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NCHRP

SYNTHESIS 325

NATIONAL
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HIGHWAY
RESEARCH
PROGRAM

Significant Findings from Full-Scale Accelerated Pavement Testing

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 325

**Significant Findings from Full-Scale Accelerated
Pavement Testing**

A Synthesis of Highway Practice

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Pavement Design, Management, and Performance, and Materials and Construction

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Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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FOREWORD

*By Staff
Transportation
Research Board*

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

Information exists on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, “Synthesis of Information Related to Highway Problems,” searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

The synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

The objective of this synthesis was to document and summarize the findings from the various experimental activities associated with full-scale accelerated pavement testing (APT) programs. These programs have generated significant findings and benefits with regard to pavement design, analysis, evaluation, and construction practices over the last 30 years. For this report, accelerated pavement testing was defined as the controlled application of wheel loading to pavement structures for the purpose of simulating the effects of long-term in-service loading conditions in a compressed time period. The focus of the synthesis was on the reported findings and their application to research and practice. The actual and potential benefits to the U.S. pavement community are addressed. Secondary areas of interest include relevant airfield pavement research, environmental effects, newly initiated programs, coordination efforts between programs and partners, future directions and strategies, and obstacles and lessons learned.

The proceedings of the First International Conference on APT held in Reno, Nevada, in 1999, served as a point of departure for a comprehensive literature review. Various other sources were explored, including the bibliography contained in 1996’s *NCHRP Synthesis of Highway Practice 235*. A questionnaire, which was distributed internationally, was used to gather information that was unpublished. Summaries of the views of the respondents were then compiled relative to evaluation, validation, and improvement of structural design; vehicle–pavement–environment interactions; evaluation of materials and tests; enhancement of modeling in pavement engineering; development and validation of rehabilitation, construction, and management strategies; pavement engineering applications and issues; and improvement of pavement economics and management through APT applications.

A panel of experts in the subject area guided the work of organizing and evaluating the collected data and reviewed the final synthesis report. A consultant was engaged to collect and synthesize the information and to write this report. Both the consultant and the members of the oversight panel are acknowledged on the title page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

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This study was managed by Jon Williams, Synthesis Studies, who worked with the consultant, the Topic Panel, and the Project 20-5 Committee in the development and review of the report. Assistance in project scope development was provided by Donna Vlasak, Senior Program Officer. Don Tippman was responsible for editing and production. Cheryl Keith assisted in meeting logistics and distribution of the questionnaire and draft reports.

Crawford F. Jencks, Manager, National Cooperative Highway Research Program, assisted the NCHRP 20-5 Committee and the Synthesis staff.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

SIGNIFICANT FINDINGS FROM FULL-SCALE ACCELERATED PAVEMENT TESTING

SUMMARY

A large volume of knowledge exists globally in the field of accelerated pavement testing (APT). The focus of this study was to tap this source of knowledge for application to research and practice. In particular, the focus was on programs operational during the past 20 years. A number of the APT programs are featured prominently because they have been operational for extended periods of time. For this report, accelerated pavement testing was defined as the controlled application of wheel loading to pavement structures for the purpose of simulating the effects of long-term in-service loading conditions in a compressed time period. This included programs of the Council for Scientific and Industrial Research in South Africa, France's Roads and Bridges Research Center (Laboratoire Central des Ponts et Chaussées), the Australian Road Research Board, and, more recently, the APT program in California in the United States. In *NCHRP Synthesis of Highway Practice 235*, published in 1996, Metcalf presented a comprehensive overview of APT programs with details about the extensive range of APT facilities in existence at that time.

A wide variety of APT programs are operational in the world today. Twenty-eight such programs were reported as being currently active, with 15 of these in the United States. Most of these tests are being conducted at fixed sites. However, there are still programs that focus on field studies in the belief that this results in improved vehicle-pavement-environment interaction. Of the new facilities, the National Airport Pavement Testing Facility is unique. That it can simulate full-scale landing gear (undercarriages) of aircraft is indicative of its sheer size. The other facilities are conventional linear trafficking test devices that have, in most cases, been customized to suit specific needs. It is notable that the latest generation of test devices either has partial or full environmental control. The test track at the National Center for Asphalt Technology at Auburn University, Auburn, Alabama, is similar to the WesTrack test facility at Reno (Nevada), except that the former is in a different climatic zone and the trucks have drivers instead of being remotely controlled.

