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16. Abstract

The overall objective of the Roadway Research Initiative study was to describe an advanced testing capability, on that would speed implementation of the results from traditional computer and laboratory-based research efforts by providing a reusable test bed for evaluating field performance under actual traffic and environmental conditions. A longer-term benefit would result from the development of performance-based models for use in mechanistic pavement design procedures.

The report describes the concept of the Roadway Research Implementation Center, including test program goals and objectives. Test-site configuration is illustrated, cost estimates are presented, and the organizational structure is suggested. Finally, immediate steps are recommended for utilizing the 1/3-scale mobile load simulator in the final design of the test center.

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RECOMMENDATIONS FOR ESTABLISHING THE TEXAS ROADWAY RESEARCH IMPLEMENTATION CENTER

by

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Project Summary Report Number 1812-S

Study No. 0-1812

The Roadway Research Initiative

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. DEPARTMENT OF TRANSPORTATION

Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

and the

TEXAS TRANSPORTATION INSTITUTE
TEXAS A&M UNIVERSITY

July 1998

IMPLEMENTATION STATEMENT

The recommendations of this project will guide the establishment of the Roadway Research Implementation Center (RRIC). In addition to providing an organizational structure and an approach toward attaining to such a structure, the report describes the long- and short-term test program of the RRIC and details the scale model test program necessary for final design of the RRIC program. Finally, the intent is that the RRIC will be a means for implementing TxDOT research findings for years to come. It will bridge the gap between laboratory- and computer-based testing and field performance. Specific, enumerated implementation recommendations are provided in Chapter 5 (p.32) of this Project Summary Report.

DISCLAIMERS

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CHAPTER 1. INTRODUCTION AND BACKGROUND

1.1. BACKGROUND

1.1.1 Requirements for Performance Models

The American Association of State Highway and Transportation Officials (AASHTO) Design Guide (1) distinguishes between pavement structural performance and functional performance. It relates structural performance to the physical condition of the pavement, including the presence of cracking, rutting, faulting, or other manifestations of distress. Functional performance is related to how well the pavement serves its users. It is the pavement's history of serviceability, which is the quantification of ride quality. The ability to reliably predict the structural and functional performance of a pavement is an essential element of every pavement management system (PMS).

Assessment of the likely impact on (1) pavement performance of roadway construction material properties, (2) pavement design procedures, or (3) construction equipment depends on the adequacy of the testing methods and predictive measures employed. Designs for new construction, as well as the options for pavement rehabilitation, require accurate evaluations of the contributions to pavement performance life of the materials, methods, and equipment proposed for use. Likewise, the ability to predict with confidence the benefits to be gained through application of routine pavement maintenance materials and procedures requires performance models that have been proven for actual traffic conditions.

Figure 1 shows a schematic of a PMS. Field-proven, performance-based models that allow reliable predictions of pavement response to wheel loads and environmental factors are indispensable elements of the PMS phases — planning, design, construction, and maintenance. In addition, how changes in such variables as materials, design methods, construction equipment, maintenance intervals, and procedures impact anticipated pavement life must be quantifiable if the PMS is to be a valid management tool. The body of data required to develop these models does not exist in current databases. The development of adequate models depends on the existence of load-response data that accurately reflect traffic variables, materials properties, layer geometry, and environmental conditions.

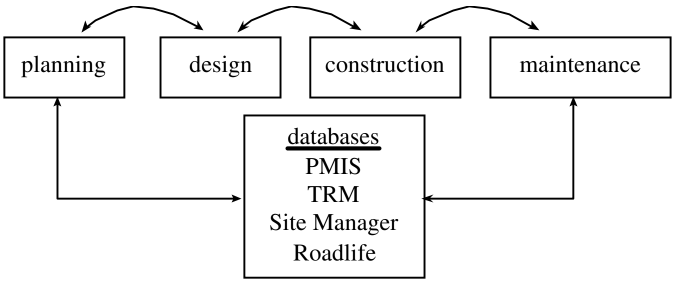

Figure 1. PMS

1.1.2. Test Methods to Support Performance Modeling

Current models have been proposed on the basis of laboratory test results, full-scale test roads, and accelerated pavement testing (APT) data. Laboratory testing offers the advantages of lower cost, shorter test duration, and the ability to vary environmental conditions (temperature and moisture regimes). On the other hand, laboratory scale tests cannot accurately replicate load conditions, pavement geometry, or material aging effects.

Full-scale test roads have been the only means available for accurately applying traffic load and environmental conditions. Limitations owing to scaling are avoided, and pavement response data and the development of distress mechanisms are actual representations of in-service conditions. However, test road results are limited in application because the environmental and subgrade conditions are indicative of only one location. Extrapolation of the results to other locations can generate significant errors in performance predictions. Also, the time scale of a road test is a serious limitation. The gathering of pavement life data requires the passage of time and accumulation of traffic loads. As numbers of truck loadings on today's high-volume roads continue to increase (this trend is discussed in National Cooperative Highway Research Program (NCHRP) Synthesis 235 [2]), test roads cannot provide data quickly enough to meet the demand. The AASHO Road Test (11) is perhaps the best known and most widely reported road test. For two years (1958−1960) tests loops were subjected to 1,114,000 load repetitions. Current performance models are based on these very important results, although applying these relationships to today's loading conditions requires extrapolating by a factor of 10 to 50.

APT offers a means of rapidly applying a lifetime of traffic loads to a test pavement on a compressed time scale. APT devices vary in their simulation accuracy. Size, number of wheels per axle, axle suspension systems, and load rates vary over a wide range. The Texas mobile load simulator (MLS) appears to offer a superior simulation capability, because it utilizes actual truck wheels, axles, and suspensions. It also offers a faster loading rate (approximately 5,000 axles per hour) than other devices. However, the limitations common to all APT devices are that

a) owing to the short time involved, accelerated testing cannot account for the effects of pavement aging, and
b) since environmental and subgrade conditions represent only the local test site, test results cannot be directly exported to other locations.

The 1/3-scale model mobile load simulator (MMLS) is a low-cost APT device that applies up to 7,200 single-wheel applications per hour by means of a 300-mm-diameter, 80-mm-wide tire. Its capabilities include testing at variable temperature and moisture conditions and under overload and underload conditions; its size is such that scaling aggregate gradation and layer thickness is not always a requirement.

There is a requirement to develop a capability (equipment and procedures) to bridge the gap between laboratory-scale testing and full-scale test roads. This capability should deliver results in a fraction of the time necessary to fail full-scale test road pavements, and it should adequately account for environmental effects on pavement condition and life. The performance models developed from such test data should be applicable over a wide range of subgrade types and climatic conditions.

1.2 OBJECTIVES AND SCOPE OF THE STUDY

1.2.1 Objectives

The overall objective of the Roadway Research Initiative study was to describe an advanced testing capability, one that would constitute a predictive link between laboratory research and field performance. Specifically, the desired capability would serve as a means to speed implementation of the results from traditional computer- and laboratory-based research efforts by providing a reusable test bed for evaluating field performance under actual traffic and environmental conditions.

Other study objectives were to enhance the capability of the Texas Department of Transportation (TxDOT) to respond to legislative initiatives concerning such issues as axle load and configuration impacts on road damage, and the development and use of local, nontraditional pavement materials on the basis of indisputable test results. Additionally, such a test capability should support the development and verification of new pavement materials and design procedures by expeditious field testing in a low-risk environment. Specifically, new materials with superior strength and stiffness properties could be proof-tested under actual field conditions, without the potentially costly and embarrassing risk of failure of a test section on a high-volume roadway. One of the most significant study objectives was to recommend a method to bring industry, specifically the materials, construction, trucking, and instrumentation industries, into a partnership with both TxDOT and academia for attaining the previously mentioned objectives. A test bed for joint evaluation of equipment, materials, and specifications is desired.

1.2.2 Scope

The remainder of this report will describe the concept of the Roadway Research Implementation Center (RRIC). Proposed test goals, test section matrices, and test protocols are introduced in Chapter 2. The physical configuration, instrumentation desired, potential sites, and cost estimates are presented in Chapter 3. Chapter 4 describes the organizational structure, the roles of the participants, and the test planning process. Chapter 5 presents recommendations for moving forward, while the appendix describes in detail the background for the scale model testing of pavement components.

1.3 THE ROADWAY RESEARCH IMPLEMENTATION CENTER CONCEPT

1.3.1 Basic Elements of the Concept

As contemplated, the RRIC will be a reusable test bed through which TxDOT, industry, other states, and international agencies will work jointly with Texas universities to investigate and resolve roadway issues of mutual concern. These issues include research and development projects that would apply APT and actual highway traffic loadings to develop superior instrumentation systems, materials, designs, and construction methods for pavements. Most importantly, such a center would serve to implement research findings obtained through traditional laboratory studies.

Excellent transportation systems are key to Texas' success in the ongoing competition for economic development. Superior roads — roads capable of meeting the challenges of increasing traffic volumes and potentially damaging axle configurations and weights associated with the North American Free Trade Agreement (NAFTA) — will require the development of advanced roadway materials, structures, design, and construction methods. The proposed RRIC will constitute a unique set of capabilities for field testing of full-scale pavements and associated structures, utilizing actual, measured highway traffic and accelerated methods. The concept is illustrated by the parallel test road/APT facility shown in Figure 2.

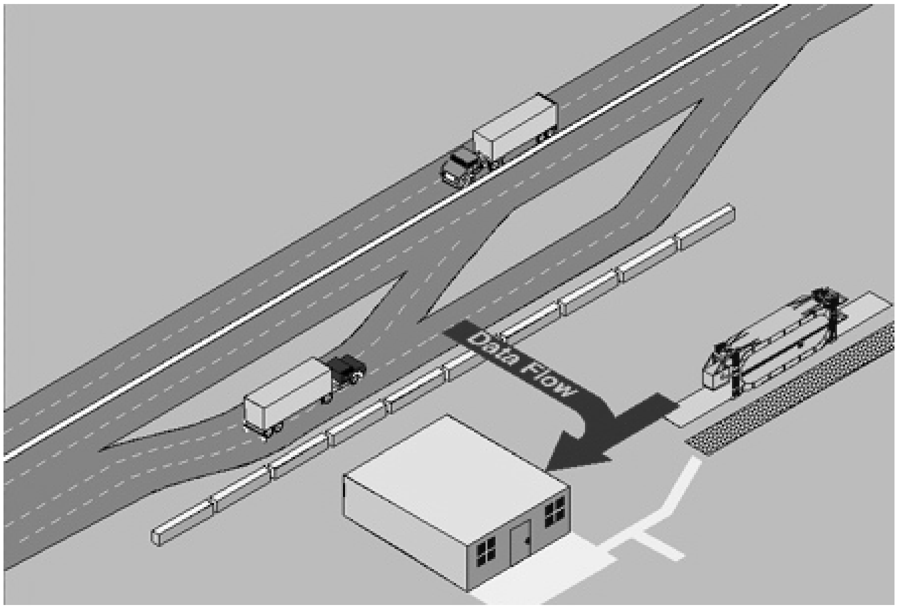

Figure 2. RRIC Concept

The advantages of such a capability include field validation of new materials, designs, and instrumentation systems, as well as rehabilitation/construction process testing prior to deployment on public roads. In addition, a mission of the center will include the field testing of construction/repair materials to assist local highway officials throughout Texas in making material selections with confidence in their performance. There is no similar capability in existence today that can provide such a bridge between laboratory data, mathematical models, nondestructive testing, and field performance.

The proposed center will characterize highway traffic with weigh-in-motion (WIM) instrumentation so that analytical efforts can include accurate load functions. As stated above, the center will permit tests on a variety of structures, and it will facilitate changes to structures, as test results dictate. A significant benefit will be the ability to calibrate accelerated test results with actual traffic tests, accounting for such variables as sequence of loading, speed, weather, and time effects. The ability to relate future field performance to design specifications will pay off in enhanced credibility and resource savings.

The proposed center will also serve to foster partnering among industry, TxDOT, and the sponsoring universities. There will be opportunities for all parties to contribute funding, expertise, technology, and research needs to identify and solve roadway problems of mutual concern.

Perhaps the most important applications are direct calibration of the APT device data with actual truck loadings under controlled conditions that limit extraneous variables. This calibrated relationship can then be exploited by MLS testing at various locations around the state. This process, based on a well-defined load model, would then accurately account for local climate, subgrade, and material variables.

Another major application for the APT/real traffic combined data is the development of pavement performance models that will support accurate predictions of performance of pavements subjected to 50 to 100 million equivalent single axle loads (ESALs). The effects of overloading, high tire pressures, varying wheel configuration, and vastly increased numbers of trucks on the road can be investigated under controlled conditions. No existing capability can provide as complete and as timely a solution to these traffic issues — issues sure to be exacerbated by NAFTA-related trucking.

Equally important testing at the RRIC will involve field evaluations for new products, new construction methods, and new equipment. Industry, university researchers, and TxDOT personnel will be able to assess performance under actual traffic or under APT alone. Transportation engineers can then apply these successful new ideas without fear that the material might fail under actual traffic conditions (and consequently require costly removal).

1.3.2 The Five-Step Process

The fundamental approach of the RRIC test program would include five phases. The program would be structured to move to successively more realistic, more rigorous testing as new or recycled trial materials, structural designs, etc., successfully complete the preceding steps. The intent is to estimate, then verify, performance of a candidate material or design procedure using the lowest-cost testing alternative. Low-performance alternatives can be eliminated prior to undergoing more expensive full-scale testing. On the other hand, the performance of those alternatives that advance to full-scale field testing can be predicted with a higher level of confidence than is currently possible. The following discussion illustrates the process.

1. *Concept development on the basis of theory and literature search.* This phase includes defining the requirement for a new material or process. For example, the requirement may be to develop locally available, low-quality aggregate for use as a base course. This test phase would identify potential additives, anticipated engineering properties, and trial mix designs.
2. *Laboratory testing.* This phase establishes relationships among fundamental mix design parameters and strength, stiffness, and durability of the product. Basic performance estimates can be determined for low cost, and nonpromising candidates can be eliminated from further consideration.
3. *Field simulation with the 1/3-scale MMLS.* In this phase, product performance under more realistic wheel loadings and variable temperature and moisture extremes is measured. The intent is to move the candidate materials to a test environment that more accurately reflects field conditions (without incurring the higher costs associated with full-scale testing). This phase will result in performance models that will be verified in later field trials.
4. *Full-scale simulation with the MLS.* Candidate mix designs that have performed successfully thus far will enter this more rigorous phase, which involves applications of wheel loads by means of actual truck bogies and suspension systems.
5. *Actual traffic loadings on instrumented test road.* This critical phase will subject test sections to mixed traffic under actual environmental conditions. In addition, constructability concerns can be evaluated and actual cost functions can be determined. As performance models are calibrated, transfer functions can be devised to relate limiting values of pavement distress predicted from 1/3-scale MMLS and full-scale MLS tests to actual field results. These transfer functions will allow the application of the APT devices to predict material performance/remaining life of highway segments in any location around the state.

1.4 PAYBACK

As traffic volumes increase and as user delay costs resulting from prolonged lane closures or detours increase, it becomes even more important to develop procedures and materials that can be used for rapid rehabilitation projects. In such cases, heavily traveled urban freeway sections can be reconstructed or overlaid in minimal time and returned to service immediately. The RRIC offers an indispensable test facility for this process. Traffic can be diverted over the parallel test road or original interstate as required without delays or safety compromises as new materials, methods, and equipment are proven.

Approximately 50 to 60 percent of the TxDOT $2.4 billion construction and maintenance budget is spent on pavements. A 1-percent improvement in performance (represented by a 1-percent increase in service life) will yield $14 million per year available for other uses. The benefits of improved performance are seen not only in new construction and reconstruction projects, but also in the cases of maintenance and rehabilitation. Improvements in surface treatment selection timing, design methodologies, materials performance, and construction techniques also result in increased service life. A one-year increase in treatment performance life would substantially reduce the pavement maintenance and rehabilitation backlog, since about 20 percent more mileage could be treated with the same amount of maintenance funds. Similarly, about 12.5 percent more mileage could be treated with the same amount of rehabilitation funds within a given performance period.

1.5 COOPERATIVE AGREEMENT

An important attribute of the RRIC concept is the cooperative nature of the proposed organization. This will be further explored in Chapter 4. Joint planning and sharing of facilities and equipment with each participant providing personnel as required will streamline costs and eliminate duplication. While appropriated funds will be sought for initial construction, the universities are receptive to investing in manpower and equipment, which will be required to support planning and structural design for the initial test series. Ongoing operations would be jointly supported by TxDOT, Texas A&M University, The University of Texas at Austin, and industry affiliates through direct funding, donated materials and equipment, and manpower.

CHAPTER 2. THE ROADWAY RESEARCH IMPLEMENTTION CENTER TEST PROGRAM

2.1 OVERALL TEST PROGRAM GOALS

The RRIC test goals, consolidated into four broad areas, encompass short- and long-term goals, qualitative or comparative performance studies of materials and rehabilitation processes, and more basic performance-based modeling of pavement systems. The test program as envisioned will include test sections subjected to actual highway traffic alone, sections tested by the MLS alone, and sections for which MLS results are calibrated by actual traffic response data.

2.1.1 Identify Truck Component/Pavement Interaction

The shorter-term components of this goal include:

(a) Quantifying load damage equivalency
(b) Correlating nondestructive testing methods with MLS and real traffic data

Data supporting these subgoals will become available as test sections designed for lower numbers of axle repetitions begin to accumulate distress early in the program.

The longer-term subgoals include:

(a) Determining remaining life and effect of rehabilitation options
(b) Predicting pavement response/distress resulting from proposed truck weight/tire configuration changes

A greater volume of data encompassing the performance of test sections subjected to greater numbers of axle loadings will be required to satisfy these goals.

2.1.2 Develop Performance-Based Models

Models that predict the following response limits can be postulated early in the test program, as distress versus load data become available. As more complete data from sections designed for longer life are incorporated into the database, the models will be validated and improved. The response limits include:

(a) Fatigue in bituminous layers
(b) Rutting in bituminous layers
(c) Rutting in unbound aggregate layers
(d) Rutting in the subgrade
(e) Fatigue and load transfer in concrete layers

2.1.3 Document Field Performance of New Materials and Equipment

This goal supports the requirement for proof testing of materials, procedures, and equipment prior to deploying them on in-service roadways. It has a short-term perspective. Subgoals are:

(a) To document the performance of pavement maintenance and repair materials

(b) To enhance the usage of recycled paving materials
(c) To test materials and procedures for expedient rehabilitation of high traffic volume roadways and subsequent early reopening to traffic

2.1.4 Provide Training for Engineers and Technicians

Opportunities for hands-on training for the installation and usage of sensors (e.g., strain gauges, deflectometers, weigh-in-motion devices, and temperature and moisture sensors) are limited. A goal of the RRIC will be to provide such opportunities through training programs that focus not only on sensor installation and usage, but also on the use of nondestructive testing equipment (ground penetrating radar, falling weight deflectometer, spectral analysis of surface waves).

2.2 TEST SECTION MATRICES

2.2.1 Flexible Pavement Sections

Four parameters which have significant impact on the performance of flexible pavement sections are asphalt concrete (AC) layer thickness, AC layer stiffness, base thickness, and base stiffness. Assigning realistic upper and lower bound values to each parameter will result in a 4 x 4 test matrix. The parameters are shown in Table 1, and the test matrix is illustrated in Figure 3.

Table1. Flexible Pavement Parameters

Parameters	Units	High Value	Low Value
AC Thickness	mm	152 (6 in.)	76 (3 in.)
Base Thickness	mm	304 (12 in.)	152 (6 in.)
AC Stiffness (annual average)	MPa	4137 (600,000 psi)	2068 (300,000 psi)
Base Stiffness	MPa	1379 (200,000 psi)	207 (30,000 psi)

The matrix shown in Figure 3 is the basis for the experimental design and configuration of the RRIC.

Procedures described in the AASHTO Guide (1), Part II, Chapter 3, were utilized to design the structural sections that have the layer and material parameters shown in Table 1. Structural cross sections are shown in Figure 4. It should be noted that English units are used in Figure 4, since these units are used in the AASHTO Guide. For quick reference, divide stiffness values in psi by 145 to obtain MPa. Divide layer thicknesses in inches by 0.03937 to obtain mm. The estimated numbers of 18-kip equivalent single axle loads (ESALs) to functional failure are noted for each section. In addition, the finite elements model, Ilipav, was used for a limited analysis of shear stresses in the AC and granular bases of the sections with lower structural numbers. On the basis of that analysis, it was concluded that the estimated numbers of ESALs are reasonable. Assumptions used in the AASHTO design procedure were:

Subgrade resilient modulus: 35-50 MPa (5-7 ksi)
Reliability: 50%
Allowable loss of serviceability: 2.4

AC Thickness		LOW		HIGH	
AC Stiffness		Low	High	Low	High
Base Thickness	Base Stiffness				
LOW	Low	1	2	3	4
	High	5	6	7	8
HIGH	Low	9	10	11	12
	High	13	14	15	16

