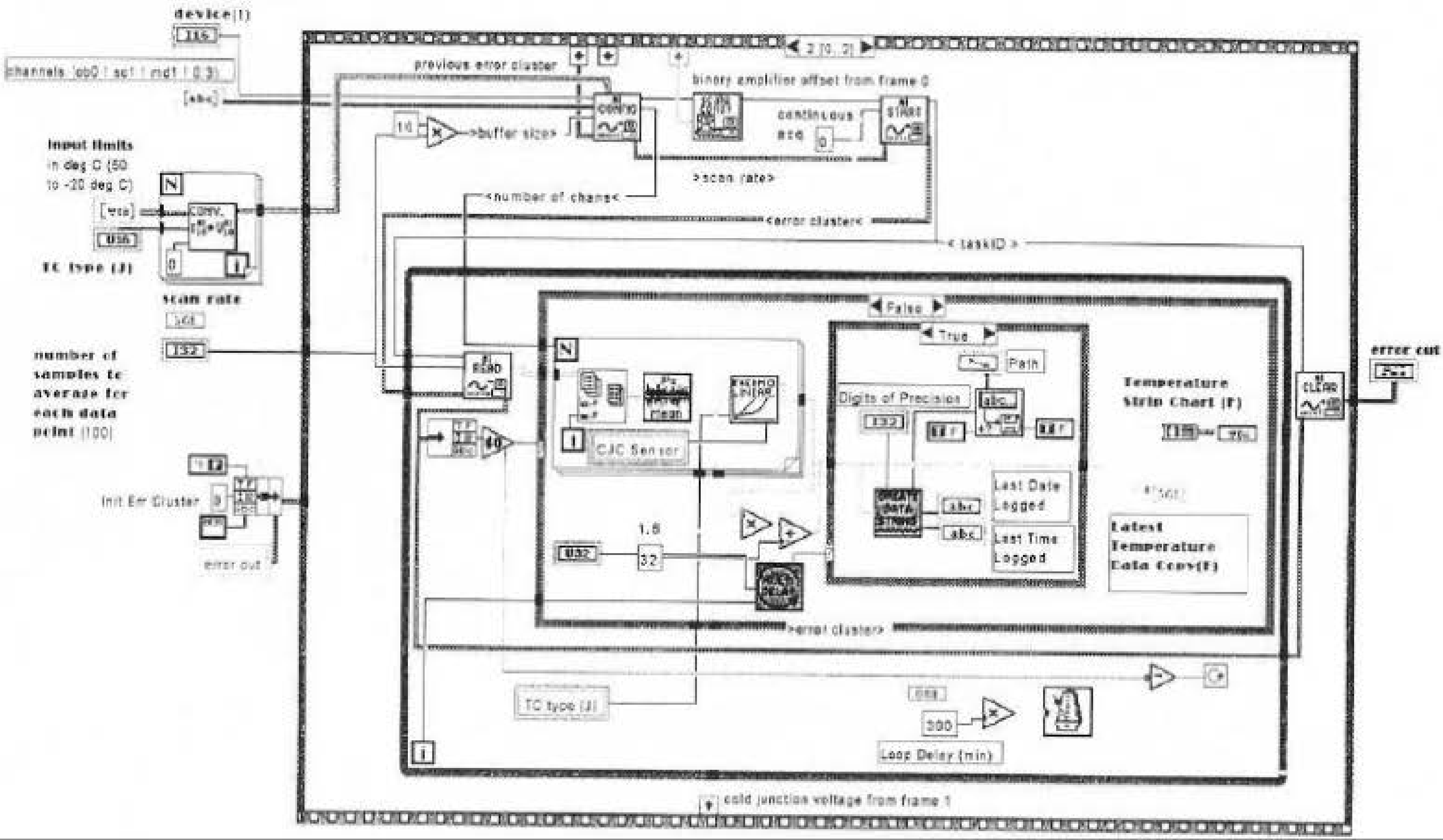

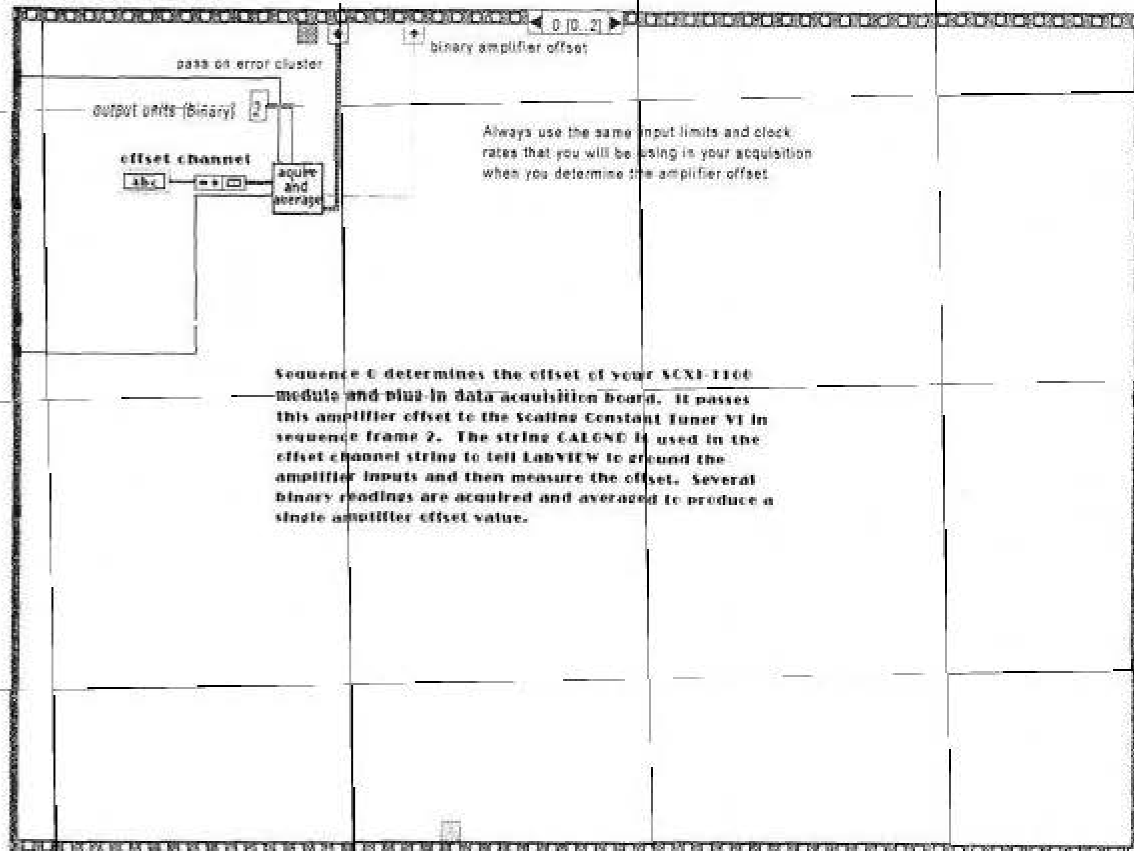
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binary amplifier offset
pass on error cluster
output units (Binary)
2
offset channel
abc
acquire and average
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Sequence 0 determines the offset of your SCXI-1100 module and plug-in data acquisition board. It passes this amplifier offset to the Scaling Constant Tuner VI in sequence frame 2. The string CALGND is used in the offset channel string to tell LabVIEW to ground the amplifier inputs and then measure the offset. Several binary readings are acquired and averaged to produce a single amplifier offset value.

97

References

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