The information used for this study was obtained through a questionnaire distributed internationally. The respondents to the questionnaire added considerable value to the synthesis through their detailed answers. The information was not only relevant but of a quantitative and qualitative nature difficult to obtain cost-effectively through any other means. This information was supplemented by a detailed study of the extensive bibliography that is available on APT. The international APT conference that was held in Reno in 1999 provided the most recent comprehensive update on APT information.

An important aspect of APT is the Co-operative Science and Technology study program of the European Community (COST). This organization is currently working in parallel with the current synthesis toward establishing a knowledge base on APT in Europe. There is some overlap; however, both efforts should benefit from the understanding that was reached between the TRB A2B09 committee on APT and the COST 347 committee. According to this agreement there will be as much exchange of information as possible. The agreement

paved the way for the European APT programs to share their knowledge by participating in the survey conducted as part of this project.

The analysis for this synthesis was done by reviewing the available information in terms of elements of a pavement system. The results were then synthesized and the significant findings were categorized relative to the different pavement elements. Summaries of views of the respondents were compiled relative to the following topics:

- Evaluation, Validation, and Improvement of Structural Designs;
- Vehicle–Pavement–Environment Interaction;
- Evaluation of Materials and Tests;
- Enhancement of Modeling in Pavement Engineering;
- Development and Validation of Rehabilitation, Construction, and Maintenance Strategies;
- Pavement Engineering Applications and Issues; and
- Improvement of Pavement Economics and Management Through APT Applications.

These views were considered to be important, because they are related to the direct experience of the users and their application and use of significant findings. The questionnaire responses also contained categorized references, which were used to compile an annotated topical bibliography that is provided at the end of this report.

The extensive list of applications that were collated as a product of the synthesis was primarily generated by the delegates themselves. It provides examples of what can be achieved if APT is used prudently in a systematic manner. The following overview presents the generic core of significant findings in terms of applications.

APT has been instrumental in validating and refining agency structural design guidelines. Improvements in structural design have also been brought about by the insight gained on the effect of a number of factors on pavement performance, including

- The influence of water on performance and related failure mechanisms,
- The importance of bond between layers and the quantification of the effect,
- The interaction between structural composition and material characteristics,
- The influence of concrete slab configuration, and
- The influence of support under concrete slabs.

The scope of APT studies is very large, which was evident from the analysis of the questionnaire responses that were received from APT programs worldwide. This analysis and the many case studies that were taken from the bibliography have made it possible to access the large number of applications in a logical manner, depending on the needs of the reader. These were included as integral parts of the various chapters, covering specific fields of pavement engineering, and related appendixes.

This synthesis is constructed such that the details of the various aspects of APT that were reviewed have been captured and embedded in a number of locations for subsequent retrieval by researchers and practitioners who are active in APT or in using the results of APT. An index is provided that should prove useful in this regard. More particularly, the following findings are noteworthy:

- Unique, unconventional pavement structures have been tested and evaluated through APT.

- Diagnostic studies of failure mechanisms provided a basis for understanding and counteracting distress mechanisms.
- A wide range of structural design packages has been evaluated or developed and this has greatly enhanced implementation.
- Systematic investigation of the vehicle–pavement–environment interaction is feasible through APT, but it will require a dedicated collaborative effort and commitment to overcome the constraints owing to the extended nature of such a study.
- The large number of APT tests relating to pavement materials is indicative of the potential of APT to provide sound answers about pavement materials. More particularly, it has been shown to be useful for answering questions relating to the use of new materials, composite materials, and materials with complex physical characteristics.
- APT is a tool for the confirmation and validation of laboratory test procedures.
- APT has become an important tool for developing and evaluating models.
- APT is an important means of answering questions related to rehabilitation, construction, and maintenance. Answering those questions would be more difficult and take far longer without APT experiments.