Figure 3. Flexible pavement test matrix

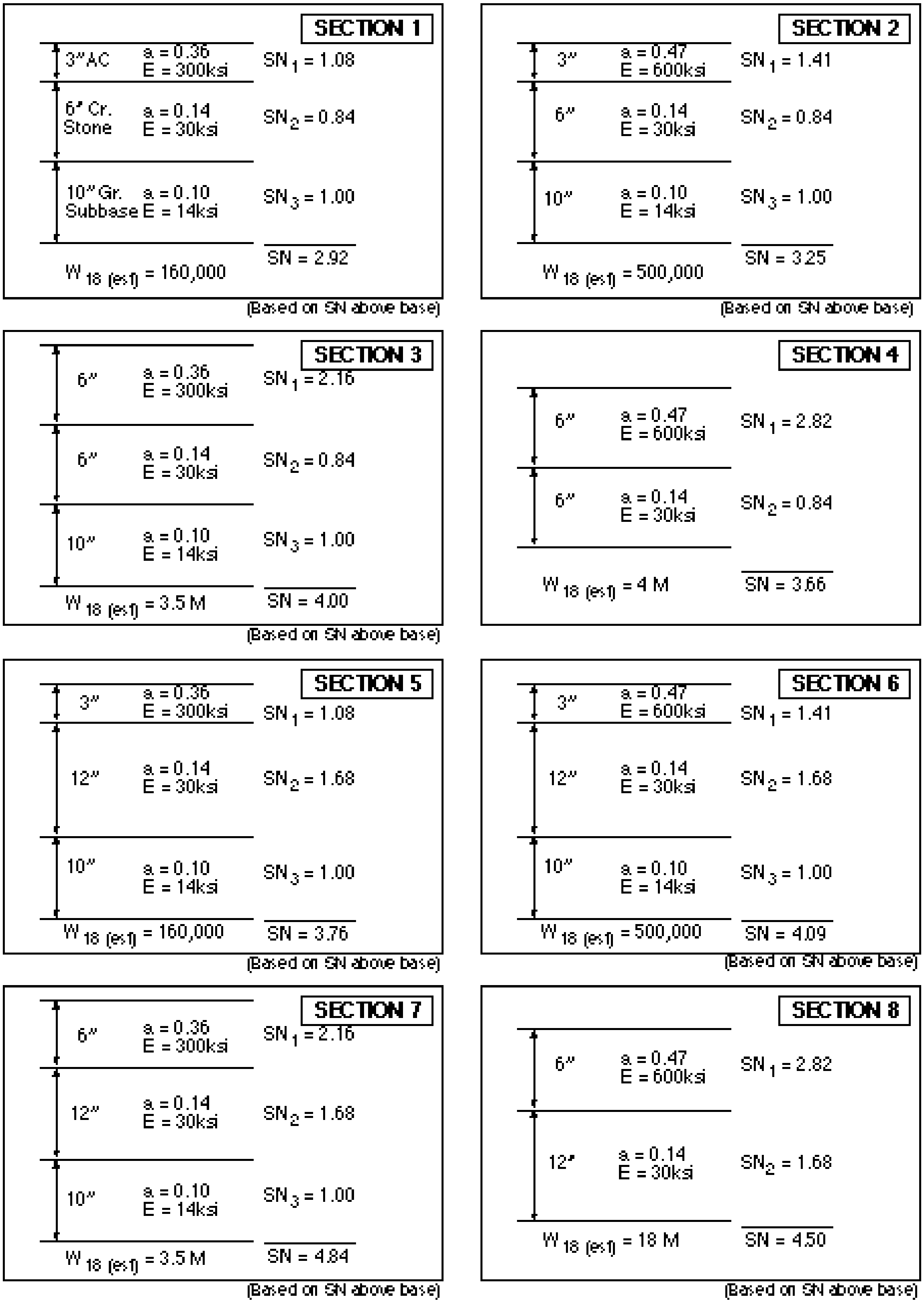

Figure 4. Flexible Structural Sections

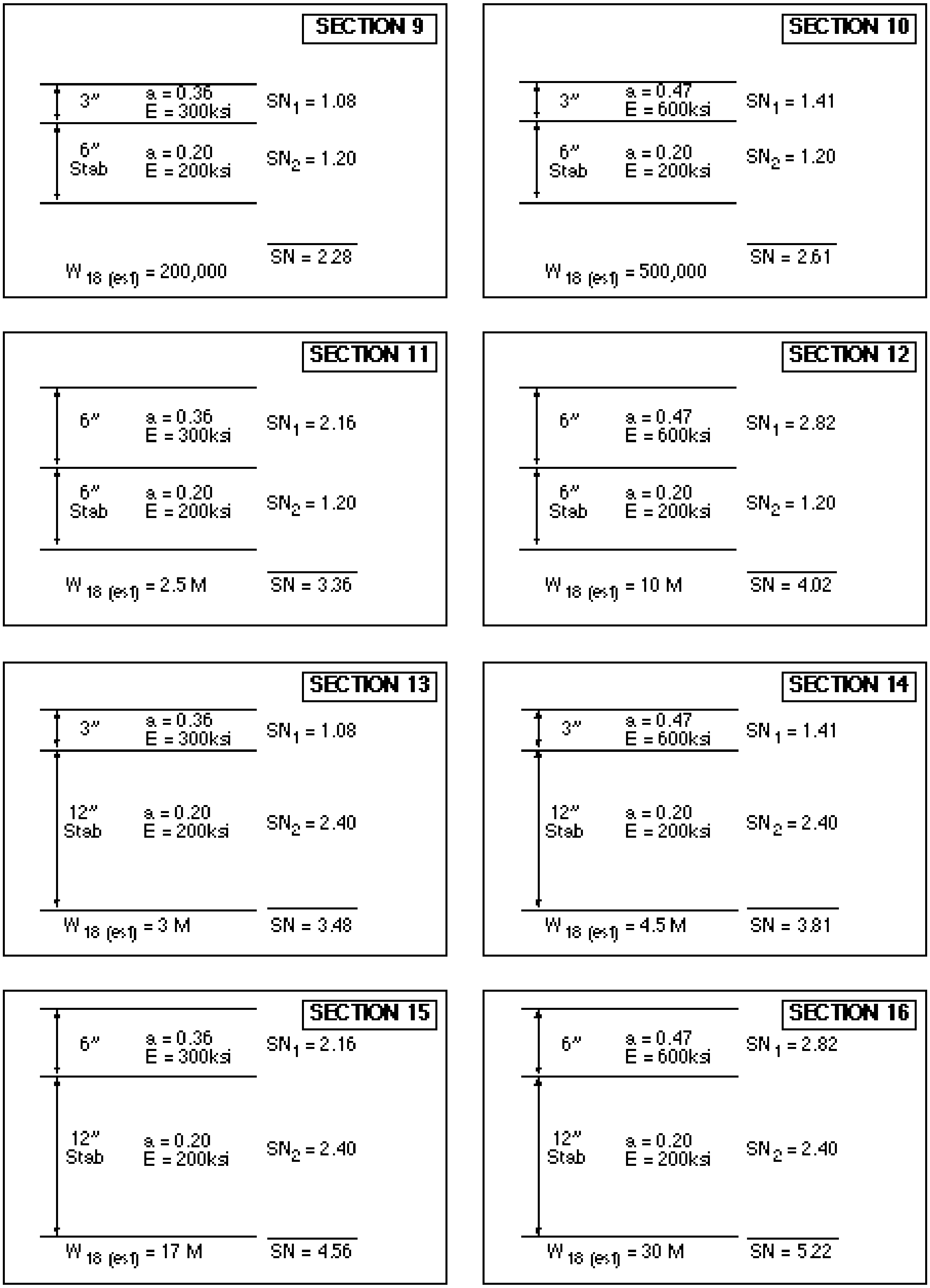

Figure 4. Flexible structural sections (cont'd)

The test matrix just described would result in progressive failure of the test sections commencing a few months after they are opened to traffic and continuing for several years. Approximately 75 percent would fail in less than five years and six sections should experience failure in one year. It should be noted that, at present, IH-35 in the Austin area carries approximately 1,000,000 ESALs per year in each direction. This process of planned functional failure would begin to supply worthwhile modeling data within months of beginning the test. The continuing performance of the sections with higher structural numbers would reflect the effects of extremely high numbers of loads, as well as the environmental effects. These results would validate the models proposed from the earlier test data.

2.2.2 Rigid Pavement Sections

A similar analysis could be conducted using the matrix for rigid pavement sections shown in Figure 5 and the parameter values shown in Table 2.

Table 2. Rigid pavement parameters

x	Units	High Value	Low Value
PCC Thickness	mm	254 (10 in.)	127 (5 in.)
PCC Strength, S_c’	MPa	7 (1000 psi)	3.5 (500 psi)
Subbase Stiffness	MPa	1379 (200,000 psi)	104 (15000 psi)
Subbase Drainage	—	1.25	0.90

It can be shown that the service lives of these test sections would range from less than one year to over twenty years. Costs to construct both of the test matrices described in this chapter would be prohibitive. One option would be to place all flexible sections initially and place portland cement concrete (PCC) overlays (‘whitetopping’) on the first sections to fail. Another alternative is to select a limited number of PCC sections, which are designed for the same traffic levels as selected asphalt sections, document construction/maintenance costs and performance lives, and develop criteria to support pavement type selection. Additionally, a viable alternative is to place a small number of full-depth concrete sections and monitor maintenance /repair history over the long run. The actual mix of pavement types should be among the first activities undertaken by the working group recommended in Chapter 5.

2.3 TEST OPERATIONS

It is important that the RRIC test program simultaneously support multiple goals. That is, the test sequence may include experimental sections for evaluating the performance of a specific material or process, but at the same time, basic response data can be collected that will support future performance prediction models. For example, two new overlay processes can be compared on adjacent sections. The immediate goal may be to document the number of axle loads to failure, but the more basic goal can include recording axle numbers, loads, classification, speeds, pavement deflections, strains, and growth of distress manifestations.

PCC Thickness		LOW		HIGH	
PCC Strength		Low	High	Low	High
Subbase Stiffness	Subbase Drainage				
LOW	Low	21	22	23	24
	High	25	26	27	28
HIGH	Low	29	30	31	32
	High	33	34	35	36

Figure 5. Rigid pavement test matrix

2.3.1 Applying the Test Loads

In order to calibrate MLS test results to those of actual truck loadings, it will be necessary to structure RRIC test operations to apply the MLS to identical test sections at the appropriate times and collect comparative response data. This can be accomplished by the following sequence:

1. As part of the design process for the original test sections, as well as the design of subsequent sections, laboratory mix design/characterization results will be verified by use of the 1/3-scale MMLS. The MMLS utilizes 300-mm-diameter pneumatic tires to apply up to 7,200 loads per hour. It can run unattended, except for the requirement to stop and measure pavement distress, twenty-four hours per day. The tire size is sufficient to minimize scaling concerns, and the device can be used in laboratory settings where temperature and moisture variations can be controlled. Alternatively, it can be applied to actual field pavements. The performance of each test section can be predicted in advance by means of the

MMLS. Thus, verification of the adequacy of the proposed test matrix and the predicted numbers of loads to failure becomes possible. This step will allow more accurate determination of the sequence of the sections along the road.

2. Selected test sections with predicted service lives ranging from very short, through intermediate, to very long, will be duplicated alongside the test road. The MLS will test portions to failure immediately following construction.
3. Traffic will be diverted from the original interstate highway onto the instrumented test road. At preselected intervals, traffic will be put back on the primary road, and pavement distress will be measured on the test road. Simultaneously, portions of the duplicate sections will be tested to failure by the MLS. In addition, trucks loaded to preselected weights will be driven directly over the test road sensors and basic data recorded.
4. The process will continue (actual traffic data, distress measurement, MLS applications, controlled truck loadings) until sections progressively fail and are replaced by different materials/structural geometries for subsequent tests. Each of the loading elements is an irreplaceable link in the test chain which ties together laboratory-scale test predictions, models based on MMLS results, MLS verification of the models, and final calibration which accounts for actual traffic mixes, speeds, seasonal environment variations and construction effects. Basic transfer functions for such failure mechanisms as fatigue, rutting, etc. can be readily quantified and applied directly to MLS or MMLS characterization of pavements in other climate zones with different subgrades.

2.3.2 Data and Results

The test program will require constant collection of certain data and periodic measurement of other data. For example, continually recorded load data will include wheel loads and numbers of axles. In addition, actual traffic load magnitudes, speeds, and axle configurations will be required. Also, air and pavement temperature and moisture conditions will be recorded regularly.

Pavement response data, primarily strains and deflections, will be recorded at intervals under MLS loads and controlled truck loadings. At the same intervals, pavement distress data will be collected. Specifically, roughness, cracking, rutting, stiffness, and strength values will be recorded.

It will be possible to measure truck performance as well. Such parameters as accelerations, dynamic loads, component fatigue, and tire behaviors are important indicators of pavement/vehicle interaction and can be readily measured.

The types of data collected can be utilized for immediate qualitative or comparative studies of the performance of materials, construction techniques, and equipment, traffic control sensors/transmitters, and pavement rehabilitation options. The data will also form the technical basis for longer-term solutions for material characterization and performance models, truck/roadway interactions, MLS/truck correlation, and environmental effects versus load damage.

2.4 TRANSFER FUNCTION DEVELOPMENT EXAMPLE

Figure 6, published by Hugo et al., (3) illustrates how MLS load applications can be combined with actual traffic applications to quantify environmental effects on pavements and develop transfer functions that link laboratory predictions of service life to field results.

Figure 6(b) illustrates the accumulation of traffic axle loads, $N_{traffic}$, with time. It also shows the numbers of MLS axle loads that will cause failure, N_i, at various intervals during the life of the pavement section. The magnitude of the "locus of failure points" curve at any time, t_i, can be used to estimate the cumulative environmental effects from time of construction to t_i:

$$N_{env} = N_1 - N_2 - N_{traffic}$$

Figure 6a contains the plots representing distress accumulation (rutting, fatigue, etc.) versus time for MLS loadings (dashed lines) and actual traffic (solid lines). The slope of the distress versus time lines (D_1 and D_2) are representative of locations on the time line and can therefore be correlated to the rate of damage accumulation under actual traffic loadings at different stages of the pavement's life.

Figure 6c represents the relationships between strains and numbers of load repetitions to failure, as defined by the limiting distress, D_{limit}, in Figure 6a.

Curves representing laboratory results, MMLS, MLS, and actual traffic loading data for the test sections can be plotted and the shift factors calculated. In this way, predictive models for pavement life can be calibrated, and appropriate transfer functions can be applied to MMLS and MLS test results to yield reliable service life estimates for a wide range of climate or subgrade conditions. The procedure described will allow analytical separation of environmental and load effects on pavement life and will extend the usefulness of accelerated pavement testing devices as tools for effective pavement management.

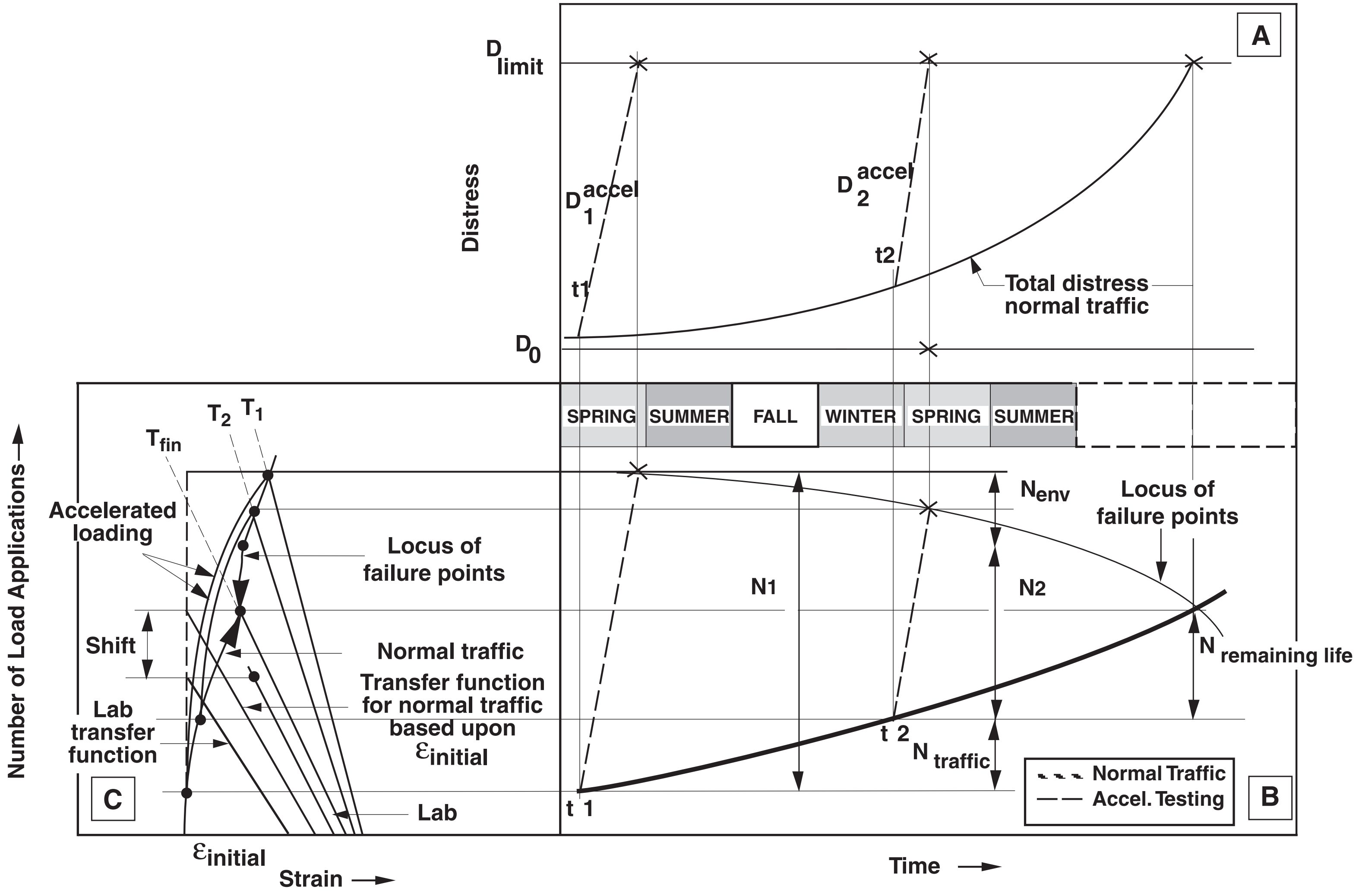

Figure 6. Concept for performance modeling based upon MMLS, MLS, and actual truck loadings

CHAPTER 3. ROADWAY RESEARCH IMPLEMENTATION CENTER CONFIGURATI0N, INSTRUMENTATION, POTENTIAL LOCATION, AND COST ESTIMATES

3.1. SITE CONFIGURATION

The proposed Roadway Research Implementation Center (RRIC) is shown in Figure 7. The site consists of a test road parallel to a segment of IH-35, road sections for mobile load simulator (MLS) applications, and indoor space for maintenance, training, and administration functions. The 2.4-km (1.5-mile) parallel test road contains a weigh-in-motion system (WIMS) and 20 −122-meter (400-ft) long test sections. This arrangement is sufficient to accommodate the sixteen-cell test matrix proposed in Chapter 2, plus selected replicate sections or portland cement concrete (PCC) sections. All sections contain three lanes to be consistent with plans to eventually add a third lane to IH-35 at this site.

The test sections are placed so that those anticipated to fail within the first year are at the departure end with a ramp for returning traffic to the main road located just prior to these sections. This ramp is necessary so that traffic can remain on the longer-lived test sections while those nearing failure are undergoing diagnostic studies. The seven MLS test sections, which duplicate selected test road sections, are each 46 meter (150 ft) long by 4.5 meter (15 ft) wide. The length accommodates up to three tests to failure on each section. The concept of applying model mobile load simulator (MMLS), MLS, actual traffic, and controlled truck loadings to facilitate development of performance models was described in Chapter 2.

3.2 INSTRUMENTATION

Van Deusen et al. (7) analyzed sensor selection criteria and conducted laboratory tests on strain, displacement, and pressure sensors for the MnRoad project. Their recommendations were incorporated into the project. is presented Baker et al. (6) provide detailed installation and testing procedures regarding sensor implementation. Pilson et al. (5) studied types, numbers, and locations for strain and pressure sensors in pavement test sections. These references constitute a sound experience basis for sensor selection for the RRIC.

A typical test section would be equipped with multidepth deflectometers (MDD), thermocouples, and strain gauges. Selected sections would include Time Domain Reflectometry (TDR) for monitoring the moisture content of subgrade and base course materials.

Vogelzang (4) notes that researchers at the LINTRACK facility at the Delft University of Technology abandoned attempts at measuring soil stresses because of the very large dispersion in the data resulting from disturbance in the media, mismatches of soil and gauge stiffness, and damage to the gauge. Acknowledging the questionable accuracy of stress gauge measurements, Pilson et al. (5) recommended the Kulite 0234-40-100G pressure cell if pressure measurements are to be attempted. Baker et al. (6) documented the use of the Kulite 0234 and the Geokon 3500 gauge at the MnRoad test site. MnRoad researchers report satisfaction with the pressure gauge data.

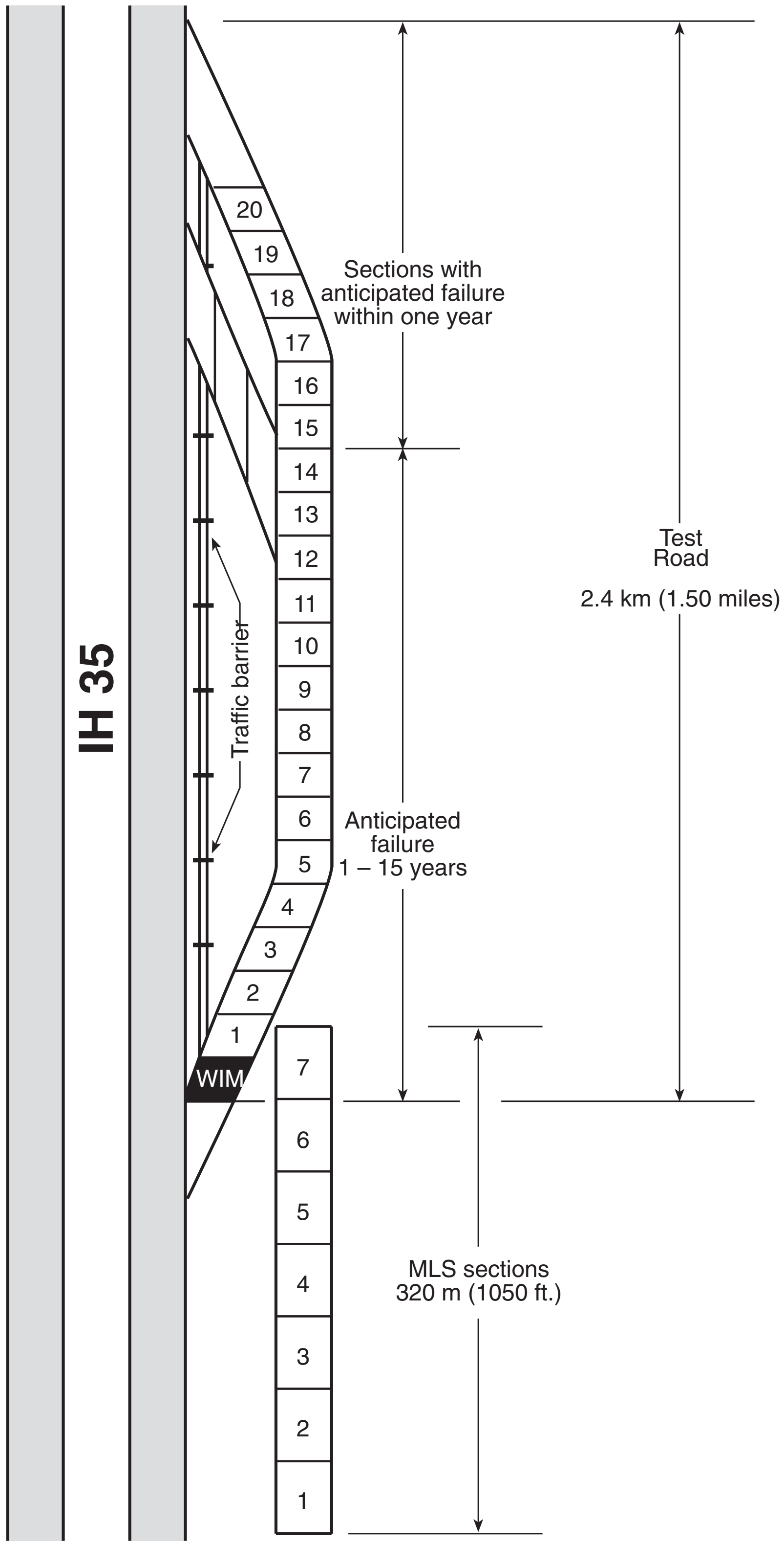

Figure 7. RRIC

The use of pressure gauges is not an essential part of the RRIC data collection process. However, opportunities would exist to experiment with the use of such gauges on a limited basis. The cost and handling complexity of these gauges restricts their usefulness. The more important data to be collected include longitudinal and transverse strains in the asphalt layers, deflection at various depths within the pavement structure, load magnitude, and axle classification. Pilson et al. (5) recommend using the HBM DA3 strain gauge, on the basis of experience with the MLS test series at Victoria. MnRoad is using Dynatest PAST-2AC and Alberta Research Council strain gauges with success. The LINTRACK facility has reported confidence in the use of the Tokyo Sokki Kenkyujo Company, T.M.L. KM-100-HAS strain gauge. The selection of type of gauge and numbers to be installed would depend upon the outcome of the detailed design phase, as proposed in Chapter 5.

Vertical strains in granular pavement layers and in the subgrade can be estimated from differential MDD measurements. In addition, other critical data will be recorded periodically when traffic is diverted off of the test road. These data include falling weight deflectometer (FWD) deflections, layer stiffness from seismic tests, rut depth, and crack length determination.

Load data for the MLS will be obtained by current methods (CAPTELS-type WIM and strain gauges mounted on the axles). For the test road, a more complex WIM system is required. Garner and Lee (8) describe an augmented system manufactured by the PAT Traffic Control Corporation. An inductance loop in each traffic lane detects the vehicles and triggers the computer. A staggered pair of weigh pads in each lane provides weights, speed, and distance between axles. An infrared sensing unit in each lane indicates dual or single tires and determines the lateral position of the tires. The layout is shown in Figure 8. The associated software can collect and store the data in a number of ways: daily traffic volume, ESALs per day, ESALs per axle category, etc.

3.3 POTENTIAL LOCATION

To avoid the great expense and delay associated with acquisition of additional land along IH-35, it would be desirable to site the RRIC on already state-owned right-of-way. A stretch of IH-35 immediately south of the Corn Hill overpass, which is south of Jarrell, Texas, appears to be acceptable. There are two segments on each side of IH-35. Each segment is about 3.2 km long, for a total of 6.4 km on each side of the highway. The distance between the edge of IH-35 and the service road is on the order of 23 meters, and there is space to relocate the service road closer to the fenceline, if necessary. In general, the terrain is level, a factor that will serve to hold down some construction costs. The straight 3.2-km segments do not cross drainage features or exit ramps, further facilitating construction. Finally, the favorable terrain enhances motorists' field of vision so that traffic control can be easily managed.

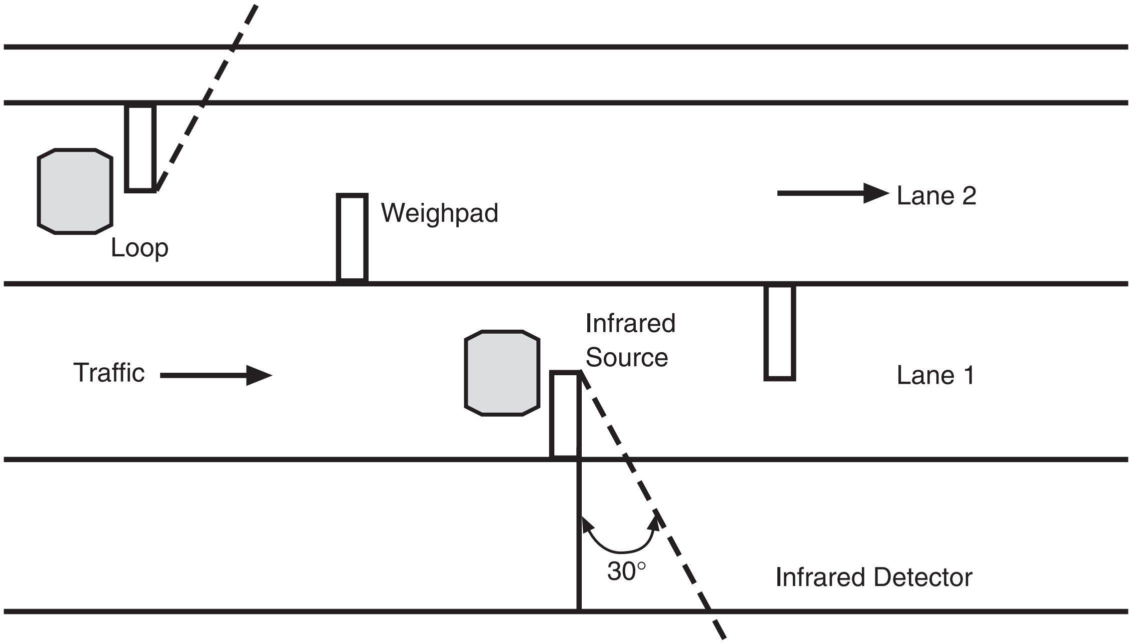

Figure 8. WIM system

Figure 9 is a set of aerial photos showing the location. The figure is an aerial photo of a segment of IH-35 stretching south for about 6.4 km from the Corn Hill overpass. Note the absence of drainage crossings or approach ramps in the 3.2 km stretches. Figure 10 is a photo looking south on the east side of IH-35 along the southern portion of the area shown in Figure 9. Figure 11 is a view to the north on the west side of the road just to the south of Corn Hill. Particularly noteworthy in the photos is the level terrain and sufficient distance between the travel lanes of the interstate and the service road.

Figure 12 illustrates the placement of the RRIC on the west side of IH-35. The photo has been expanded transversely.

3.4 COST ESTIMATES

3.4.1 Initial Acquisition Costs

To arrive at a representative cost estimate, reported costs of instrumentation sensors from other applications were sought, and TxDOT average low-bid unit price construction reports for June 1998 were used. The following assumptions were made:

1. The average thickness of the AC surface layer is 115 mm (4.5 in.).
2. The test road has three 3.7-meter (12-ft) wide lanes plus two, 3-meter (10-ft) shoulders constructed of the same materials as the traffic lanes.
3. The test road is 2.4 km (1.50 miles) long. This length allows twenty 122-meter (400-ft) long test sections.

4. The MLS test sections are 4.5 meter (15 ft) wide with the same average section thicknesses as the test road.
5. The 320-meter (1050-ft) long MLS site will accommodate seven 46-meter (150-ft) long test sections.

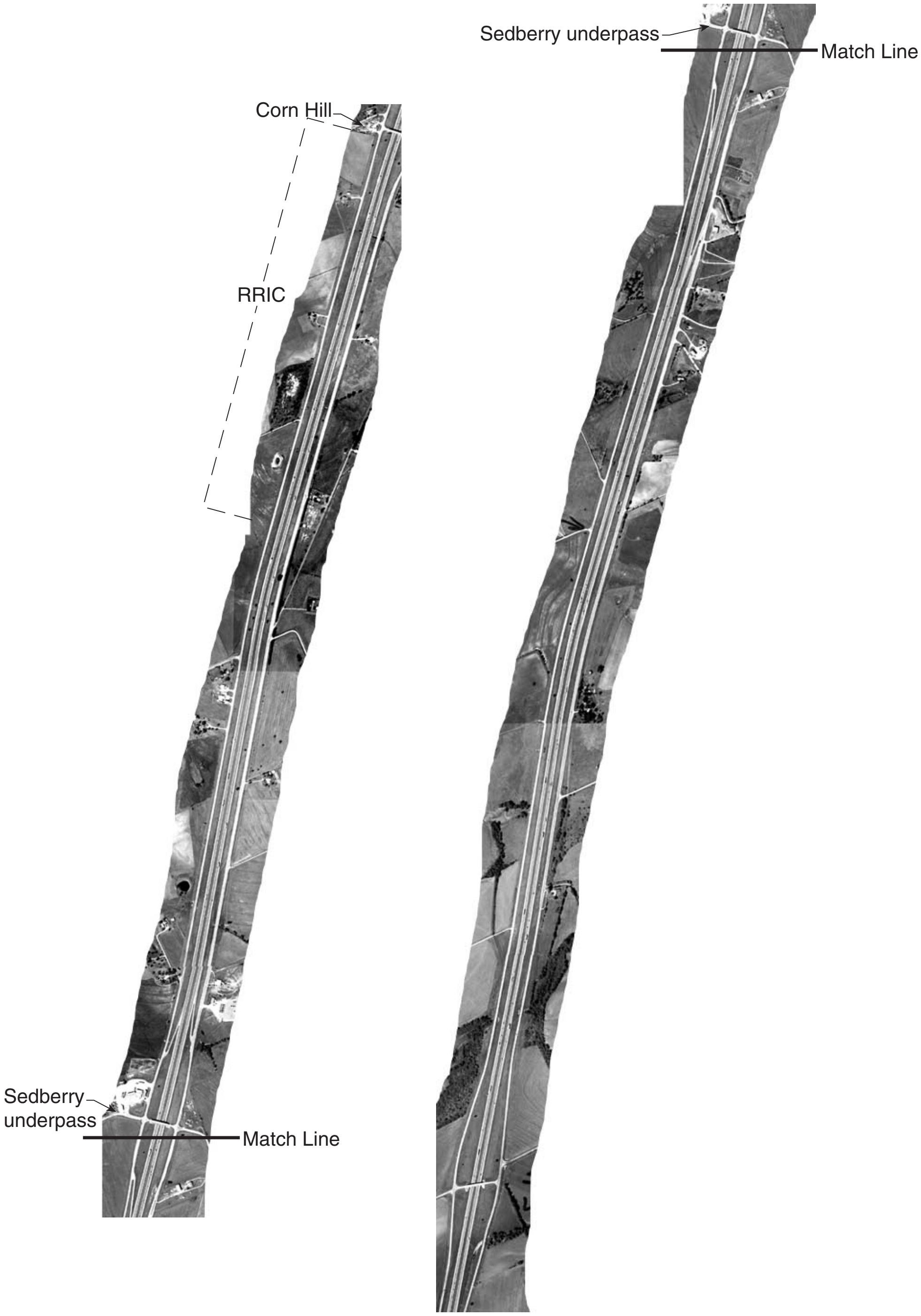

Figure 9. Aerial photo of IH-35 south from Jarrell, Texas

Figure 10. View to the south—East side of IH-35

Figure 11. View to the north—West side of IH-35

Figure 12. RRIC potential site

Figure 13 shows the average dimensions for the MLS test sections. Figure 14 shows average dimensions for the test road sections.

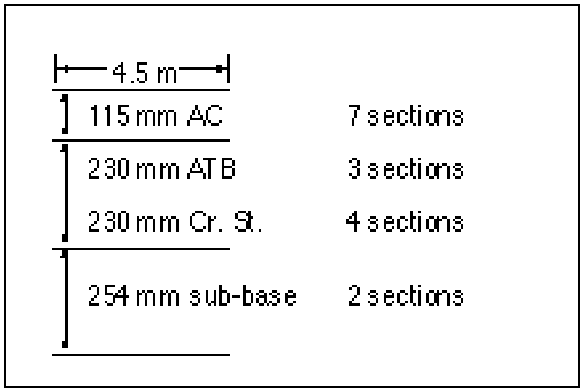

Figure 13. Average dimensions for MLS test sections

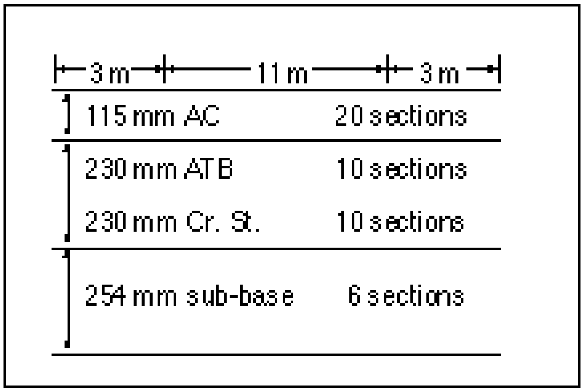

Figure 14. Average dimensions for test road sections

Table 3 shows cost estimates for constructing the test site, Table 4 summarizes instrumentation costs, and Table 5 shows total cost estimates for the initial construction.

As envisioned, operations at the RRIC will require running the MLS twenty hours per day, six days per week in order to test the required numbers of sections. This will necessitate use of a dedicated machine. Additional acquisition costs will be about $3.5 million for the MLS and $100,000 for the environmental chamber-equipped MMLS. Thus, the total estimated acquisition costs would be approximately $7.8 million.

3.4.2 Recurring Operations Costs

Annual operations costs for the RRIC will vary depending upon the numbers of new test sections constructed in any given year, the availability of donated materials and equipment, and the necessity of replacing pavement sensors. Construction costs can vary from $15,000 to $50,000, depending on the type of test section selected (McNerney et al.,

[10]). Nevertheless, it is possible to estimate the annual requirement by looking at the scope of activities at the site and collecting costs in each category.

Table 3. Construction costs

Item	Units	Unit Cost ($)	Quantity	Cost ($)
100 Prepare R.O.W.	KM	11,174	2.81	31,400
152 Road grader (subgrade)	KM	8,672	2.81	24,400
247 Subbase	CY	17.00	3,280	55,800
347 Cr. St. base (9 in.)	M^2	10.00	21,300	213,000
345 ATB	Ton	37.00	11,892	440,000
340 AC	Ton	55.00	11,963	658,000
Service road and parking	SY	12	2,500	30,000
514 Traffic barriers	M	85.00	2,332	198,000
Metal building	SF	90.00	4,000	360,000
Water/power/sewer				100,000
Total				2,110,600
Mobilization 10%		211,060		
Contingency 7%		147,750		
Total Construction				2,469,410

Note: Bid data are for the Austin District, if available. Otherwise, statewide average data are reflected.

Table 4. Instrumentation costs

Data Acquisition	**Cost ($)**
Sensors (installed) $40,000/section	800,000
Computer systems	500,000
Total	1,300,000
WIM System	
Load cells, inductance loop, infrared detectors (3 lanes)	60,000
Data Collection	20,000
92 meter continuously reinforced concrete pavement (305 mm thick)	56,000
Total	136,000
Miscellaneous	
Signage, traffic control, etc.	200,000
Total Cost	1,636,000

Table 5. Total site costs

Construction	2,469,410
Instrumentation	1,636,000
Total	4,105,410

There will be three major functions. The first, planning and overhead, includes planning future test requirements, developing future budgets, recruiting new industry members, disseminating results of completed tests, and overseeing current testing. Costs associated with this category include salaries for the six-person staff and normal administrative functions. The second major function, test design and construction, includes the detailed planning for upcoming test series, engineering design of test sections, construction, and sensor installation. The final functional category is current testing. The main activities would include MLS and MMLS operations; data collection, analysis, and reporting; and test section maintenance and repair. Figure 15 summarizes the RRIC major functions. Figure 16 shows cost estimates for each function and the staff elements involved with each. A reasonable estimate for the annual funding required to carry out a robust test program is $1,320,000. It is recognized that a portion of the requirement may be realized by using donated materials or equipment.

Planning and Overhead

- Planning Future Test Requirements
- Budget for next year
- Review and oversight of current testing
- Recruiting membership
- Dissemination of previous test results

Current Testing

- MLS and model MLS testing on parallel roadway and individual pads
- Data acquisition
- Analysis
- Reporting
- Maintenance and repair of MLS
- M & R of test sections/pads

Test Design and Construction

- Detailed planning for upcoming work
    - Test Plan
    - Pad/section dimensions, materials, etc.
    - Instrumentation
- Construction
- Sensor installation

Figure 15. RRIC functional Activities

Planning and Overhead		Current Testing		Test Design and Construction
Salaries	$360,000	MLS ops	$510,000	$250,000 (Equipment ops, pavement materials, instrumentation)
Travel	$10,000	Computer Support	$10,000	
Misc.	$10,000	Test Sec. M&R	$30,000	
Fringes	$70,000	Fringes	$50,000	
		Data collection, analysis and reporting	$20,000	
	$450,000		$620,000	$250,000
Total $1,320,000				
Staff: RRI Staff: Director Engineer – Assistant Director Data Acquisition/Data Base Manager Administrative Assistant Data Base Assistant Advisory Committee Board of Directors		**Staff:** RRI Staff MLS Crews – TxDOT Principal Investigators and project staff – from University, TxDOT, and industry		**Staff:** RRI Staff and P.I.s

Figure 16. RRIC annual operations budget

CHAPTER 4. ROADWAY RESEARCH IMPLEMENTATION CENTER ORGANIZATION

4.1 INTRODUCTION

In August of 1996, a one-day conference was held to identify the general direction to be followed in defining the Roadway Research Initiative (RRI). Representatives from TxDOT divisions and districts, and researchers and administrators from the Texas Transportation Institute (TTI) and the Center for Transportation Research (CTR) were in attendance. The discussions became the framework for subsequent development of the test program goals and objectives, site configuration, and organizational structure. During the next year, meetings were held with representatives of the Associated General Contractors of Texas, Texas Aggregates and Concrete Association, Texas Hot Mix Asphalt Pavement Association, and Texas Chapter of American Concrete Pavement Association, and the Federal Highway Administration (FHWA). These sessions led to the organizational structure presented herein.

In December of 1997, an all-day meeting was held to evaluate progress and direction of the RRI concept. All the organizations listed above were represented, as well as Texas Tech University, The American Trucking Associations, AAA of Texas, Caterpillar, Inc., and Texas Motor Transportation Association. The group recommended that subcommittees be constituted to define how industry might best participate in the RRIC organization. Subsequently, meetings were held at CTR with industry and university representatives for this purpose. The organizational structure was finalized, and the test program was reviewed for technical relevance and importance of the goals.

4.2 PROPOSED STRUCTURE

4.2.1 GENERAL

The center shall carry out a program of research, education, technology transfer, and testing and evaluation in support of the state's investments in various roadway systems. The center, through facilities, personnel, and infrastructure, both existing in the founding institutions (TxDOT, TTI, and CTR) and in the private sector, shall advance the cost-effectiveness and safety of roadway infrastructure in Texas and beyond.

The RRIC shall be established as a component of the Texas A&M University System under TTI. The operating budget, staffing, and activities of the center shall be approved by the board of regents of the Texas A&M University System. The center staff shall be housed at CTR at The University of Texas at Austin. The test facilities of the center shall be the property of TxDOT. Equipment and facilities of the universities, operated in support of the center, remain university property.

Provisions of Articles 16, 17, and 18 of the existing Cooperative Research Agreement (CRA) (as amended) shall govern intellectual property rights.

4.2.2 Board of Directors

The board of directors shall consist of one representative from each of the three founding institutions. Members will be appointed for three-year terms by the chancellor of the Texas A&M University System, the dean of Engineering at the University of Texas at

Austin, and the executive director of TxDOT . The board of directors will establish policies and provide oversight to all operations of the center, and will conduct the performance evaluation of the center's director. The chairperson of the board of directors shall be elected by the members for a three-year term. The first chairperson shall be the director of CTR.

4.2.3 Director

The center will be under the leadership and supervision of the director and shall be managed as a joint program among the founding institutions. The director shall be jointly selected by and hold a joint appointment between TTI and CTR. The director will oversee the center's day-to-day operations, direct the planning process, ensure test results are properly reported, and direct the staff.

4.2.4 Staff

A small permanent staff will be required to operate the center. The intent of the organization is to utilize staff of the founding institutions as necessary. For example, the MLS will be operated by field crews from the TxDOT Pavements Section, and research project investigators will be university and TxDOT researchers. The following staff positions are recommended:

Engineer — Assistant Director
Data Acquisition Manager
Business Manager
Administrative Assistant
Database Assistant

Figures 15 and 16, in Chapter 3, show staff functions and cost estimates.

4.2.5 Advisory Board

The advisory board will consist of representatives of the founding institutions and organizations known as sustaining members. Sustaining members are those public or private organizations which have indicated intent to supply equipment, material, manpower, or funds to support center operations. The extent of participation is intentionally unspecified. It may range from supplying personnel for project planning teams to purchasing equipment for the site to paying for a test series. Minimum advisory board membership should include one or more TxDOT district pavement engineers, representatives from TxDOT's Construction and Design Divisions, and TTI and CTR researchers. Sustaining membership should, at the least, encompass the materials and construction industries.

The advisory board shall assist the director with oversight of the planning, programming, experimental design, and current testing functions. It shall designate subcommittees as required to carry out the various functions.

4.3 TEST PLANNING CYCLE

The recurring planning cycle is shown below. The director, assisted by the advisory board, is responsible for the timely completion of each phase of the cycle. It will be necessary to coordinate the planning phase with the TxDOT research management structure to ensure the RRIC program is addressing department goals. The process will be facilitated by the participation of department and university personnel in the problem identification process.

PROGRAM DEVELOPMENT (Program year minus 2)	**DESIGN** (Program year minus 1)	**TEST** (Program year)
1. Solicit problem statements	1. Design test sections	1. Construct test sections
2. Develop test plans	2. Conduct MMLS testing	2. Apply traffic, MLS loadings
3. Prepare proposals	3. Revise designs	3. Collect data, report results

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

1. A test program (described in Chapter 2) that utilizes instrumented pavement sections, mobile load simulator (MLS), model MLS (MMLS), actual traffic, and controlled truck applications offers unique flexibility in solving a wide scope of roadway issues requiring short-term results up to longer-term, more fundamental model development. Shorter-term applications include low-risk proof testing of new materials, equipment, or structural design alternatives under actual traffic conditions. Longer-term projects include development of transfer functions defining limiting values of pavement distress for use with mechanistic design methods, calibration of the MLS and 1/3-scale MMLS test results with actual traffic, and creation of accurate pavement performance prediction models for new construction and rehabilitation alternatives.
2. As described in Chapter 4, there is interest among representatives of the materials, construction, consulting, and trucking industries in establishing a capability to jointly investigate roadway transportation issues that are of mutual interest. Some of these issues concern the development of new paving materials, new construction methods, use of recycled materials, development of construction specifications, weight/tire configuration/damage studies, and pavement/truck interaction investigations. Finally, the opportunity exists to demonstrate to the people of Texas that the best technologies available are being harnessed by government, industry, and state universities to provide superior, longer-lasting roads at reasonable costs.
3. An essential component of the proposed test capability is the 1/3-scale MMLS, which can be used effectively to transition laboratory results to the full-scale test site. As described in Chapter 2 and in the appendix, the MMLS can be used to verify laboratory performance predictions for asphalt material layers and unbound aggregate layers. The relatively low cost and short duration of model testing allow this procedure to be used to simulate the expected performance of the full-scale Roadway Research Implementation Center (RRIC). In essence, the MMLS allows the RRIC test matrix to be pretested prior to final design. Decisions on actual test section geometry and placement on the test road will be delayed pending the MMLS test results.
4. Acquisition costs for the RRIC include a new MLS, a 1/3-scale MMLS, and construction of an instrumented parallel test road and MLS test sections. Several acceptable sites are located along IH-35 between Georgetown and Jarrell, Texas, on state-owned right-of-way. Cost elements are detailed in Chapter 3. Initial acquisition costs are approximately $7.8 million and are dependent on the length of the test road and numbers of instrumentation/sensors selected. (Annual operations are discussed in Chapter 3.) The planning cycle is discussed in Chapter 4. Annual costs are approximately $1.3 million for supporting the full program as described.

5.2 RECOMMENDATIONS

The following is a series of recommended steps leading up to a full RRIC test capability.

1. Establish an interim steering committee, which would oversee preliminary preparations prior to the establishment of the board of directors. This step can be accomplished by means of a memorandum of agreement between the two universities and TxDOT, implementing the organization described in Chapter 4. The steering committee would consist of three members: the representative of the executive director of the Texas Department of Transportation (TxDOT), the director of the Texas Transportation Institute (TTI), and the director of the Center for Transportation Research (CTR). The steering committee will be the approval authority for initial RRIC site configuration and test matrix composition.
2. The steering committee will appoint a director for the RRIC. The director will exercise day-to-day oversight for all activities leading to the establishment of the RRIC. These activities include, but are not limited to, organizing the working committee to flesh out the initial MMLS test plan, assisting in the procurement and operation of the MMLS and MLS, recruiting corporate members, and completing the steps leading to construction.
3. Establish a working group, consisting of district pavement engineers, staff from the design, construction, and transportation planning and program divisions, TTI and CTR researchers, regional FHWA, and industry representatives. Initially, the following industry associations should be asked to provide representation: Texas Aggregates and Concrete Association, Texas Chapter of the American Concrete Pavement Association, Associated General Contractors of Texas, and the Texas Hot Mix Asphalt Pavement Association. The working group will form subcommittees as required and will recommend site configuration and test program details for the steering committee's approval.
4. Procure one or more 1/3-scale MMLS and execute the test program recommended by the working group. The initial program should validate laboratory predictions of the performance of the full-scale sections. The ninety-six-cell test matrix described in the appendix should form the basis for the effort.
5. As results are realized from the MMLS test series, final decisions regarding the RRIC initial configuration can be made.
6. Establish a subcommittee of the working group to recommend specific sensors (type, numbers, etc.) and data collection systems for use at the site.
7. Confirm site selection and conduct appropriate field tests (FWD, GPR, soil sampling, etc.) to support final test section design.
8. Transition the site designs to the appropriate TxDOT office for preparation of bid documents and project advertisement/award.

The process is illustrated in Figure 17.

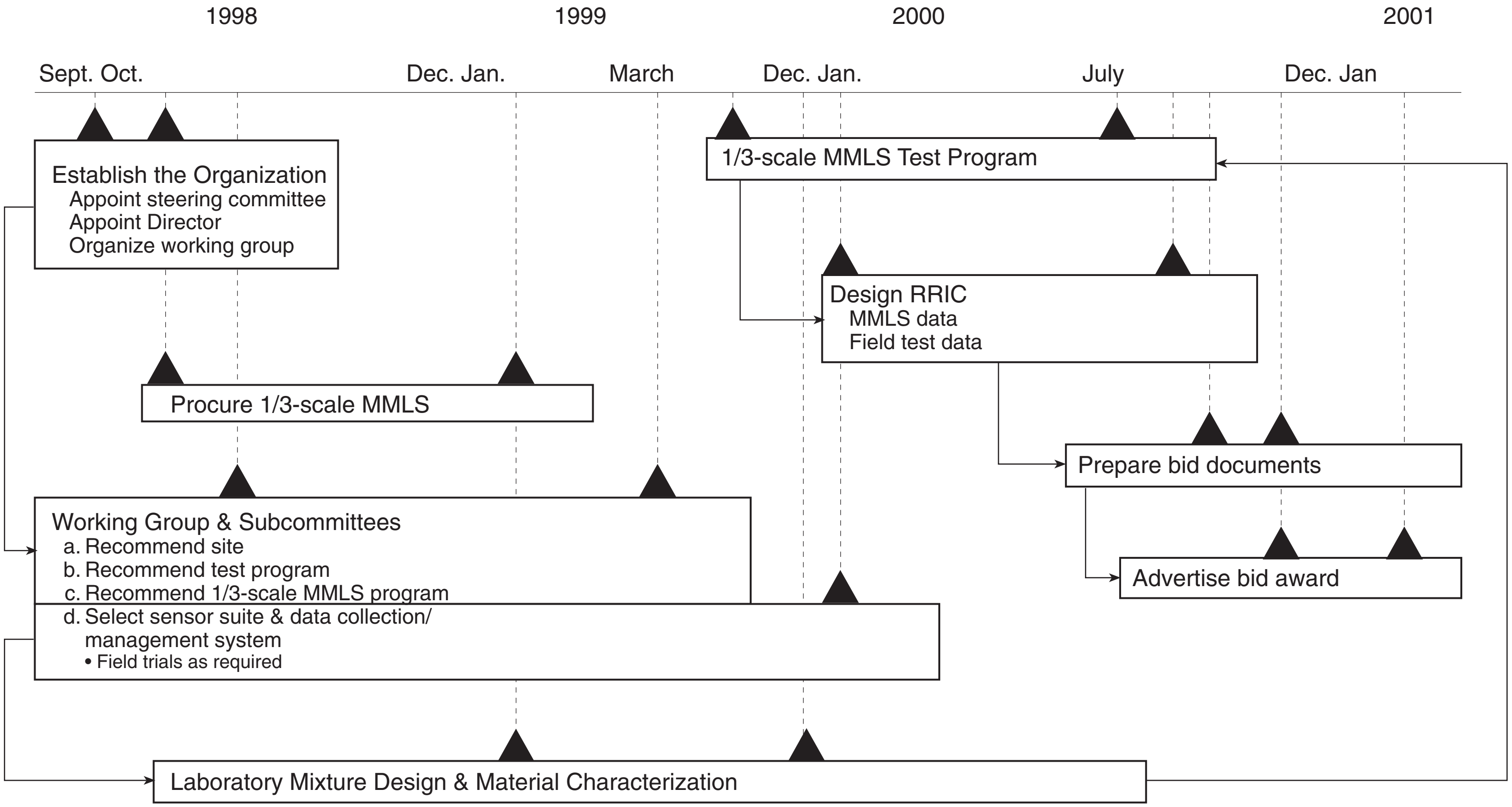

Figure 17. Implementation timeline

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APPENDIX

The Role of Model Testing in APT Programs with a Strategy Towards Implementation of 1/3-Scale MMLS APT Under RRIC

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Center for Transportation Research
May 1998

Abstract

Small-scale testing of pavement structures and materials provides an alternative means for preliminary indicator or ranking tests prior to, or in place of, expensive full-scale accelerated pavement testing (APT). This paper describes past performance testing of scaled-down asphalt pavements using model testing. Scaled-down APT considerations for visco-elastic and elasto-plastic materials are outlined.

In light of the possible role of model testing in APT, attention was given to performance modeling, validation of asphalt mix design, ranking of candidate blends, environmental conditioning (durability), distress and load equivalency, and scaling of granular materials.

In order to carry out scaled tests effectively, dimensional analysis considerations need to be met. This implies that the laws of similitude require observation. In particular, scaled-down pavement layers need to be subjected to the same stresses and strains as the full-scale pavement under equivalent loading. In addition, the material properties of the scaled-down layer must be equivalent to the full-scale materials. Various tests have been carried out with different materials at full scale and small scale. The test results are discussed with a comparison between the full-scale and scaled-down material properties. These results are critically reviewed with regard to the effectiveness of the scaling down of materials, the testing device, and other influences, particularly environmental aging and moisture influences in the scaled context.

Conclusions have been drawn with respect to the appropriateness of scaling down of pavement materials. The three main material response characteristics identified for scaled-down performance testing are stiffness, strength, and permanent deformation. The volumetric differences between full-scale and comparable scaled-down materials must also be considered.

To improve performance prediction, further research into scaled-down APT should be directed towards:

- the possible effects of deviation from laws of similitude and of applying different scaling factors,
- material properties of scaled-down materials and in particular permanent deformation considerations,
- comparative permanent deformation performance through dynamic triaxial testing,
- the influence of the larger filler fraction of scaled-down materials,
- the scaling down of mechanical test equipment and procedures for tests on scaled-down materials, and
- artificial aging compared to environmental aging.

A strategy towards implementation of 1/3-scale MMLS model testing to support full-scale APT under Roadway Research Implementation Center (RRIC) is presented. The RRIC design variables include AC surfacing stiffness and thickness and base stiffness and thickness. Using the MMLS, additional factors not accounted for in the full-scale APT under RRIC can be evaluated. The influence of these factors on the response and subsequent performance of the scaled pavements may then be transferred to the full-scale experiments. A matrix of experiments has been designed to assess the influence of degree of subgrade saturation, test temperature, aging of the asphalt surfacing, and overload testing on pavement performance using the MMLS.

Given that the 1/3-scale MMLS can run twenty hours a day with four hours routine maintenance, at this rate and a seven-day working week, the time to completion of the MMLS tests is estimated at 382 days. It was further shown that using additional MMLS devices reduces project time significantly. It is anticipated that up to seventy-five million MMLS axle loads may be applied during the project as proposed. This large number of axles suggests that maintenance of the MMLS may be critical to ensure efficient management of the project.

Table of Contents

Introduction

Among all Accelerated Pavement Testing (APT) devices, the Texas mobile load simulator (MLS) has the ability to test the widest range of variables within a pavement system (1). The many variables impacting pavement systems and the great amount of tests necessary to evaluate these variables has necessitated finding means whereby it would be possible to expedite the testing of different variables, prior to conducting full-scale APT under the Roadway Research Implementation Center (RRIC) program. Accelerated testing on laboratory scale is favored as a cost efficient yet effective means of doing this.

The objectives of this report are to:

- Describe the model mobile load simulator (MMLS) devices;
- Outline theoretical approaches to model testing;
- Report on past experiences with MMLS testing;
- Expand on the possible role of model testing in APT;
- To recommend a strategy for implementation of model testing to support the RRIC program.

Presently, two scaled-down versions of the MLS are in operation. These model versions are discussed, and the technical specifications of each are tabulated. The theoretical approaches and considerations relating to scaled-down model testing are then discussed. The possible role and benefits of model testing in APT programs are outlined with consideration given to:

- Performance modeling;
- Validation of asphalt mix design;
- Ranking of candidate blends;
- Environmental conditioning (durability);
- Distress and load equivalency;
- Scaling of granular materials.

Typical results of past MMLS rutting and fatigue performance testing are shown and the significance of environmental distress and conditioning is outlined. Apart from asphaltic materials, the scaling of granular materials for model testing has also been researched. Conclusions are drawn and recommendations are made towards a strategy for implementation of a model-testing program to supplement full-scale APT under RRIC.

An implementation strategy for 1/3-scale MMLS model testing is presented. An extensive MMLS testing program is proposed. Additional factors not considered for full-scale APT under RRIC are incorporated. Recommendations are made with regard to project scheduling, failure criterion, and program duration.

MMLS Model Mobile Load Simulator Accelerated Pavement Testing APT Devices

Overview

The model mobile load simulator (MMLS) Mk.1 was introduced as a scaled-down 1:10 accelerated pavement testing (APT) device for use in a controlled environment (2). A schematic of the MMLS Mk.1 is shown in Figure 1. This MMLS was originally developed as a demonstration model for the Texas mobile load simulator (TxMLS) but was later mechanized for evaluating 1:10 APT. The main advantages of this type of scaled APT device are that:

the load is always moving in one direction,

many repetitions are possible in a short period, and,

a relatively high trafficking speed is possible.

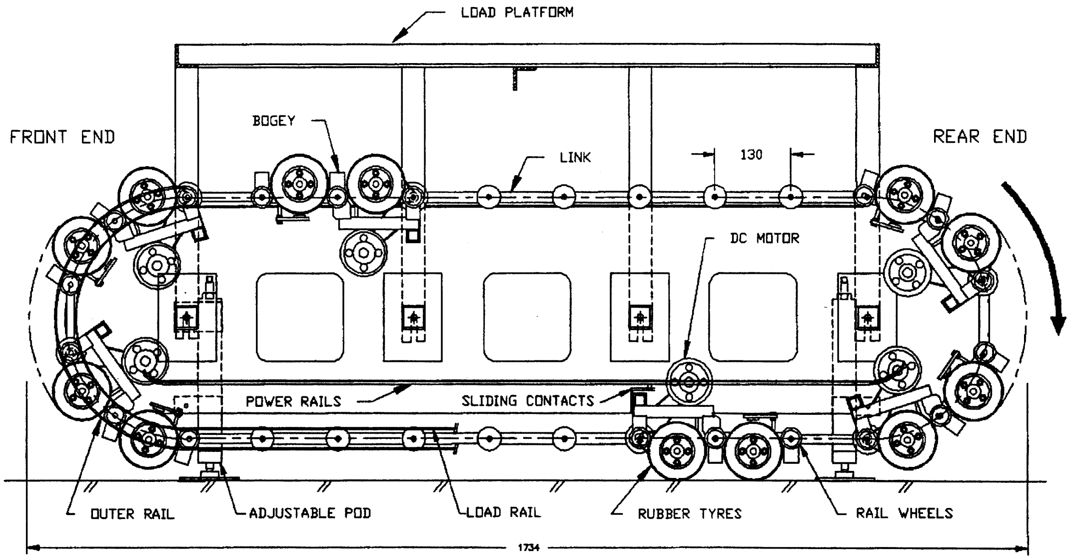


Figure 1. The MMLS Mk.1

To date, the MMLS research has focused on the permanent deformation and fatigue performance of scaled-down asphalt pavements (3, 4). Similarities between TxMLS and MMLS performance have been sited as:

Similar rutting and fatigue performance

Similar behavior in terms of stiffness loss

Similar strain behavior

Typical results of MMLS testing are presented later. A general lack of knowledge on the subject of scaled-down APT testing has, to a degree, restricted the use of the MMLS as an investigative tool. For this reason it has primarily been used for comparative assessments (5). Knowledge gained through use of the MMLS has, however, been instrumental in the development of the full-scale TxMLS (6) and the development of scaled-down testing strategies.

Many practical difficulties were experienced with the scaling down of material properties and the thickness of model pavement layersby 1:10. To overcome some of the scaling constraints experienced with certain tests using the MMLS Mk.1 and to facilitate a wider spectrum of applications, a larger, more

robust machine was developed, the MMLS Mk.3. The relative scale of the MMLS Mk.3 allows pavement structures to be scaled down by a factor of 3– - 4.5. In many cases this is more practical than scaling down pavement layers by a factor of 10. The thickness of a full-scale layer of 200 mm can be scaled down to 50 mm.

Figure 2 shows a schematic of the wheel configuration of the MMLS Mk.3.

An advantage of the MMLS Mk.3 is that it can be used for doing field tests on conventional pavements (provided the maximum particle size is less than 25 mm). In this regard it is specifically suitable for testing the rutting characteristics of asphalt. It can also be used to test seal coats. The device has four wheels (300 mm diameter,) and these can be laterally displaced up to 35 mm. Alternatively, the lateral wheel load distribution can be done by displacing the machine transversely intermittently during trafficking. In this way, the distribution can be controlled to a predetermined distribution pattern. Another advantage is that with inflatable tires, the tire pressure can be varied.

The immediate benefit of these scaled APT devices is that testing can be done at a fraction of the cost of full-scale APT. Furthermore, testing can be done at laboratory scale under controlled environmental and testing conditions. This allows many of the variables impacting pavement systems to be controlled directly. Examples are the control of pavement temperature and trafficking speed. These factors have a direct influence on the stiffness of asphalt layers and hence the response of the pavement under loading. Controlling these variables eliminates uncertainties often associated with the development of APT performance models. In the development of APT performance models, a great amount of tests are necessary to evaluate impacting variables and this has necessitated finding means whereby it would be possible to expedite the testing of the different variables, prior to conducting full-scale APT. Accelerated testing on laboratory scale is favored as a cost efficient, yet effective, means of doing this.

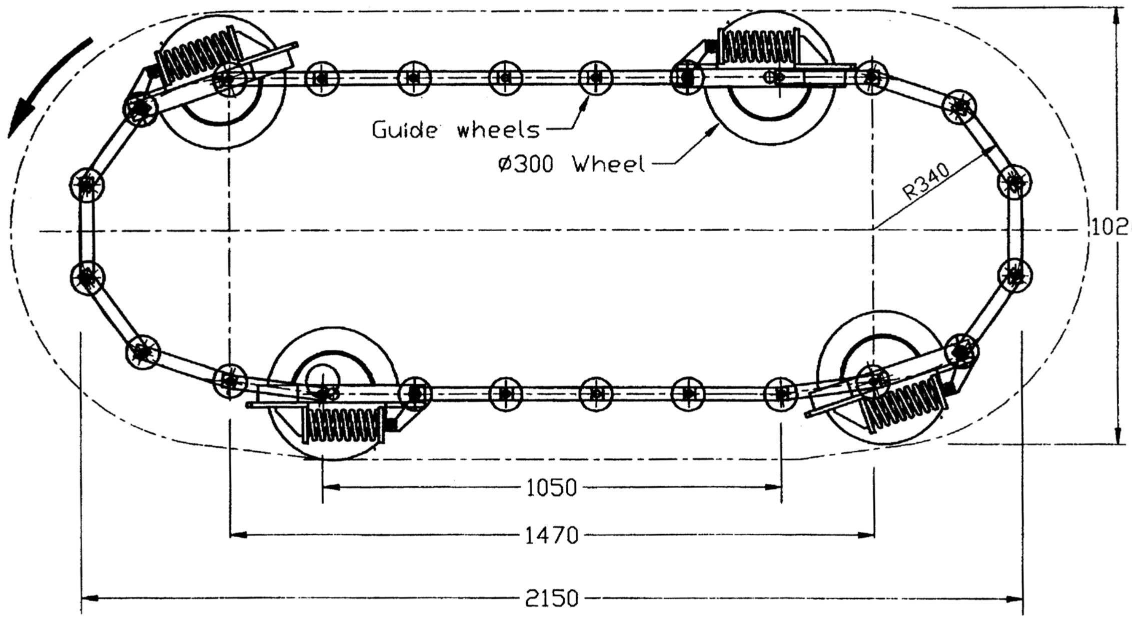


Figure 2. Wheel Configuration of the MMLS Mk.3

Technical Specifications

Technical data for the MMLS devices are summarized in Table 1.

Table 1. Technical Specifications for MMLS APT Devices

	MMLS Mk.1	**MMLS Mk.3**
No. of bogies	6	4
No. of axles	12	N.A.
No. of wheels	48	4
Tires per axle	4	1
Wheel diameter	100 mm	300 mm
Tire width	25 mm	80 mm
Lateral spread of tracks	± 10 mm	35 mm
Total track width of wheel set	85 mm	80 mm
Nominal load per axle	800 N	N.A.
Nominal load per wheel	200 N	1, 900 N – 2, 700 N
Load monitoring	Electronic	Automatic
Load control	Manual	Automatic
Tire footprint area	3.6 cm^2	34 cm^2
Tire contact pressure	560 kPa	560 kPa – 800 kPa
Nominal speed	1.1 m/s	2.5 m/s
Nominal axle/wheel loads per hour	10, 000	7, 200
Nominal motor supply voltage	12 DC	220 AC
Power consumption	500 Watt	1, 500 Watt
Dimensions:;		
Length	1, 700 mm	2, 400 mm
Width	480 mm	600 mm
Height	750 mm	1, 150 mm
Weight	180 kg	600 kg
Extra dead-weight needed	700 kg	200 kg

Theoretical Approaches and Considerations Relating to Scaled APT

Scaled-down APT testing requires consideration of the following differences between scaled-down and normal trafficking:

loading functions (rate, mode and magnitude),

dimensional and material properties,

transfer functions (scaled-down to full-scale),

time domains, and,

environmental influences.

The first two differences are critical to the application of scaled-down APT and are discussed here. The last three differences become important when considering the role of model testing in APT and will be discussed later.

Loading Considerations

If one assumes an elastic pavement response, then the fundamental principle underlying model testing is that a pavement's structural composition, when scaled down, is subject to the same stresses and strains as a full-scale pavement under equivalent loading and assuming the same material properties i.e. stiffness and Poisson's ratio. In the case of the MMLS MK.1, this is valid provided the load contact pressure of the scaled-down (1:10) vehicle is the same as the full-scale vehicle, and the total applied load is one hundredth the full-scale load. This is shown below:

$$P_F = \frac{F_F}{\pi \cdot r_F^2} = P_S = \frac{F_S}{\pi \cdot r_S^2}$$

But

$$r_S = \frac{r_F}{10}$$

Therefore

$$F_S = \frac{F_F}{100}$$

Where:

P_F = Full-scale tire pressure

P_S = Scaled-down tire pressure

F_F = Full-scale wheel load

F_S = Scaled-down wheel load

r_F = Full-scale contact area

r_S = Scaled-down contact area

The rate and mode of loading is an important consideration when testing visco-elastic materials such as asphalt at elevated temperatures. This is discussed in greater detail in the next section.

Physical Dimensional and Material Properties

The visco-elastic response of scaled-down asphalt pavements under MMLS loading prompted research into the dimensional effects of loading functions with respect to full-scale testing. Kim *et al*. (7) have shown that for extrapolation from scaled to full-scale to be valid, the laws of the theory of similitude must be satisfied. This means that all variables with given physical dimensions must be reproduced at exactly the same proportions and with the same properties from the full-scale to the model. Complete similitude may not be possible in most cases. The use of scaled models will still be valid if one can ensure that the variables that are not properly scaled have a negligible effect on the measured response both in the field and in the laboratory. This is a difficult task requiring theoretical knowledge and expert engineering judgement.

Dimensional analysis considerations have been used to assess whether the results of laboratory tests can be extrapolated to predict the response observed in full-scale testing. In the mathematical modeling of any physical phenomenon, it is necessary to first select the parameters that control the behavior one is attempting to predict. Once these parameters have been selected, dimensional analysis allows their combination in terms of dimensionless quantities that must have the same values in model and full-scale in order to satisfy laws of similitude. The three dimensions involved in most mechanics problems are length (*L*), mass (*M*) and time (*T*). If the material properties are influenced by temperature, as is the case for asphalt, temperature would be a fourth dimension which would need to be considered. An overview of the laws of similitude as they relate to scaling down is beyond the scope of this paper and the reader is referred to the work of Kim *et al*. (7). To summarize, they found that the response of the full-scale pavement is identical to the model if the following parameters (**N** is the scaling factor) are used and the materials are linear elastic:

Material properties	**1:1**
Length	**1:N**
Load amplitude	**1:N^2**
Stress on the surface	**1:1**
Velocity of loading	**1:N**

For visco-elastic materials, inertia effects resulting from dynamic loading require that the velocity of the bogies should be the same in the model and the full-scale for pavements with the same properties. The MMLS models do not have a suspension system (only quasi-static loading) and hence inertia effects under MMLS testing are ignored. It should be noted that visco-elastic response under transient loading is accounted for under model testing, as the rate of loading corresponds to the full-scale. The 1:10 scale parameters are illustrated in Figure 3.

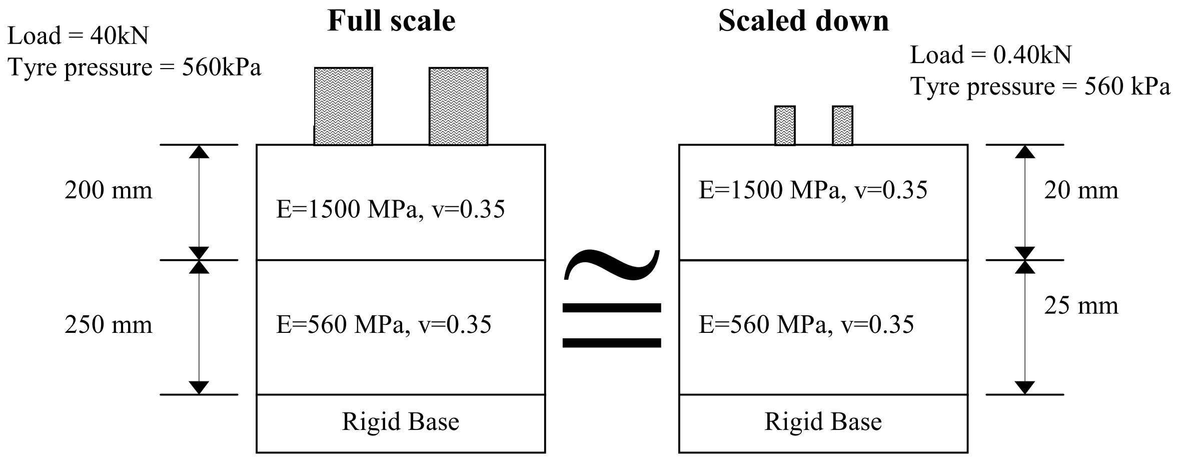


Figure 3. 1:10 Scaling of a Full-scale Pavement

When there is a lack of complete scaling between full-scale and model pavement structures, it is still possible to select a thickness of base layer such that strains in the full-scale and the model pavement are very similar for the asphalt surfacing layer. This is illustrated in Figure 4. Even though total displacements are not properly reproduced, this possibility permits use of the model to study specific aspects of the asphalt layer or other layers, such as rutting or fatigue without scaling down the pavement exactly or totally. In this case preliminary structural analysis is necessary to determine thickness of the model layers and material properties. The same approach could be followed for granular structures.

MMLS studies have shown that a scaled model could be used to reproduce at least some aspects of real pavement behavior. More research is necessary, especially regarding the material properties of the scaled pavement. For visco-elastic full-scale and scaled-down materials it is considered important to at least analyze:

Stiffness,

Strength (indicating fatigue behavior), and

Permanent deformation behavior.

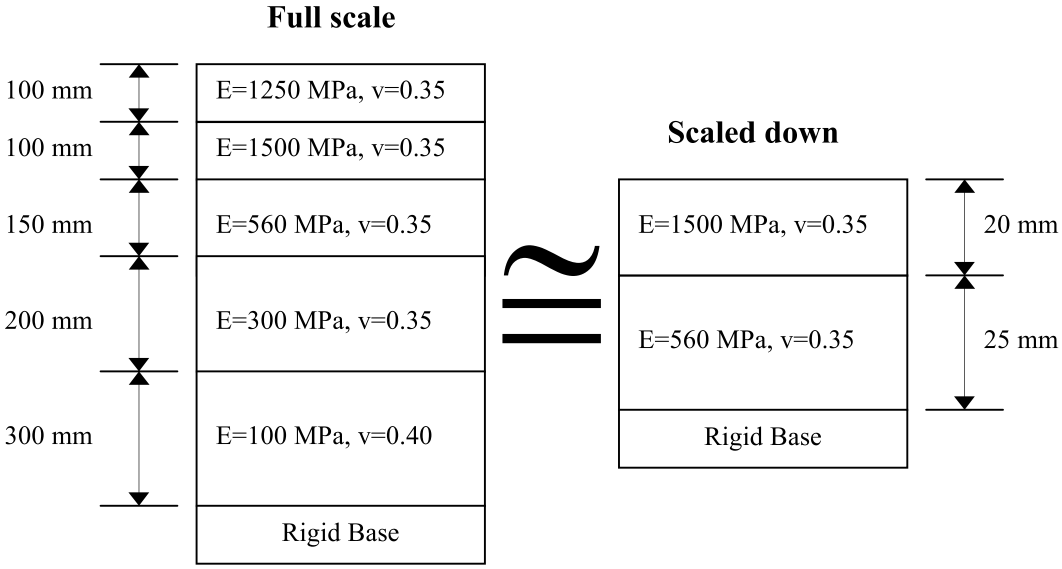


Figure 4. Full-scale and Scaled Pavement Equivalents

The Possible Role of Model Testing in APT Programs

Hugo (8) was the first to show the relationship between APT and other pavement engineering methodologies (see Figure 5). This figure illustrates that APT forms an essential bridge between laboratory testing and Long Term Pavement Performance (LTPP) studies. The use of APT complements LTPP studies as pavement response, subsequent performance under controlled load, and environmental conditions can be monitored in a relatively short period with significant lifetime cost benefits. The author has superimposed the relative position of Model APT testing into this benefit-cost diagram (dotted line).

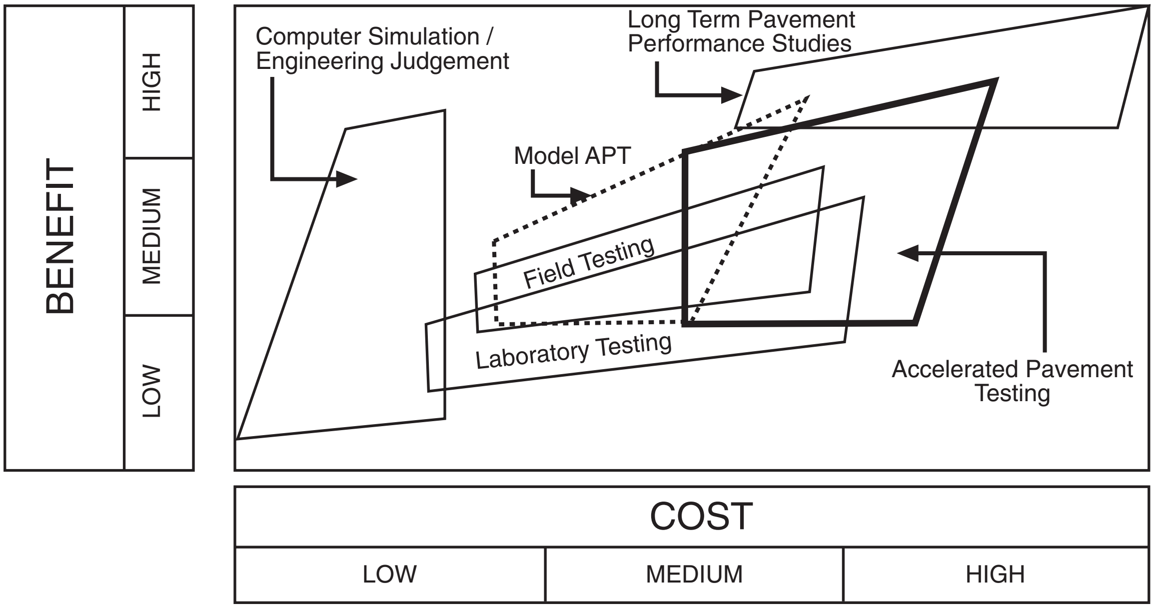


Figure 5. The Place of APT in Pavement Technology [after Hugo (8)]

It has already been shown that scaled APT testing has been used to evaluate the rutting and fatigue performance of scaled-down asphalt mixtures. Scaled APT testing can however be extended to assess other structural and functional aspects of pavement performance. Table 2 lists the primary factors influencing the performance of pavements. The factors the author believes could be evaluated with scaled model testing have been marked with an asterisk.

Table 2. Factors Impacting Pavement Performance

Structural	Functional
Deformation (Rutting)*	Skid resistance*
Stiffness*	Riding quality
Fatigue*	Rutting (safety)
Reflective cracking*	Noise*
Shrinkage cracking*	Social aspects (environment)
Durability*	
Permeability*	

The ability to evaluate these factors at a performance-related level emphasizes the significance of scaled APT. In light of the possible role of model testing in APT, attention should be given to the following fields:

Performance modeling

Validation of asphalt mix design

Ranking of candidate blends

Environmental conditioning (Durability)

Distress and load equivalency

Scaling of granular materials

Each of these can be incorporated into model testing programs to complement full-scale APT. Each will be discussed in detail.

Performance Modeling

This is an important aspect of scaled APT and deserves special consideration. The following pavement distress criteria are usually considered in performance modeling:

Fatigue

Permanent Deformation

Aging

Low-Temperature Cracking

Water Sensitivity

The MMLS Mk.1 has been used to evaluate scaled asphalt pavements in terms of asphalt permanent deformation or rutting, and fatigue failure. The results of rutting performance tests done at the University of Stellenbosch in South Africa (2, 9) and fatigue testing at the University of Texas at Austin (3, 10) in the USA are shown. The model tests were all done on scaled-down pavement structures. The effects of scaling down on material properties are discussed and examples of the MMLS performance testing are presented to give the reader a broad overview of the research undertaken. The finer details of the studies have been excluded; complete details have been published elsewhere (9, 10). A summary of findings from past performance tests is given.

Details of research into the influence of asphalt aging on rutting and fatigue performance using the MMLS Mk.1 are illustrated. No MMLS performance evaluation has been done on low-temperature cracking or the moisture susceptibility of asphalt mixtures.

Scaling Effects on Material Properties

The asphalt mixture gradations of the model MMLS pavements were scaled to allow a more realistic comparison between the tire contact area and the maximum aggregate size in the mix. Table 3 compares the full-scale gradation of a large aggregate mixture with the scaled-down version used in an MMLS rutting study.

Table 3. Full-scale and Scaled-down Gradations of a Large Aggregate Mixture

	Percentage Passing	
Sieve Size, mm	**Full-scale**	**Scaled**
53	100	100.0
37.5	90	100.0
26.5	74	100.0
19	67	100.0
13.2	54	100.0
9.5	46	100.0
6.7	43	98.5
4.75	41	91.3
2.36	27	65.1
1.18	16	43.4
0.600	12	30.6
0.300	10	22.5
0.150	9	16.2
0.075	7.4	12.1

As discussed previously, the material mechanical properties of the full-scale and scaled-down mixtures must be 1:1 for dimensional purposes. Table 4 and Table 5 show the material and mechanical properties of the full-scale and scaled-down mixes respectively. The results are average values of at least six test specimens compacted using both the Marshall and Hugo hammer. The Hugo hammer introduces a kneading/impact type of compaction with the aid of minor changes to a conventional Marshall hammer. These changes include a new hammer face that has indentations and a turning action through 30 degrees of the hammer face after each blow causes the kneading effect (11).

Table 4. Comparison of Full-scale and Scaled-down Material Properties

Property	Full-scale	Scaled
Marshall Optimum Binder Content, %	4	7.3
% passing 0.075 mm sieve	7.4	12.1
Bulk Relative Density	2.497	2.367
Maximum Theoretical Density	2.580	2.435
Voids in Mix, %	3.2	3
Voids in Mineral Aggregate, %	12.3	17.7
Voids Filled with Binder, %	74.3	84
Film Thickness, micron	6.9	7.5
Static Creep Modulus, MPa	101.5	100

Table 5. Comparison of Full-scale and Scaled-down Mix Engineering Properties

Property	Scaled		Full-scale	
Compaction method	Hugo	Marshall	Hugo	Marshall
Optimum binder content, %	7.3	7.3	4	4
Dynamic creep modulus, MPa	5.5	8.3	10.2	47
Stiffness, MPa	1943	2087	2240	3258
Indirect tensile strength, kPa	709	1042	576	709

Permanent Deformation Tests

The MMLS has been used to investigate the effect of variation in binder content on the long term rutting performance of scaled-down large aggregate asphalt pavements (9). It was found that the binder content of the pavement had a notable effect on its rutting performance. Pavements constructed at a lower than optimum binder content performed considerably better than those constructed at or above optimum. This is in agreement with practice and confirms that comparisons with the MMLS are realistic.

Typical MMLS rutting profiles measured under MMLS loading on high and low binder content pavements are shown in the figures that follow. Permanent deformation testing was carried out at a temperature of 40 °C. Use was made of artificial aging of the asphalt to simulate long-term environmental aging. The influence of aging is apparent in the figures. The number of days each pavement section was aged prior to MMLS testing is indicated. Resistance to permanent deformation increases with aging. Aging of asphalt mixtures prior to model testing is an important consideration and will be discussed in greater detail in the next section.

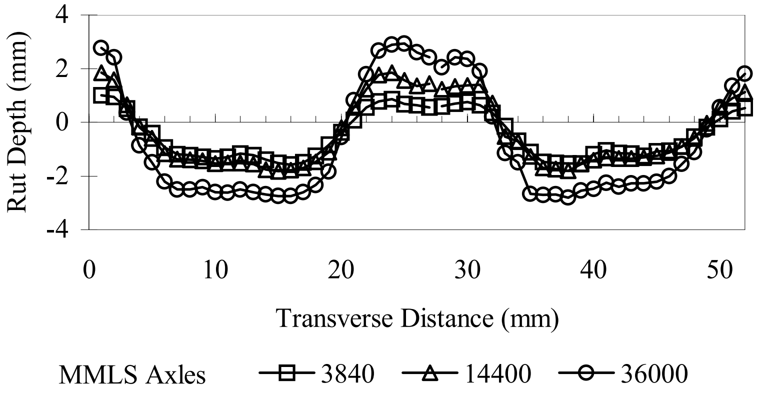


Figure 6. MMLS Rutting Profile for a High Binder Content Pavement (7 days aging)

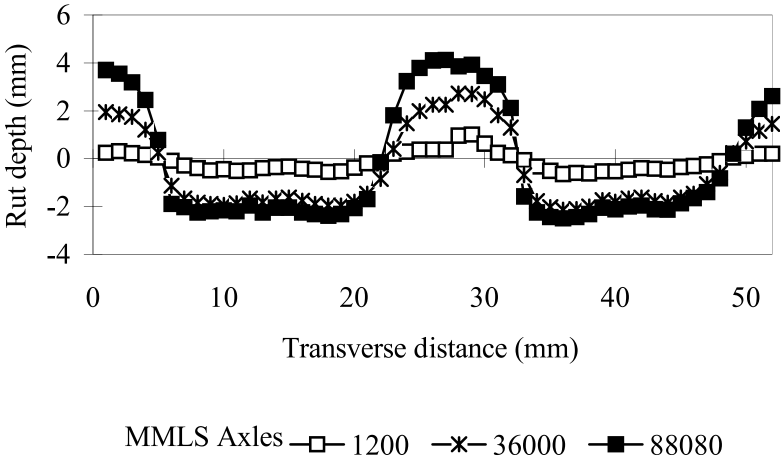


Figure 7. MMLS Rutting Profile for High Binder Content Pavement (28 days aging)

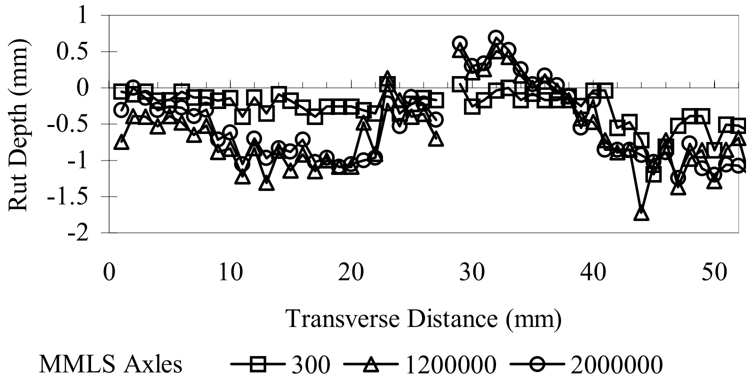


Figure 8. MMLS Rutting Profile for a Low Binder Content Pavement (7 days aging)

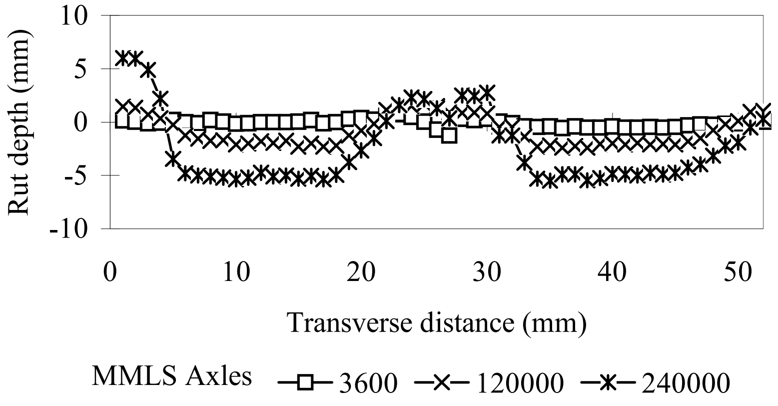


Figure 9. MMLS Rutting Profile for Low Binder Content Pavement (No aging)

Fatigue Tests

MMLS fatigue testing have been carried out at a temperature of 5 °C. In a particular test, the influence of aging on the fatigue performance of a scaled asphalt pavement was evaluated. One half of the trafficked model pavement was artificially aged; the remaining half was unaged. Use was made of Spectral Analysis of Surface Waves (SASW) techniques to allow a non-destructive means of determining in-situ pavement stiffness (3). A decrease in stiffness is indicative of pavement deterioration, in this case, fatigue distress. Figure 10 illustrates this for the MMLS pavement in question. Cumulative cracking of the MMLS pavement was also measured with trafficking as shown in Figure 11.

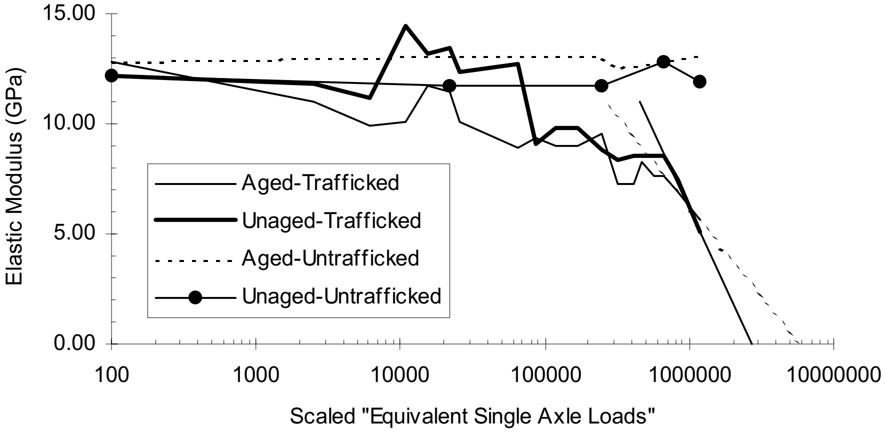


Figure 10. MMLS Pavement Stiffness Measurements at 5 °C using SASW

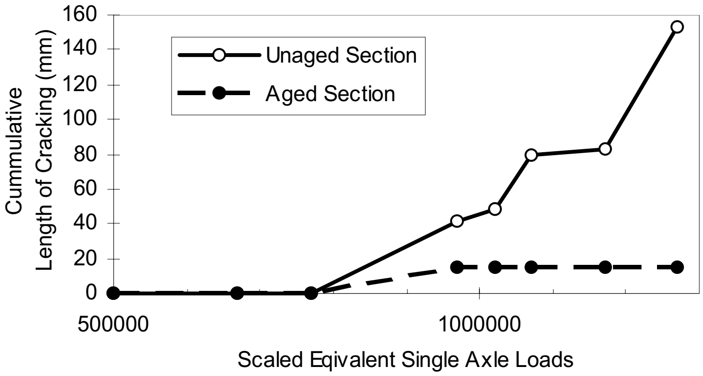


Figure 11. Cumulative Total Crack Length Measured under MMLS Trafficking

Summary of Findings

The discussion that follows focuses on the material and mechanistic properties of full-scale and scaled-down materials and how these properties influence the mechanistic characteristics of particularly visco-elastic pavement structures.

Gradation

In scaling down pavement materials, the initial difference between the full-scale and comparable scaled-down materials is noted with the filler content of the mix. For practical reasons, no attempt has been made to scale down the fraction of the mix finer than 0,075 mm. The resultant filler fraction of the scaled-down materials may be double that of the full-scale equivalent, as is shown in Table 3.

Due to specific surface considerations for the fine fraction, a higher filler content requires a higher binder content. If cognizance is not taken of this detail, the mastic of the full-scale and comparable scaled-down mix may differ significantly, which will influence the mix response. This factor partly explains the higher indirect tensile strengths achieved for the scaled mix in Table 5, compared to the full-scale mix. If the fraction finer than 0.075 mm was scaled-down then even more bitumen would be necessary because of the greater surface area.

Stiffness

From dimensional analysis it has been established that:

the material property scale factor must be 1:1 for comparable response in the full-scale and scaled-down model, and

for visco-elastic materials, the scale factor for speed of trafficking must also be 1:1.

Along with speed of loading, temperature also influences the stiffness of visco-elastic materials. Table 5 shows that it is possible for full-scale mixes and their scaled-down equivalents to have relatively comparable stiffness values, at a particular temperature and frequency of testing (in this case 25°C and 10 Hz). This comparison, however, needs to be extended to a range of temperature and frequency values in order to establish master curves for stiffness.

Mix stiffness, however, is also influenced by the bitumen properties and macro volumetric properties (voids in the mix, volume of bitumen and volume of aggregate) of the mix. In order to achieve comparable stiffness properties, the binder content of a scaled-down mix has invariably been considerably higher than that of the full-scale mix. Given that the voids in the mix of the full-scale and scaled-down mixes must be the same, an increase in binder content for the scaled-down mix must be countered by a decrease in the volume of aggregate in the mix. Thus, given the bitumen stiffness values shown in the Uge nomograph (12) of Figure 12, this will always result in a lower mix stiffness at higher binder contents. The resultant difference in stiffness between full-scale and scaled-down mixes will impact on the fatigue and permanent deformation characteristics of the mixes, and this should be accounted for when comparing full-scale and scaled-down performance relationships.

Because of the influence of temperature on asphalt stiffness, consideration should be given to temperature profile differences between the model pavements and thick full-scale pavements. Monitoring of temperature profiles on model pavements indicated a uniform temperature profile for asphalt lifts up to 20 mm thick (5).

Permanent Deformation

At higher testing temperatures (40 °C), the permanent deformation characteristic would, to a great extent, be influenced by the stiffness of the aggregate structure of the mix. Scaling may influence this stone skeleton, in that the larger filler fraction could break the aggregate interlock. Aggregate angularity and fractured faces should not be allowed to vary between full-scale and scaled-down gradations. The dynamic creep test gives an indication of the permanent deformation characteristics of asphaltic materials. The lower dynamic creep moduli determined for the scaled-down materials as shown in Table 5 suggest a less stable skeleton structure. This suggestion is however not conclusive as another aspect to consider is the scaling down of dynamic creep tests done on scaled materials in accordance with the laws of similitude. This may not always be practical and for this reason, the scaling down of mechanical test equipment and procedures for tests on scaled-down materials compared to tests on full-scale materials requires further research.

Fatigue

The bitumen characteristics and stiffness of the mix influence the fatigue relation of asphalt mixes. The fatigue function will hence depend on temperature and rate of loading, as well as mixture volumetric properties. In particular, therefore, cognizance needs to be taken of differences in stiffness and volumetric properties between full-scale and scaled-down mixes when comparing their fatigue characteristics. The strength characteristics of asphalt mixes will also reflect on fatigue behavior.

Additional research is necessary to relate model fatigue performance to laboratory, full-scale APT and fatigue in the field under real traffic. This must include the development of shift factors to account for crack propagation, traffic wander etc. Another important concept is the definition of failure. This is considered in more detail under environmental conditioning.

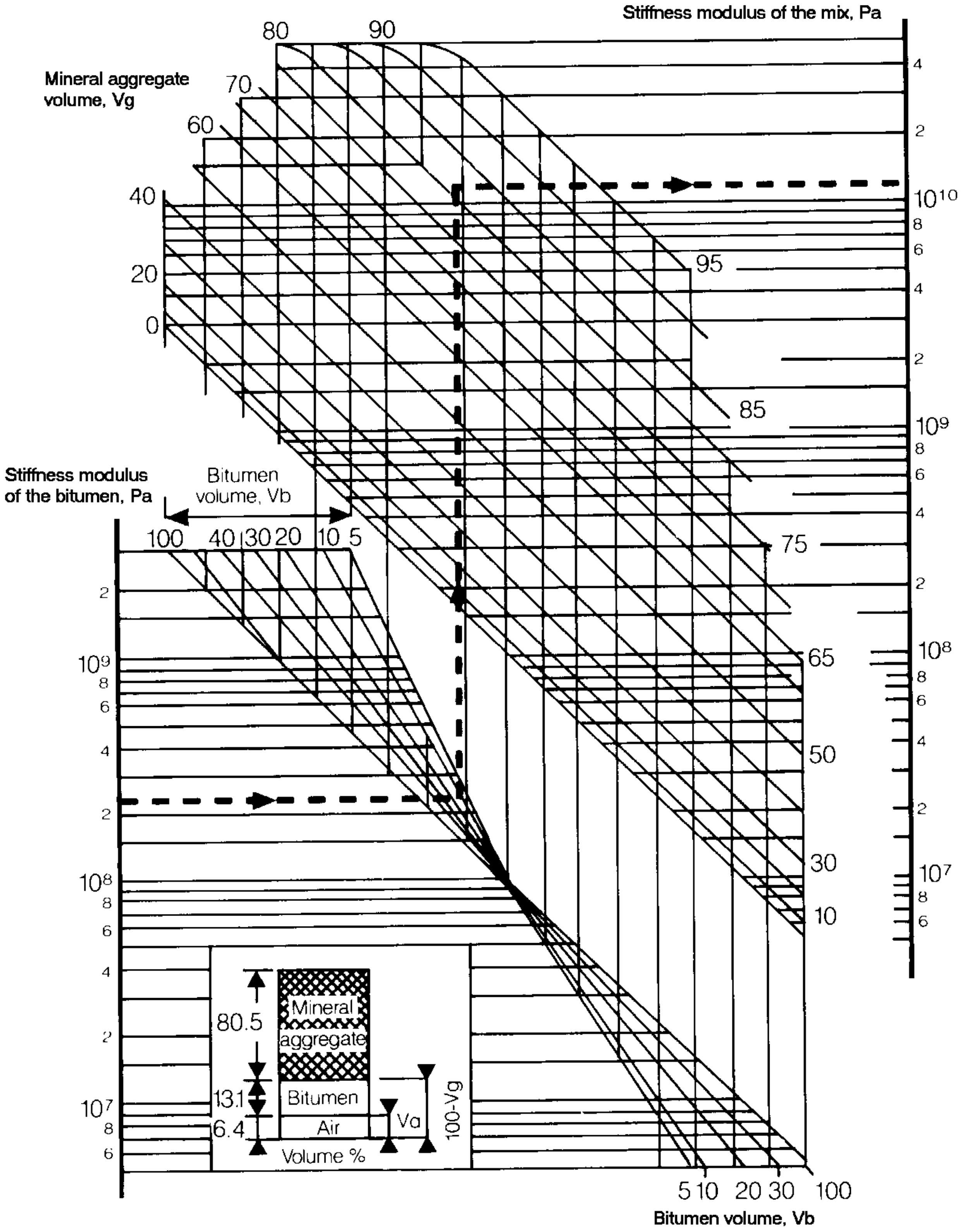


Figure 12. Nomograph for Predicting the Stiffness Modulus of Mixes

Validation of Asphalt Mix Design

The recent trend in asphalt mix design is the shift from empirical towards more performance-based methodologies. In addition to assessing the volumetric properties, the SHRP SUPERPAVE™ mix design method incorporates accelerated performance-related tests for asphalt-aggregate mixes (13). A major shortcoming of these tests is that specimens for testing can best be got from rolling-wheel compaction for it's obvious similarity to field compaction processes. Model testing with the MMLS Mk.3 can be done directly in the field. Furthermore, model testing allows a direct evaluation of the performance-related properties of asphalt mixes as actual transient wheel loads are applied.

As part of a research study initiated to validate SUPERPAVE™ mix design parameters (5), the MMLS Mk.1 was used and it was found that model testing had the ability to assess the influence of aggregate properties such as fine aggregate angularity on pavement performance where other laboratory mechanical tests failed. The model has also been instrumental in determining the significance of gradation restriction zones implemented in the SUPERPAVE™ design methodology. Still other SUPERPAVE™ parameters that should be validated are the recommended initial, design and end compaction levels, limits on voids in the mineral aggregate (VMA) and voids filled with binder (VFB), the gradation restricted zone and control points and other aggregate related properties.

Ranking of Candidate Blends

The cost of full-scale APT is such that any reduction in the number of test variables is beneficial. As scaled APT allows a direct assessment of the performance-related properties of materials, it can be used to rank candidate asphalt mixes prior to full-scale testing. This allows full-scale testing to be done on performance optimized blends.

It has been shown by van de Ven *et al*. (5) that the MMLS Mk.1 is able to rank asphalt mixtures in terms of rut susceptibility. Furthermore, it has been shown that the MMLS is able to rate the rut susceptibility of asphalt mixtures in a relatively short time; about three hours or after 30 000 MMLS axle loads (9). It is therefore recommended that all candidate blends be ranked using model testing prior to full-scale APT.

Environmental Conditioning

If full-scale APT is done in the field, it is particularly difficult to control environmental influences on pavement performance. Controlling and assessing these environmental factors on laboratory scale using scaled APT is feasible. Full-scale APT can be used to apply a pavement's design life traffic over a very short period of time, however, no account can be given of climatic or environmental distress. This is a major shortcoming of full-scale APT that can be addressed using scaled APT.

Climate affects the performance and mechanical properties of pavement materials and subsequently the pavement structure’s ability to withstand traffic loads (14). The underlying reason is that seasonal weather variations introduce variations of material properties and therefore periodic changes of the specific pavement characteristics.

Accelerated Pavement Testing cannot directly account for real-time climatic effects on the performance of pavements. To account for these effects, the desired environmental conditions must be induced artificially. The principle climatic conditions impacting pavements are ultra-violet light and heat (aging), water and temperature. Each of these conditions can be simulated and incorporated into a testing program. The challenge however, is to gauge the quantitative influence of these simulated conditions on accelerated pavement performance to eventually relate this to real-time environmental influences.

Croney and Croney (15) have considered the impact of climatic variation on the performance of pavements. They state that the expeditious testing under APT makes it difficult to consider climatic effects on pavements and this limits the application of findings from accelerated pavement testing. In this section, an overview of environmental distress and conditioning is given. Environmental conditioning on laboratory scale and subsequent evaluation of environmental distress using model testing has practical benefits that can be carried over to full-scale APT.

Environmental Distress

Hugo *et al*. (16) have illustrated the traditional relationships between pavement distress and time (see Figure 13a). The figure shows a conceptual application of accelerated pavement testing to evaluate environmental effects on pavements. It can be seen that a certain distress occurs in a pavement because of the combined effects of load and environment. At any given time, the relative contributions of the environment and loading to the total distress manifestation are not assessable. However, when accelerated loading is used to hasten the distress to a limiting level (D_{limit} in Figure 13a), the rate at which distress occurs (slope of D_1 and D_2 in Figure 13a) is an indication of the relative positions of t_1 and t_2 on the time scale and the degree of distress caused by the environment.

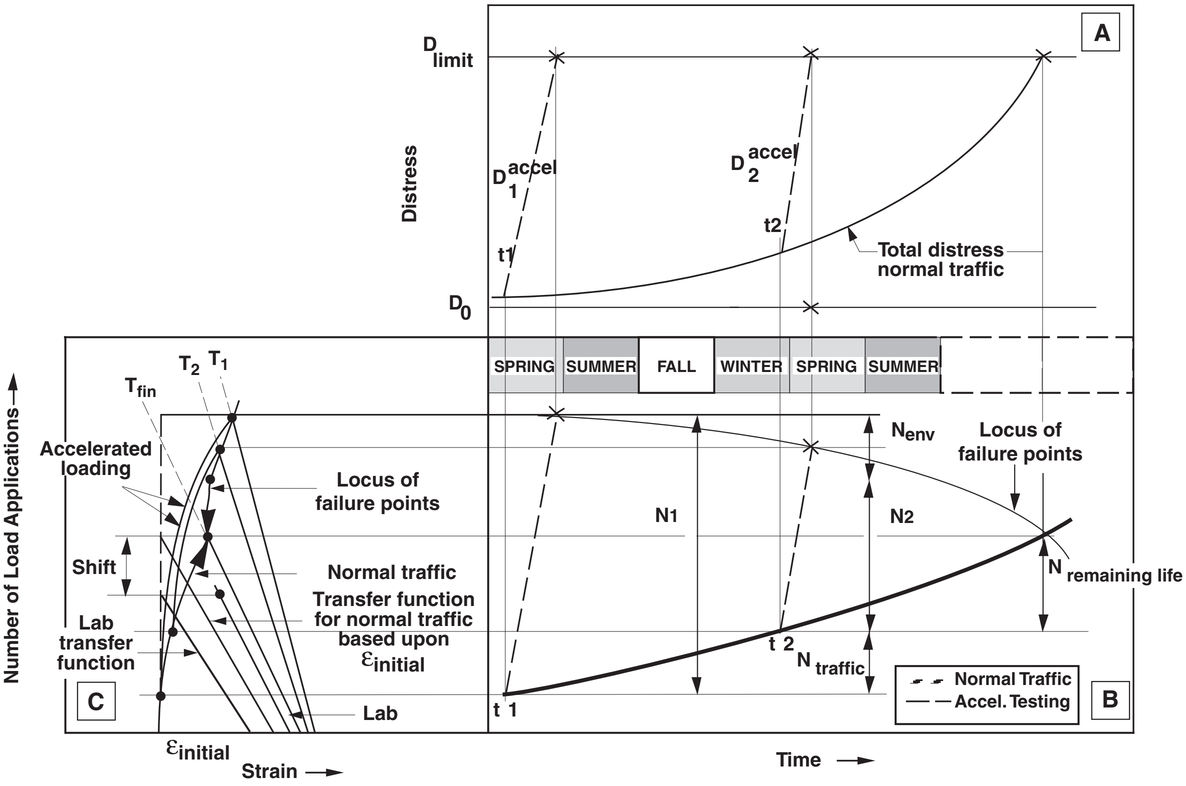


Figure 13. Conceptual Application of Accelerated Pavement Testing to Evaluate Environmental Effects on Pavements

Figure 13b shows how two similar pavement sections are tested to failure under the same environmental conditions but at different times during the life of the pavement. This is one of the possible options of a full-scale or scaled-down accelerated climatic testing program i.e. APT testing of a naturally or artificially aged pavement over time. The difference between the number of accelerated load applications (N_1 and N_2) can be attributed to two factors: the additional traffic that used the second section and aging or environmental effects. Because traffic between testing of the first and second sections, $N_{traffic}$, can easily be measured, the reduction (or, in some cases, increase) in N_2, the remaining life, must be attributed to environmental effects, as given in Equation 2.

$$N_1 = N_2 + N_{traffic} + N_{environment} \tag{1}$$

$$N_{environment} = N_1 - N_2 - N_{traffic} \tag{2}$$

These relationships can be used to evaluate the effect of procedures designed to simulate or even counteract environmental distress and to estimate the remaining life of a pavement structure. A similar approach may apply to other accelerated climatic testing options by applying the principles of Miner's hypothesis. Further research into this possibility is required.

Conditioning with Ultra-violet Light and Heat for Aging Purposes

Traxler *et al*. (17) and Dickenson (18) have done extensive research into the hardening effect of UV light and solar radiation on asphaltic materials. Ultra-violet light from the sun can cause stiffening or aging of asphalt surfacing layers by oxidation of the bitumen (asphalt) binder. The degree of oxidation is a function of the void content of the asphalt layer. Oxidation can occur up to depths of 20mm from the surface layer although most of the oxidation occurs in the upper 5mm. This must be taken into account when aging thin model pavements. Oxidation of the binder can be measured in the laboratory from infra-red spectra. The influence of oxidation can be assessed by the change in viscosity of the binder with aging.

The oxidation or hardening of asphalt pavements under normal traffic conditions is a continuous long-term process that changes the physical properties of asphalt over time. The aging process of an asphalt pavement is dependent on the prevailing climatic conditions. A hot, dry climate will accelerate the chemical reactions associated with aging and a cold, wet climate will retard the aging process. An increase in stiffness of the mix and an increase in the binder viscosity are characteristic of aging. The rate of aging of asphaltic material is also directly related to the volumetric properties of the mix, particularly the voids and binder content.

Under accelerated loading conditions, the hardening of the pavement must be accelerated artificially. The effect of aging can be quantified using the two parameters shown below. These parameters can be compared to AI and OR values from naturally aged pavements to correlate the effect of the aging process.

$$\text{AI (Aging index)} = \frac{\text{viscosity of aged sample}}{\text{viscosity of unaged sample}} \tag{3}$$

$$\text{OR (Oxidation ratio)} = \frac{\text{oxidation level of aged sample}}{\text{oxidation level of unaged sample}} \tag{4}$$

Bell *et al*. (19) have reported extensively on research into the aging of asphaltic materials. High temperatures are also used to age the binder in pavements. This is done by applying high temperatures to pavement surfaces using infra-red lighting or alternative light sources and maintaining the pavement surface at an elevated temperature for prolonged periods. This method is usually used in conjunction with UV light as discussed previously. Aging units incorporating UV and infra-red lighting may be used to age entire test sections or parts of test sections. This is very practical on model scale. The effect of aging can be gauged with the AI and OR parameters.

Progressive aging of pavement sections together with analytical modeling of aging effects has been done during MMLS tests (3, 9). Techniques to simulate aging on small scale for APT include heating the surface of the scaled pavement to a temperature of 100 °C using electric light sources and maintaining this temperature for a specific number of days. Preliminary indications are that 7 days of artificial aging in this manner is roughly equivalent to 2 years of environmental aging in the field (3). These findings are not conclusive and further research into the aging of asphalt for APT must be undertaken. The effects of aging on permanent deformation and fatigue distress of a scaled-down asphalt mix have been illustrated in Figure 6 through Figure 11.

Water Conditioning

It is a well-known fact that for a given amount of traffic, pavement distress will occur more rapidly if the pavement is frequently wetted. The response of the pavement under loading will depend on the moduli of the granular pavement layers, which are related to moisture content.

The introduction of water into a pavement system is done to simulate cyclic rainfall seasons, rising of water tables and for analyzing the effect of water related pavement distress such as raveling of pavement surfaces, stripping of underlying pavement layers, weakening of subgrade or base materials and even, in special cases, the effect of freeze-thaw cycles.

Water can be introduced by running water over the pavement surface during or intermittently between accelerated testing. This is usually done by sprinkling or hosing the pavement surface. Other possible ways of introducing water into pavement systems include the use of feeder pipes alongside test sections that allow water to drain into the subgrade or the use of electro-osmosis systems that make use of electric potential to transport water through pavement granular layers (20). These methods would be beneficial for controlling the moisture content of subgrade and base materials. The influence of moisture content on scaled granular materials is discussed in more detail later.

To evaluate the moisture sensitivity of asphalt mixtures and the potential of stripping, the MMLS Mk.3 can be used to test asphalt pavements that are totally saturated. Test pavements can be constructed within water basins such that the pavement surface is continually under water during trafficking.

The time at which water is introduced into the pavement system during testing is critical. Water that penetrates cracked surface layers and leads to weakening and pumping of base material can cause rapid deterioration of a pavement structure as illustrated in Figure 14. With this in mind, a strategy for dry/wet testing must be established. This may include the introduction of water at the onset of testing, periodically during testing at specific intervals or towards the end of testing. The definition of pavement failure should account for the influence of water ingress.

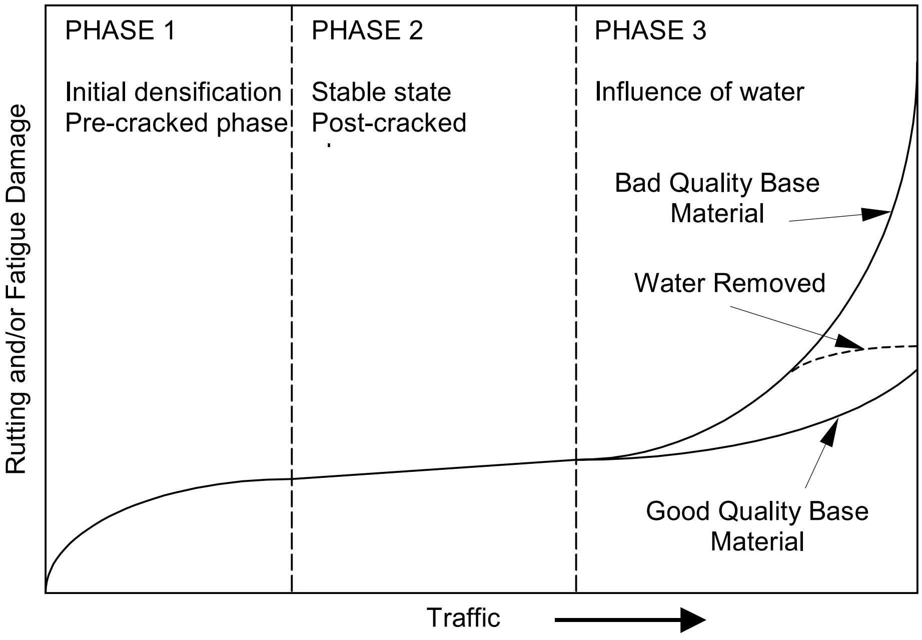


Figure 14. Indicators of the Behavior of Granular Base Pavements

APT Test Temperatures

As mentioned previously, APT is usually done at a constant high, ambient or low temperature throughout a test period to accelerate a distress mode, be it rutting, fatigue or low temperature cracking. The aim is to keep as many variables as possible constant. The modulus of asphalt is strongly dependent on temperature and controls the response of the pavement under traffic loading. High temperatures typically impair the stability of asphalt mixes whereas cold temperatures may induce thermal shrinkage stresses that lead to cracking. As a special case, freeze-thaw cycles may affect the bearing capacity of base materials.

Rutting and fatigue tests on model scale have been done at temperatures of 40 °C and 5 °C respectively.

Distress and Load Equivalency

Determining the load equivalency of pavement structures is particularly important when considering traffic impact on pavement performance. Assessing the distress and load equivalency of pavement structures was one of the primary objectives of the TxMLS test program (8). Evaluating the load equivalency of asphalt pavement structures using the full-scale TxMLS has not been very successful. Attempts at 15 percent overload testing have overstresses the machine resulting in excessive maintenance and time delays. Overload tests using the MMLS Mk.3 to assess the equivalency of scaled-down pavement structures are possible. Equivalency factors determined using model testing should be applicable to full-scale testing if the laws of similitude are obeyed. Further research may be necessary to validate this.

Scaling of Granular Materials

An aspect of model testing that has received little attention and which could contribute significantly to full-scale APT is the evaluation of subsurface granular materials with regard to pavement response and permeability. Particularly under thin surfacings, non-linear stress-strain characteristics are a feature of this response, which are usually not considered in performance analysis.

Research has been carried out into the scaling down of untreated and emulsion modified granular materials (21). The possible use of the MMLS to evaluate scaled-down pavements comprising granular bases has been investigated. The feasibility of scaled-down APT of pavements comprising granular materials was evaluated by means of static and dynamic triaxial testing on full-scale and comparable scaled-down materials (1:10).

Three different types of granular materials were evaluated:

a granular emulsion mix using natural gravel (GEMS),

a G1 continuously graded crushed stone (G1), and

a waterbound macadam (WM).

The GEMS and G1 are commonly used for base layers in granular pavement structures in the drier climatic regions of South Africa. The WM is finding renewed favor in labor intensive road construction projects.

Material Properties

Table 6 shows the gradations of the full-scale and scaled-down granular materials.

Table 6. Gradations of Granular Materials (Percentage Passing)

Sieve Size (mm)	GEMS		G1		WM	
	Full-scale	Scaled	Full-scale	Scaled	Full-scale	Scaled
53	100		100		100	
37.5	100		100		65	
26.5	92		87		45	
19	84		70		40	
13.2	69		56		40	
9.5	60		48		40	

6.7	52	100	42	100	40	100
4.75	48	100	37	100	37	90
2.36	39	90	28	70	26	45
1.18	33	67	23	50	19	40
0.600	26	50	18	36	14	40
0.300	18	42	12	25	10	30
0.150	12	35	8	18	7	20
0.075	6	28	5.2	12.6	5	15

Table 7 shows the bulk (BRD) and apparent (ARD) relative densities of the full-scale and scaled-down materials as determined, as well as the Atterberg limits viz. liquid limit (LL), plasticity index (PI) and linear shrinkage (LS), determined for the full-scale materials. The water absorption (WA) and relative solid densities (RSD) of the materials were determined using Semmelink's COMPACT software (22).

Table 7. Granular Material Characteristics

Property	GEMS		G1		WM	
	Full-scale	Scaled	Full-scale	Scaled	Full-scale	Scaled
ARD+4.75	2.751	2.751	2.667	2.667	2.660	2.660
BRD+4.75	2.415	2.415	2.598	2.598	2.639	2.639
ARD-4.75	2.744	2.744	2.672	2.672	2.569	2.569
WA	2.63	0	0.63	0	0.19	0.03
RSD	2.573	2.580	2.625	2.635	2.614	2.576
LL	20					
PI	4		NP		NP	
LS	2.5					

Material Compaction

The full-scale materials were compacted in five layers within a split steel mould with a diameter of 150 mm and a height of 300 mm. Each layer was compacted using a vibrating table at high frequency and amplitude for two minutes with a surcharge of 50 kg. The scaled-down materials were compacted in five layers within a split mould with a diameter of 75 mm and a height of 150 mm. These materials were compacted using a Proctor hammer by applying 55 blows to each layer. This manner of compaction was chosen for practical reasons. The number of blows was determined through laboratory experimentation and monitoring of achieved compaction densities compared with desired densities. After compaction of the materials, the G1 and WM specimens were placed in sealed plastic bags for a minimum of two days prior to testing. This was done to allow a uniform moisture distribution within the specimens. The compacted GEMS specimens, on the other hand, were cured for one day to ensure that the break of the emulsion was complete. Thereafter, the GEMS specimens were sealed within plastic bags for seven days additional curing in the laboratory, prior to testing. The degrees of saturation and compaction densities of the specimens were also recorded prior to testing, refer Table 8.

Table 8. Optimum Moisture Contents and Compaction Densities of Full-scale and Scaled-down Granular Materials

		Full scale			Scaled down		
		OMC (%)	Degree of Saturation (%)	% SD	OMC (%)	Degree of Saturation (%)	% SD
GEMS	Mean	8	65.5	81	11	78.7	79
	[Sd]		[8.1]	[1.4]		[12.3]	[1.1]
G1	Mean	5	43.2	85.5	8	42.1	80.8
	[Sd]		[19.2]	[1.6]		[13.8]	[2.4]
WB	Mean	4	35.9	92.1	7	65.1	83.8
	[Sd]		[4.6]	[0.7]		[7.4]	[0.7]

The target compaction densities for the triaxial tests on the granular materials were the expected field densities. It was therefore necessary to control the dry densities and moisture regime values for the full-scale and scaled-down versions.

For the GEMS it was decided to keep the ratio of residual binder to total fluids content and the cement/binder ratio the same for the full-scale and scaled mixes. Using COMPACT (22), the Zero Air Voids Moisture Content (ZAVMC) was predicted to be about 9 percent for the full-scale grading. A binder content of 1.5 percent of anionic stable 60 emulsion was added i.e. with a residual binder content of 0.9 percent. This is 10 percent of the total fluids content.

For the scaled-down grading, the ZAVMC was predicted to be approximately 12 percent. Keeping the ratio of residual binder the same results in a residual binder content of 1.2 percent and an application rate of emulsion equal to 2 percent.

If the cement/binder ratio is kept constant for large scale and scaled-down mixes, then 1 percent cement in the full-scale mix is balanced by 1.33 percent in the scaled-down mix, refer Table 8.

Table 8 shows the optimum moisture contents (OMC) and resultant compaction densities of the full-scale and scaled-down materials.

Dynamic Triaxial Stiffness Testing Methodology

The triaxial tests were carried out using an electro-hydraulic Materials Testing System (MTS). Specimens were sealed using rubber membranes and set-up within the test cell. A constant cell (confining) pressure was applied using pressurized air. Confining pressures of 50 kPa, 100 kPa and 200 kPa were used. A preload of 20 kPa was applied to seat the specimens and cyclic axial loads were pulsed using a stress controlled haversine signal of 2 Hz. The load was monitored directly from the MTS and the vertical displacements of the specimen under loading using three linear variable displacement transducers (LVDT's) connected to the triaxial cell. The specimens were allowed to drain during the tests. Figure 15 shows the stresses applied to the triaxial specimens and Table 9 shows the stress levels applied.

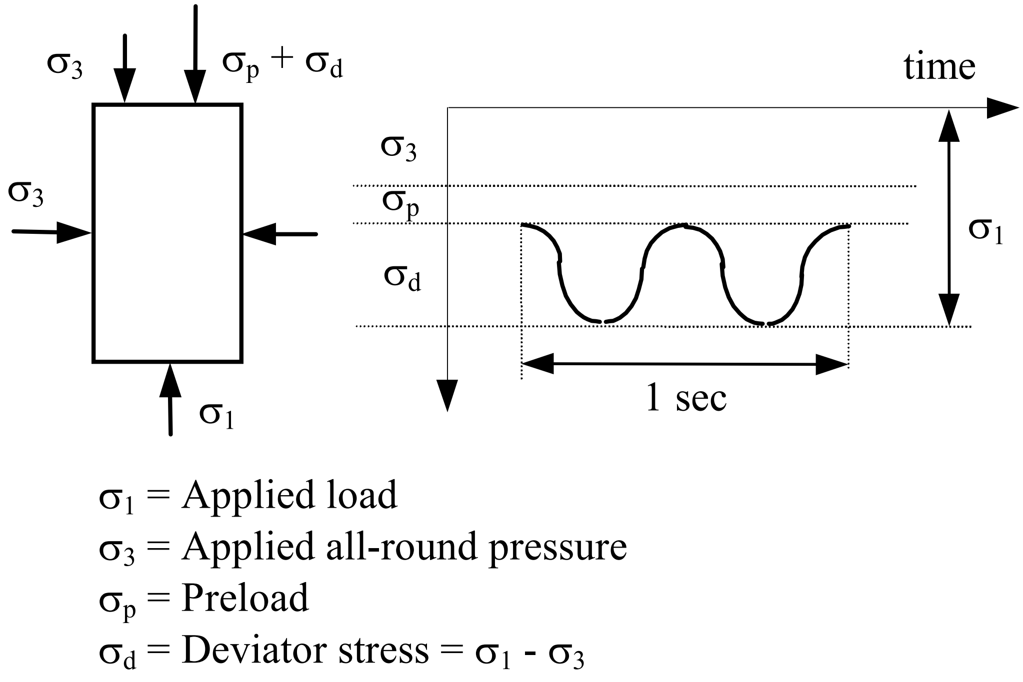


Figure 15. Stresses Applied to Triaxial Specimens

Cognizance was taken of the following points during dynamic triaxial testing :

The targeted confining pressures and the load stresses for the full-scale and the scaled-down specimens were identical.

In order to achieve equivalent load stresses, the applied axial loads were varied proportionally in relation to specimen diameter.

The ratio of specimen diameter to maximum aggregate size for the full-scale specimens was 4 and for the scaled-down specimens about 16.

The same triaxial testing procedure was followed for all the specimens tested.

The specimens were initially conditioned by applying 1200 cycles at 120 kPa and a cell (confining) pressure of 50 kPa before recording the load and vertical displacements for modulus determinations. Thereafter the applied vertical pressure was increased in steps of 100 kPa as shown in Table 9 and 120 cycles applied before recording test data for a specific applied pressure.

The test series was repeated again at cell pressures of 100 kPa and 200 kPa, reconditioning the specimens by pulsing 1200 cycles after increasing the cell pressure.

Table 9. Stress Levels Used for the Triaxial Testing

σ_3(kPa)	σ_0(kPa)			σ_d(kPa)			
50	20	100	200	300	400		
100	20	100	200	300	400	500	
200	20	200	300	400	500	600	700

Triaxial Shear Testing Methodology

Drained triaxial shear tests were carried out on virgin specimens, with maximum axial loads of less than 20 percent of the shear strengths of the materials. Specimens were loaded at a constant displacement rate of 6.25 mm/min. Tests were carried out at selected cell pressures of 50, 100 and 200 kPa and the load and vertical displacements were monitored directly from the MTS.

Calculation of Stiffness and Shear Properties

To account for the volume change during specimen loading, the applied stress has been corrected as follows:

$$\text{Corrected stress } (\sigma_d) = \text{Measured stress x } (1-\varepsilon_a) \tag{5}$$

where ε_a = measured axial strain ($\Delta L / L$) and L = specimen height.

The resilient modulus (MR) of a specimen was calculated as follows:

$$MR = \sigma_d / \varepsilon_a \tag{6}$$

The sum of the principal stresses (θ) was calculated from:

$$\theta = \sigma_d + 3\,\sigma_3 \tag{7}$$

where σ_3 = all-round pressure.

The elastic parameters of the materials (K_1 and K_2) may be determined from a linear regression of the dynamic moduli test data plotted logarithmically. It should be noted that the MR values were observed to be dependent on the confining pressure and increased in steps with increase in σ_3.The equation below applies with MR in MPa and θ in kPa.

$$\text{Log } MR = \text{Log } K_1 + K_2 \text{ Log } \theta \tag{8}$$

The shear strength parameters, the apparent cohesion (c) and the angle of shearing resistance (Φ) were determined using the Mohr-Coulomb failure criterion shown below. It should be kept in mind that the failure curve is not necessarily linear.

$$\tau = c + \sigma \tan \Phi \tag{9}$$

Dynamic Triaxial Test Results

Dynamic triaxial tests were done on at least two specimens for each of the granular materials evaluated. Figure 16 and Figure 17 show resilient modulus as a function of the sum of the principal stresses for the full-scale and scaled-down G1 and WM specimens tested (the GEMS material results were very similar). From a linear regression done on this data, the elastic material parameters, K_1 and K_2, were determined as shown in Table 10.

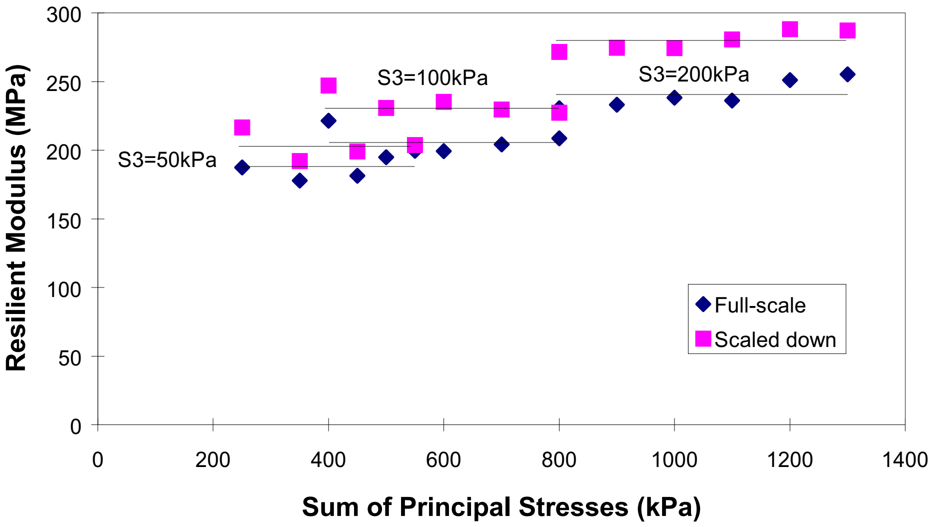


Figure 16. Stress Dependent Stiffness of G1 (Graded Crushed Rock)

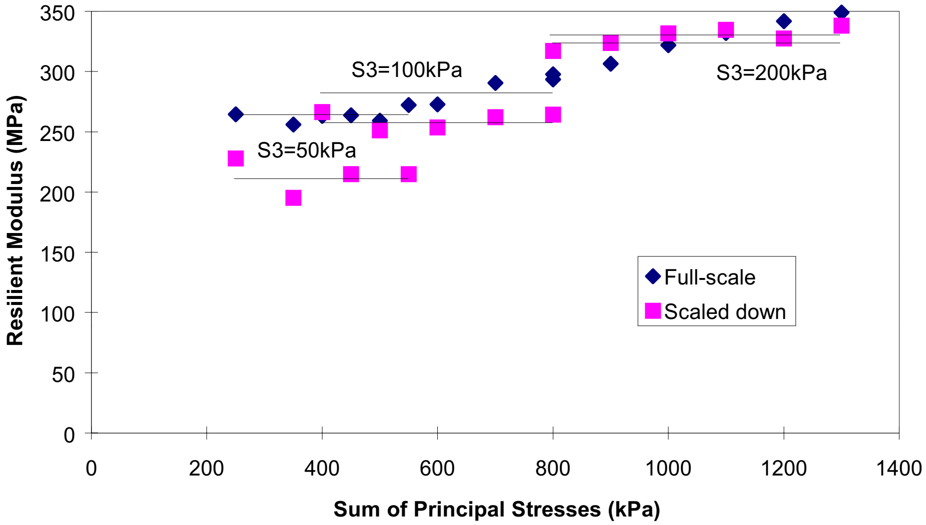


Figure 17. Stress Dependent Stiffness of WM (Waterbound Macadam)

Table 10. Shear Strength Parameters and K_1 and K_2 values for the Full-scale and Scaled-down Materials

		Full-scale	Scaled down
G1	c (kPa)	83	22
	ϕ (°)	53	52
	K_1	55.6	53.8
	K_2	0.207	0.231
WM	c (kPa)	387	73
	ϕ (°)	47	48
	K_1	78.5	32.4
	K_2	0.202	0.328
GEMS	c (kPa)	132	123
	ϕ (°)	45	39
	K_1	53.8	69.2
	K_2	0.249	0.240

Triaxial Shear Test Results

Figure 18 and Figure 19 shows the stress-strain curves determined for the full-scale and scaled-down granular G1 and WM materials (the GEMS material yielded similar results). The shear strength parameters for the full-scale and scaled-down granular materials were determined as shown in Table 10.

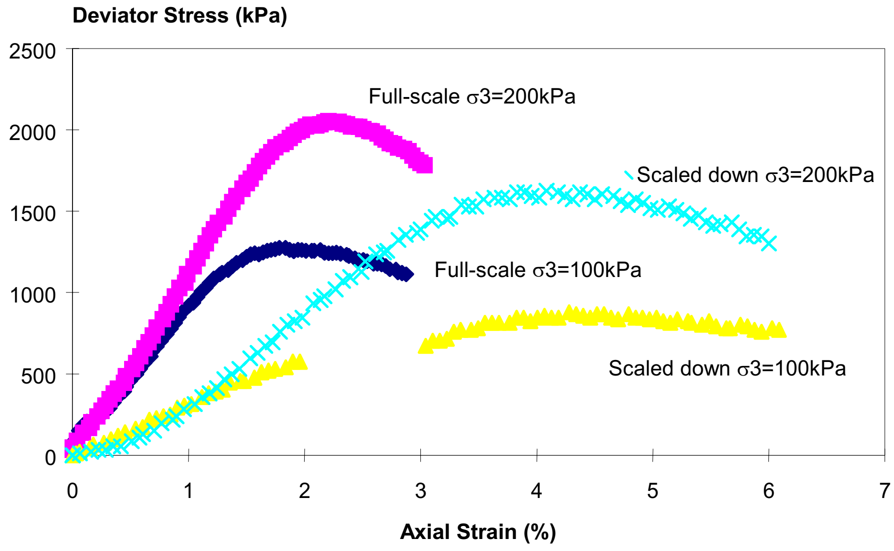


Figure 18. Stress-Strain Curves determined for G1 (Graded Crushed Rock)

Note : Break in readings for Scaled-down σ_3=100kPa due to lapse in data capture

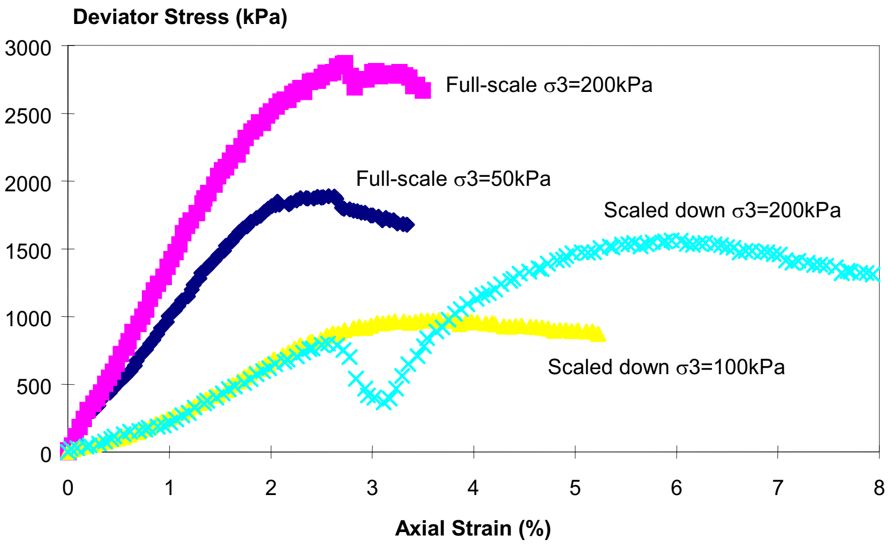


Figure 19. Stress-Strain Curves determined for WM (Waterbound Macadam)

Summary of Findings

The discussion that follows focuses on the materials and mechanistic properties of full-scale and scaled-down materials and how these properties influence the stiffness, strength and permanent deformation characteristics of visco-elastic and elasto-plastic pavement structures.

Gradation

As with asphaltic materials, the problems associated with scaling down of very fine material are also evident with granular materials. Due to specific surface considerations for the fine fraction, a higher filler content requires a higher moisture content. The reduced particle size of the scaled-down materials will also influence the maximum compaction densities of these materials compared with the full-scale versions (23). This is illustrated in Figure 20 for "well graded" materials which indicates a sharp decrease in the maximum dry density of the materials expressed as a percentage of solid density with a decrease in the maximum particle size. This accounts for the lower compaction densities of the scaled-down granular materials shown in Table 7.

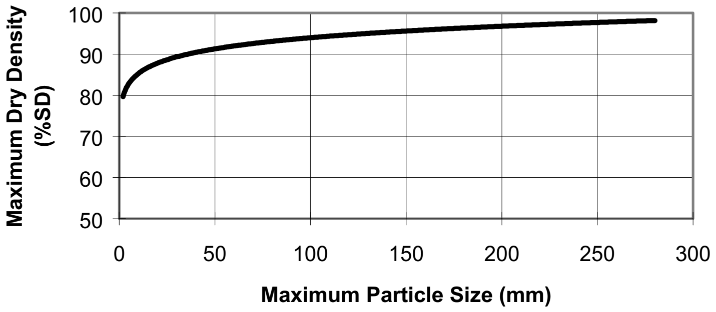


Figure 20. Estimated MDD's (%SD) of the "Ideal Grading" for Different Maximum Particle Sizes [after (23)]

For elasto-plastic materials, the comparison of full-scale and scaled-down material response is governed by particularly the stiffness and shear strength parameters of these materials. Another factor, which was not considered for this study, is the permanent deformation characteristics of the materials. It is recommended that additional research be undertaken to characterize the deformation of scaled granular materials in relation to full-scale materials.

Further research should also focus on the influence of suction or negative pore water pressure on the response of granular materials. The response of an element of soil to applied load depends crucially on its consolidation history and the current effective stress state.

Stiffness

Figure 16 and Figure 17 show that the dynamic stress dependant stiffness of the full-scale and scaled-down granular materials compare very well, the stiffness of the scaled-down materials being slightly higher. An indication of the static stiffness of the granular materials may be inferred from the slopes of the stress-strain curves shown in Figure 18 and Figure 19. From these figures it can be seen that the full-scale materials have significantly higher stiffness values. The difference in the stiffness values is an important finding which requires further investigation.

Strength

The angle of internal friction, ϕ, for the full-scale and scaled-down materials compare well; however, the cohesion differs significantly. The cohesion values of the full-scale materials were higher than those for the scaled-down versions, which indicates that the higher fine content in the mix does not necessarily increase the cohesion. The influence of cohesion on the shear strength of materials and hence on performance modeling, is important, and further research into this aspect is recommended. Using the information in Table 10, the Mohr-Coulomb failure lines for the G1 full-scale and scaled-down materials were plotted in Figure 21. From this figure it may be recognized that the influence of the shear strength parameters of the granular materials on the response of the pavement structure will depend on the magnitude of the applied and confining stresses under full-scale and scaled-down loading. For example, South African pavements constructed in drier regions typically consist of granular bases with thin asphalt surfacings or seals. The applied stresses in the base layer of these pavements will therefore tend to be high. The confining stress may be high in the upper portion of the layer but will decrease with depth. At low confining pressures, the stress-strain envelope will be such that the shear stresses in the base layer may approach the failure line; however, with high confining pressures the Mohr-Coulomb circles will have a smaller radius (low deviator stress) and shear stresses will be low.

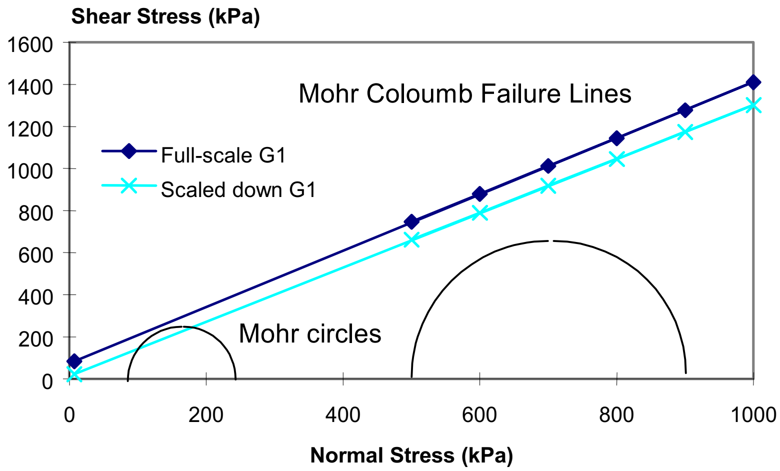


Figure 21. Stress-Strain Failure Criterion for Full-Scale and Scaled-down Materials

At low total stresses, a difference in the behavior of full-scale and scaled-down materials could be expected. Figure 21 shows that the behavior of full-scale and scaled-down G1 materials will be similar for the Mohr circle at higher σ_1 and σ_3 values, but will differ for lower stresses where the Mohr circle may exceed one of the failure envelopes. This is so because at low total stresses the difference between the full-scale and scaled-down failure lines is a greater percentage of the deviator stress than at higher total stresses.

The difference in the failure lines for the full-scale and scaled-down mixes is primarily a result of the cohesion, as the angles of friction are very similar for the different gradings. This shift in failure lines will have a lower influence on material behavior at higher principle stresses. The difference in cohesion could not be attributed directly to the fines content and is more likely to be a result of other influences such as clay fraction, moisture content and spatial effects. As previously stated, finer gradings were generated through crushing. It is likely that this crushing produced non-plastic fines in the 0,075 to 0,003 mm fraction, which would result in an overall decrease in the percentage clay fraction in the scaled-down mix. This needs to be verified through hydrometer testing.

Permanent deformation

Figure 18 and Figure 19 indicate that the strain at failure for the scaled-down materials is much higher than for the full-scale versions. From these figures it can be seen that the response of the scaled-down materials is more elasto-plastic. The difference in the strain values hints at possible differences in the permanent deformation characteristics between full-scale and scaled-down materials. This aspect requires further research for verification.

Implementation of 1/3-Scale MMLS Testing to Support APT under RRIC

Experimental Design

Using MMLS testing, it will be possible to evaluate additional factors not considered for the RRIC full-scale APT. The influence of these factors on the response and subsequent performance of the scaled pavements may then be transferred to the full-scale experiments. Factors that have not been incorporated into the RRIC experimental design of the full-scale tests but that can be evaluated using model testing are:

Aging,

Test temperature,

Moisture of the subgrade material, and,

Test load

These factors have been identified as being critical to the performance of the sections. The first factor that will have a significant influence on the life of the sections is aging of the asphalt surfacing. To investigate this factor it is recommended that two aging periods be used: i.e. 0 days (unaged) and 7 days of aging as described in this report. It is anticipated that the unaged sections will fail prematurely because of insufficient hardening of the surface and may result in unrealistic comparisons. Test temperature will impact on the stiffness of the asphaltic layers. Two pavement test temperatures are recommended to evaluate the rutting and fatigue susceptibility of the sections separately, i.e. 40 °C and 5 °C. Two degrees of subgrade saturation are recommended i.e. 80% and 20%. Variation of the test load will allow an evaluation of the equivalency of the respective sections. The MMLS can operate under a maximum wheel load of 2.7kN. To investigate equivalency it is recommended that a 25% difference in loading be applied, hence loads of 2.2kN and 2.7kN.

The Roadway Research Implementation Center (RRIC) program includes a comprehensive experimental design structure for APT testing of AC sections as outlined in Figure 22. The design variables include:

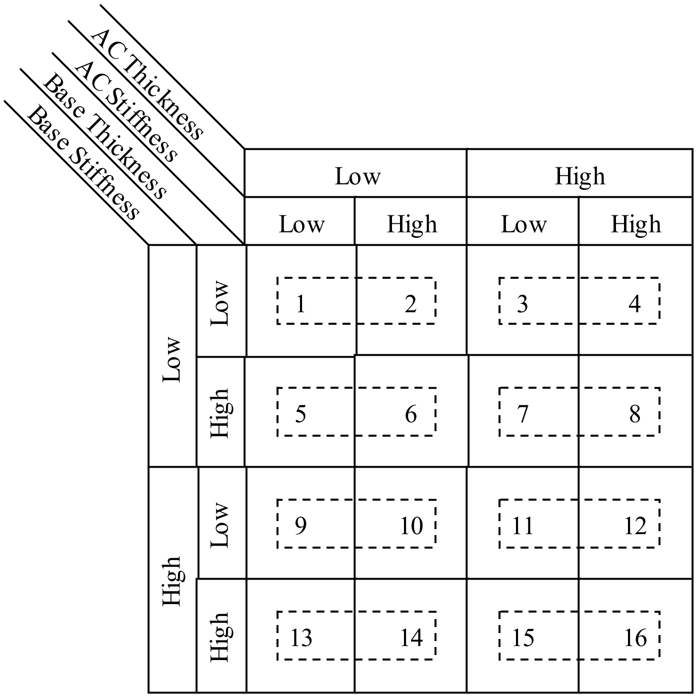
Two AC thicknesses (75mm and 150mm)

Two base thicknesses (150mm and 300mm)

Two AC stiffnesses (E=2000MPa and 4000MPa)

Two base stiffnesses (E=200MPa and 1400MPa)

The base materials will consist of crushed stone (low stiffness) and asphalt treated granular material (high stiffness).



Base Stiffness	Base Thickness	AC Thickness: Low AC Stiffness: Low	AC Thickness: Low AC Stiffness: High	AC Thickness: High AC Stiffness: Low	AC Thickness: High AC Stiffness: High
Low	Low	1	2	3	4
	High	5	6	7	8
High	Low	9	10	11	12
	High	13	14	15	16

Figure 22. RRIC Experimental Design

Each of the sections above were investigated using elastic layer theory and the AASHTO design method to determine the expected relative lives of each. The results of this analysis are shown in Table 11. The pavement sections can be divided into four classes according to the expected amount of traffic until failure i.e.:

Very Low Traffic: Sections 1, 5, 9, 2, 6 and 10

Low Traffic: Sections 11, 13, 3 and 7

Medium Traffic: Sections 14, 4 and 12

High Traffic: Sections 15, 8 and 16

From the above it is clear that the pavement structures vary within and between traffic classes. Ideally, it would be preferable to do MMLS tests on each of the pavement structures proposed by RRIC, however, to limit the overall number of MMLS tests it is recommended that MMLS testing be used to evaluate specific pavement structures from each of the above traffic classes.

If one considers that the influence of the MMLS test temperature variation factor on AC stiffness will be dominant, it is feasible to eliminate AC stiffness from the matrix shown in Figure 22. Therefore from the standpoint of the MMLS tests, sections 1 and 2 should behave similarly, as will 3 and 4 etc. The sections that are expected to behave similarly have been enclosed in a dashed rectangle. This said, it is suggested that the following sections be evaluated using the MMLS:

Very Low Traffic: Sections 1 and 10

Low Traffic: Sections 3 and 11

Medium Traffic: Section 14

High Traffic: Section 8

This approach is recommended as it broadens the scope of the MMLS tests by including the interaction of RRIC experimental design factors. This should benefit the transfer of knowledge from scale model to full-scale APT.

Table 11. Expected Lives of Sections

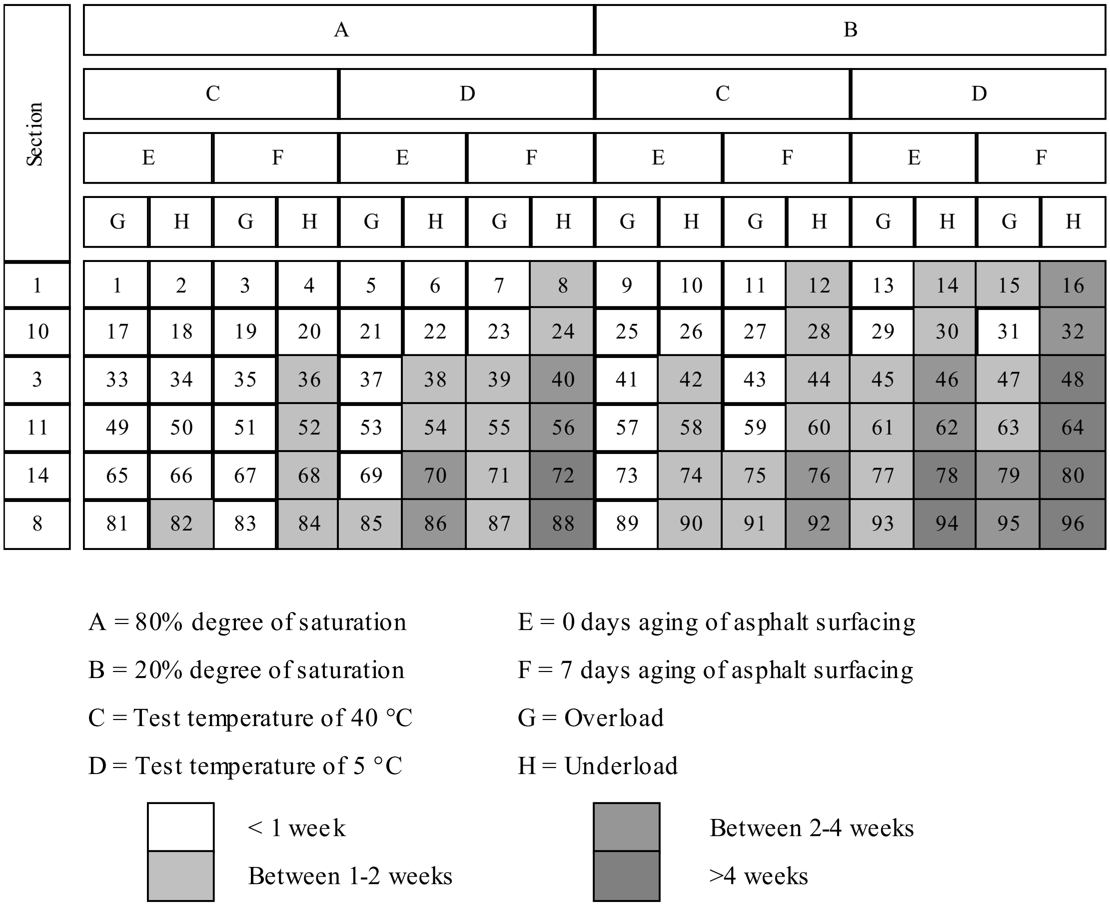
Section	W_{18}	% of Max	Section	W_{18}	% of Max
1	160k	0.5	9	200k	0.7
2	500k	1.7	10	500k	1.7
3	3.5M	11.7	11	2.5M	8.3
4	5M	16.7	12	10M	33.3
5	160k	0.5	13	3M	10
6	500k	1.7	14	4.5M	15
7	3.5M	11.7	15	17M	56.7
8	18M	60	16	30M	100

For MMLS testing of the sections, it will be appropriate to scale the pavement structures of each candidate section above the subgrade by 1:3, this to ensure that the stress/strain conditions in the full-scale pavements are represented in the scaled model pavements. Given that the maximum aggregate size of the asphalt mixture may be 25mm, and that it should preferably be at least a third of the AC layer thickness, it will be necessary to scale the aggregate gradations of the 75mm (25mm scaled down) AC layer sections 1, 10 and 14. As an example, a typical dense AC mixture gradation with maximum aggregate size of 25 mm has been scaled by 1:3 as shown in Table 12. No scaling of the base material will be necessary, provided the maximum aggregate size of the base material does not exceed 50mm. The subgrade may be assured to be semi-infinite hence no scaling is required.

Table 12. Example of a Typical Dense Mix with 1:3 Scaled Gradation

Sieve size (mm)	Percentage Passing	
	Full-scale	Scaled down
37.5	100	100
25.0	92	100
12.5	68	100
4.75	44	75
2.36	32	57
0.300	11	23
0.075	4	8

Figure 23 shows the recommended MMLS test matrix incorporating the factors as outlined. Also shown on the figure are the estimated times until completion of a test on a particular pad (see discussion later). One may argue that the influence of subgrade moisture condition will be negligible under pavement structures having thick and stiff surface and base layers such as sections 8, 10, 11 and 14. The testing of these sections under both moisture conditions is recommended from a statistical point of view as they form part of the factorial design, although an option not to test is available.



Section	A								B							
	C				D				C				D			
	E		F		E		F		E		F		E		F	
	G	H	G	H	G	H	G	H	G	H	G	H	G	H	G	H
1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
10	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
3	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
11	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64
14	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
8	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96

A = 80% degree of saturation
B = 20% degree of saturation
C = Test temperature of 40 °C
D = Test temperature of 5 °C
E = 0 days aging of asphalt surfacing
F = 7 days aging of asphalt surfacing
G = Overload
H = Underload

□ < 1 week
░ Between 1-2 weeks
▒ Between 2-4 weeks
▓ >4 weeks

Figure 23. Experimental Design of MMLS Tests

It is recommended that the MMLS test pads be trafficked until failure. A decision as to traffic wander must be made as this will have a significant influence on pavement life. Channelized trafficking is recommended as this will accelerate failure of the pavements. Two failure (end of test) criteria are recommended:

a 10 millimeter rut (mean transverse)

a 50 percent reduction in stiffness (mean SASW measurement)

After the 50 percent reduction in stiffness it is recommended that water be applied to the pavements together with additional trafficking. This will allow an investigation into the influence of water ingress and pavement cracking on performance.

Testing Strategy

Laboratory Tests

Laboratory tests are required to characterize the material properties prior to MMLS testing. Tests should include:

SUPERPAVE™ and standard binder tests

SUPERPAVE™ asphalt mixture tests

Geotechnical tests (Atterberg limits etc)

Static, dynamic and repetitive triaxial tests on asphalt and soil samples – 3 deviatoric stress levels (including tensile for asphalt specimens), 2 confining pressures preferable variable and 2 temperatures for asphalt specimens.

<u>MMLS Tests</u>

Routine monitoring of test pads during trafficking should include:

Collection of transverse profiles (at least three transverse profiles along the test pads)

SASW measurements

Crack mapping

Monitoring of pavement temperatures

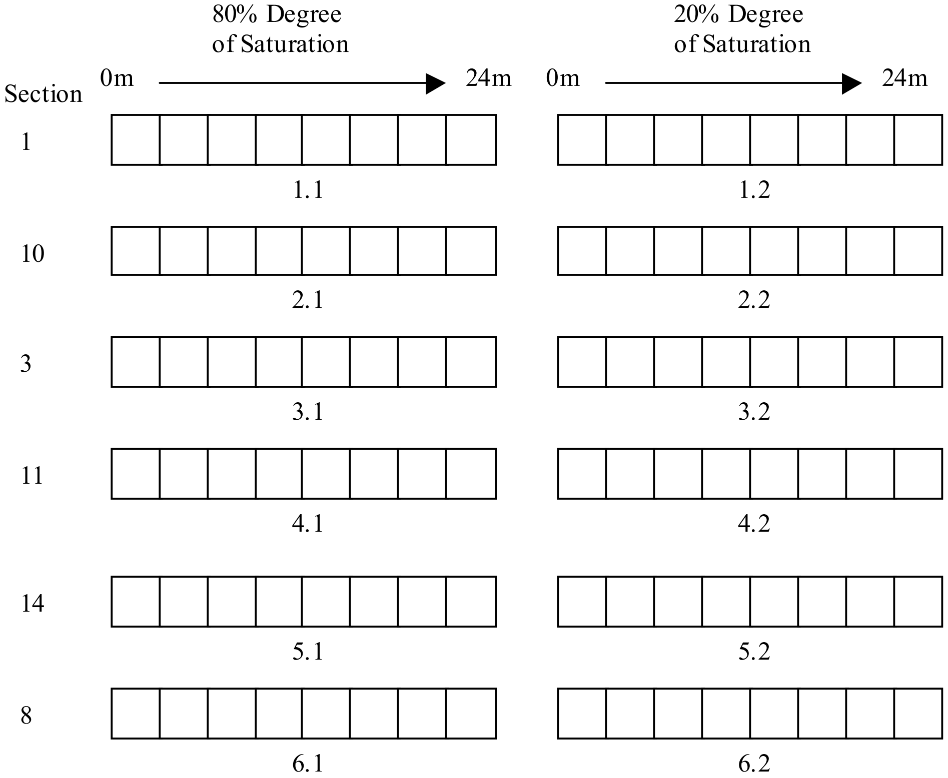
Data collection should be done after the following number of test axles: 0; 1,000; 10,000; 30,000; 100,000 and 300,000 etc. This sequence should be adjusted as appropriate. At the end of testing, cores inside and outside the MMLS wheelpaths should be taken for diagnostic purposes. It may also be appropriate to cut trenches across test pads to measure rut depth in layers, view crack initiation patterns and to measure density levels and the moisture content of subgrade material.

Test Pad Layout

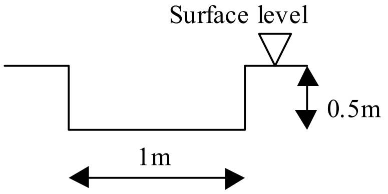
To ensure uniformity of the four test sections it is recommended that each be constructed separately as shown in Figure 24. The total length of one test pad is 3 meters with sub-sections of 24 meters to facilitate differences in subgrade moisture content. The width of the pad should be at least 1 meter. The test pads should preferably be constructed within an enclosed environment with access to overhead cranes and power supplies. The overhead cranes will be necessary to lift the MMLS, surcharge weights and environmental chamber during and between tests.

Environmental Chamber

Construction of an environmental chamber will be necessary to do tests at both 5 °C and 40 °C. It is recommended that the chamber be such that can be lifted using overhead cranes and positioned over each test pad.



Plan View



Pavement structure constructed within concrete box section. This will allow subgrade moisture to be controlled directly.

Side View

Figure 24. Layout of Test Sections

Project Schedule

The breakdown of tasks include laboratory tests on asphalt and soil specimens prior to construction of the MMLS test pads, aging of the test pads when necessary and MMLS testing of the pads. The estimates for the time to completion of tests shown in Figure 23 were calculated by assuming the relative life factors shown in Table 13. A maximum test period of 10 weeks was allocated for test pad 96. The relative time to complete MMLS tests on the other pads was calculated relative to this by accounting for differences in pavement structure. Time for temperature conditioning and routine maintenance of the MMLS has been allocated.

The number of days until completion of the MMLS tests, assuming an eight hour day and five day working week, was calculated at 1600. This is excessive, particularly in light of the fact that the MMLS can run 20 hours a day with 4 hours routine maintenance. At this rate and a seven day working week, the time to completion of the MMLS tests was calculated at 382 days.

Table 13. Relative Life Factors

Test factor	Relative Life Factor
80% Degree of Saturation	1
20% Degree of Saturation	2
40°C test temperature	1
5 °C test temperature	3
0 days aging	1
7 days aging	2
Overload	1
Underload	3

Preliminary project schedules were prepared to estimate the project duration. (These have not been included in the report but are available for review). The order of the MMLS tests was governed by the estimated time to completion; those expected to fail first are tested first. This information can then carried over to allow allocation of RRIC pavement structures. Depending on the number of MMLS devices in operation, the estimated days to project completion varies as shown in Figure 25. Given the large number of tests to be completed, it is anticipated that up to 75 million MMLS axle loads may be applied. This large number of axles suggests that maintenance of the MMLS may be critical to ensure efficient management of the project. An additional MMLS on stand-by may be beneficial.

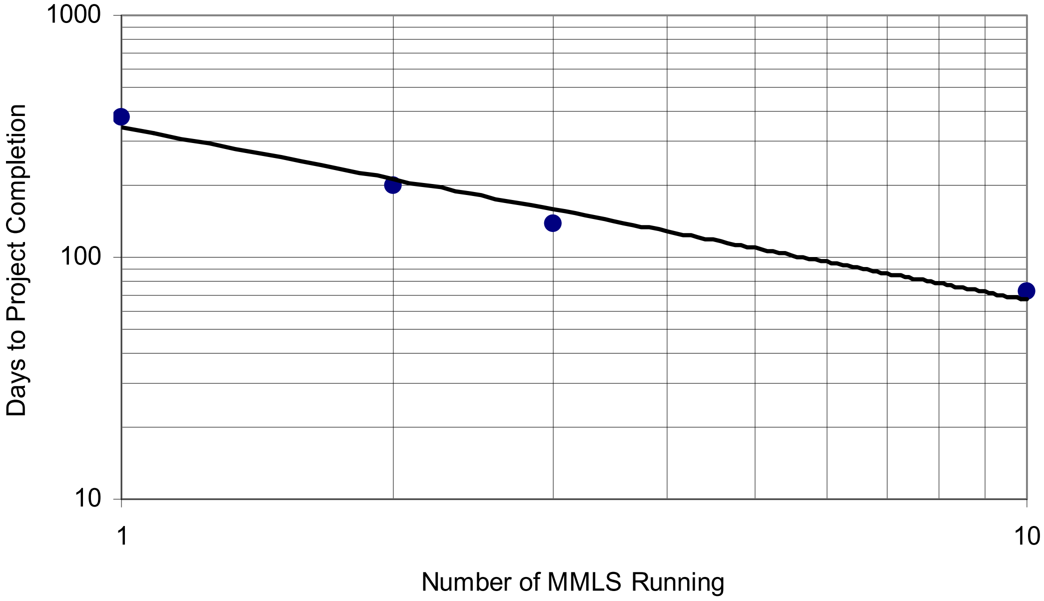


Figure 25. Estimated Project Completion Time

Conclusions

Two model MMLS testing devices are described; the mechanisms of which mirror to an extent the full-scale TxMLS. The main advantages of these devices are that the load is always moving in one direction, many repetitions are possible in a short period, and a relatively high trafficking speed is possible. Similarities between TxMLS and MMLS performance include similar rutting and fatigue performance, similar behavior in terms of stiffness loss and similar strain behavior. The immediate benefit of these scaled APT devices is that testing can be done at a fraction of the cost of full-scale APT. Furthermore, testing can be done at laboratory scale under controlled environmental and testing conditions or directly in the field. This allows many of the variables impacting pavement systems to be controlled directly which expedites the testing of the different variables, prior to conducting full-scale APT.

A dimensional analysis into scaled-down performance testing indicated that for extrapolation from scaled to full-scale to be valid:

the laws of the theory of similitude must be satisfied,

variables which are not properly scaled must only have a negligible effect on the measured response both in the field and the laboratory, and

the time scales required to reproduce the correct elastic, viscous or gravity effects need to be appropriately selected.

When there is a lack of complete scaling between full-scale and model pavement structures, it is still possible to select a thickness of base layer such that strains in the full-scale and the model pavement are very similar for the asphalt surfacing layer. Even though total displacements are not properly reproduced, this possibility permits use of the model to study specific aspects of the asphalt layer or other layers, such as rutting or fatigue without scaling down the pavement exactly or totally.

In light of the possible role of model testing in APT, attention was given to the following fields:

Performance modeling

Validation of asphalt mix design

Ranking of candidate blends

Environmental conditioning (Durability)

Distress and load equivalency

Scaling of granular materials

The three main material response characteristics identified for scaled-down performance testing are stiffness, strength and permanent deformation. The volumetric differences between full-scale and comparable scaled-down materials must also be considered.

It was found that when scaling down pavement materials, the initial difference between the full-scale and comparable scaled-down materials is noted with the filler content of the mix. It is practically difficult to scale down the fraction of the mix finer than 0,075 mm. The resultant filler fraction of the scaled-down materials may be double that of the full-scale equivalent.

Due to specific surface considerations for the fine fraction, a higher filler content requires a higher binder content. If cognizance is not taken of this detail, the mastic of the full-scale and comparable scaled-down mix may differ significantly, which will influence the mix response.

Mix stiffness is influenced by the bitumen properties and macro volumetric properties (voids in the mix, volume of bitumen and volume of aggregate) of the mix. In order to achieve comparable scaled-down and full-scale stiffness properties, the binder content of a scaled-down mix has invariably been considerably higher than that of the full-scale mix. Given that the voids in the mix of the full-scale and scaled-down mixes must be the same, an increase in binder content for the scaled-down mix must be countered by a decrease in the volume of aggregate in the mix. This will always result in a lower mix stiffness at higher binder contents. The resultant difference in stiffness between full-scale and scaled-down mixes will impact on the fatigue and permanent deformation characteristics of the mixes, and this should be accounted for when comparing full-scale and scaled-down performance relationships.

The results of model testing to evaluate the permanent deformation and fatigue characteristics of asphalt pavements are shown. At higher testing temperatures, the permanent deformation characteristic is, to a great extent, influenced by the stiffness of the aggregate structure of the mix. Scaling may influence this stone skeleton, in that the larger filler fraction could break the aggregate interlock. Aggregate angularity and fractured faces should not be allowed to vary between full-scale and scaled-down gradations.

Research has shown that the MMLS Mk.1 is able to rank asphalt mixtures in terms of rut susceptibility. Furthermore, it has been shown that the MMLS is able to rate the rut susceptibility of asphalt mixtures in a relatively short time; about three hours or after 30 000 MMLS axle loads.

If full-scale APT is done in the field, it is particularly difficult to control environmental influences on pavement performance. Controlling and assessing these environmental factors on laboratory scale using scaled APT is feasible. Full-scale APT can be used to apply a pavement's design life traffic over a very short period of time, however, no account can be given of climatic or environmental distress. This is a major shortcoming of full-scale APT that can be addressed using scaled APT. Environmental considerations should include:

Conditioning with ultra-violet light and heat for aging purposes

Water conditioning

Recognition of test temperature on pavement distress

Model testing may be applied to determine the load and damage equivalency of pavement structures. Equivalency factors determined using model testing should be applicable to full-scale testing if the laws of similitude are obeyed. Further research may be necessary to validate this.

Triaxial testing of full-scale and comparable scaled-down granular materials to implement model testing has shown that:

equivalent dynamic stiffness can be readily achieved for full-scale and scaled-down mixes for a variety of materials,

the shear strength parameters may be kept acceptably constant for continuously graded mixes if attention is given to cohesion values. In particular, the clay content and plasticity of the material requires analysis,

materials such as Waterbound Macadam (large aggregate gap-graded mixes) do not provide very similar shear strength parameters when scaled down; however, scale test results will provide conservative assessments,

In the light of this, positive possibilities exist for APT on scaled-down granular materials.

A strategy towards implementation of 1/3-scale MMLS testing to support APT under RRIC is presented. The RRIC design variables include AC surfacing stiffness and thickness and base stiffness and thickness. Using the MMLS, additional factors not accounted for in the full-scale APT under RRIC can be evaluated. The influence of these factors on the response and subsequent performance of the scaled pavements may then be transferred to the full-scale experiments. A matrix of experiments has been designed to assess the influence of the following factors on pavement performance using the MMLS:

Degree of subgrade saturation (20% and 80%)

Test Temperature (5°C and 40°C)

Aging of the asphalt surfacing (0 and 7 days laboratory aging)

Overload testing (25% overload)

Given that the MMLS can run 20 hours a day with 4 hours routine maintenance, at this rate and a seven day working week, the time to completion of the MMLS tests was calculated at 382 days. It was further shown that using additional MMLS devices reduces project time significantly. It is anticipated that up to 75 million MMLS axle loads may be applied during the project as proposed. This large number of axles suggests that maintenance of the MMLS may be critical to ensure efficient management of the project.

Recommendations

As a result of the findings and conclusions reported, the following recommendations are made towards a strategy for implementation of a model-testing program to supplement full-scale TxMLS testing.

Further model performance testing on scaled and unscaled pavements should include not only rutting and fatigue tests but also tests to assess low-temperature cracking and moisture sensitivity of pavements.

Model testing should be used to validate mix designs used to assess candidate mixes for full-scale testing. Parameters that should be validated are the recommended compaction levels, limits on voids in the mineral aggregate (VMA) and voids filled with binder (VFB), gradation characteristics and other aggregate related properties. Furthermore, all candidate blends should be ranked using model testing prior to full-scale APT.

Further research into environmental conditioning procedures designed to simulate or even counteract environmental distress is required. The focus of this research should be towards assessing the remaining life of pavement structures.

Research should also focus on the influence of suction or negative pore water pressure on the response of granular materials. This will allow a better understanding of the response of granular materials to applied loads.

To improve performance prediction, further research into scaled-down APT should be directed towards:

the possible effects of deviation from laws of similitude and of applying different scaling factors,

material properties of scaled-down materials and in particular permanent deformation considerations,

comparative permanent deformation performance through dynamic triaxial testing,

the influence of the larger filler fraction of scaled-down materials,

the scaling down of mechanical test equipment and procedures for tests on scaled-down materials, and,

artificial aging compared to environmental aging.

A strategy toward implementation of 1/3-scale MMLS model testing to support APT under RRIC is presented. It is recommended that four different pavement structures based on the RRIC design experiments be tested using the MMLS. These pavement structures and materials must be scaled by 1:3.

Factors to be considered for MMLS testing should include:

Degree of subgrade saturation

Test Temperature

Aging of the asphalt surfacing

Overload testing

It is recommended that the MMLS test pads be tested to failure. Channelized trafficking is recommended as this will accelerate failure of the pavements. Two failure (end of test) criteria are recommended:

a 10 millimeter rut (mean transverse)

a 50 percent reduction in stiffness (mean SASW measurement)

After the 50 percent reduction in stiffness it is recommended that water be applied to the pavements together with additional trafficking. This will allow an investigation into the influence of water ingress and pavement cracking on performance.

The MMLS should preferably be run for 24 hours a day i.e. 20 hours a day with 4 hours routine maintenance. Additional MMLS devices are recommended to expedite the testing program or for stand-by if required.

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