This synthesis provides ample evidence of the economic and management benefits that have been generated by APT. More particularly

- The economic gains as a result of APT are measurable. Details are given as to what has been achieved in terms of benefit-cost ratios, savings on capital expenditure, and the use of new and recycled materials and new pavement structures. Benefit-cost ratios varying from 1:1 to greater than 20:1 have been reported.
- Many ancillary artifacts have been developed in APT-related technologies in support of programs throughout the world. These have had considerable impact on the ability to understand pavement response and performance. A variety of examples are discussed. An important example is the improved understanding of tire–pavement interaction and its effect on performance.
- APT has provided a quantitative basis for communicating with decision makers about pavement performance. However, it will be necessary to upgrade APT systems to be able to account for environmental effects on a quantifiable basis.
- APT has attributes that supplement many aspects of pavement management systems and in-service pavement evaluation. If the identified gaps in the system are addressed, it may lead to rapid advances in pavement engineering and ultimately to long-life pavements with reduced maintenance costs.

The growth of APT in the United States may stimulate advances in the field of pavement engineering. This could gain additional momentum as the COST study program of the European Community (OECD COST 347) achieves its goals in Europe.

Several items were identified where further research could be undertaken to advance the practice.

- As a matter of course, the performance of in-service pavements that have been tested in APT programs could be tracked for future comparative performance studies. This would enhance continued improvement in the understanding and development of performance models.
- APT programs could, where possible, have closer association with in-service pavement evaluations, formal long-term pavement performance studies, and related pavement management systems to validate and evaluate APT results.

- Vehicle–pavement–environment interaction could be further explored to enhance the ability to do quantitative performance prediction of different pavement structures under specific conditions, which would probably be best achieved through a comprehensive collaborative APT program.

APT programs could advance pavement knowledge more rapidly by the prudent use of the available information and collaborative research efforts. This could include some planned replication to improve on the reliability of findings and to establish confidence limits.

The wide range of pavement types and configurations that have been tested through APT provide a broad foundation of knowledge on pavement engineering. A new generation of researchers has entered the APT field in the United States. This synthesis should assist them in their quest to become acquainted with all aspects of APT.

Internationally, the situation is somewhat different because many facilities have reached maturity and services are being rendered in an environment of privatization. Clients are now often road agencies and projects are being conducted on the basis of design, build, and operate. This in turn is leading to partnering and the use of APT in support of warranty contracts and improved management of pavement infrastructure.

With globalization it would seem prudent to anticipate similar wide-ranging changes in the United States. It is therefore particularly fortunate that the APT programs in the United States have entered a phase of development that should provide tools, technology, and APT practices that enable them to be well prepared for the challenge.

This development also has a negative aspect that needs to be considered. With the trend towards privatization and partnering, the results of APT studies are by default no longer in the public domain. This does not necessarily eliminate access to the information, but often it slows down the technology transfer through conferences and publications, although increasing use of the Internet may change all of that dramatically. APT activities throughout the world have become interlinked and this is greatly enhancing exchange of data and information.

CHAPTER ONE

INTRODUCTION**BACKGROUND**

A large body of knowledge exists globally in the field of accelerated pavement testing (APT). The purpose of this synthesis study is to tap this source of knowledge and to ascertain how the findings from APT programs can contribute and be applied to research and practice. For this report, accelerated pavement testing was defined as the controlled application of wheel loading to pavement structures for the purpose of simulating the effects of long-term in-service loading conditions in a compressed time period.

APT programs have been active for many years and although it would be feasible to focus on all historical programs, it was considered more appropriate to focus on the programs specifically operational during the past 20 years. During this period, pavement engineering advanced considerably, resulting in the establishment of many new concepts and improved understanding of the response and performance of pavements. This is not to say that there were not successful programs in operation before this time. Several such programs were very active during the 1960s and 1970s, and these have provided the basis for much of the more recent development. These programs were discussed in some detail in *NCHRP Synthesis of Highway Practice 235* (Metcalf 1996).

In the United States, the U.S. Army Corps of Engineers (USACE) Research and Development Center (ERDC) was already active in APT in the 1940s and currently remains active. Washington State University had a circular test track in operation in 1967, which was active until 1983 and was among the first full-scale APT facilities worldwide. The Pennsylvania Transportation Institute was active from 1971 to 1983. The South African program is another prime example, one that has endured since 1971 after having been inspired by the work of the USACE. Their technology has spread to other continents, notably Europe and the United States. The APT program of the Transport Research Laboratory Ltd. (TRL) (formerly Transportation Road and Research Laboratories) in the United Kingdom dates back to 1963. A new linear test machine was installed in 1984 and the program remains active. The Australian APT program was begun in the early 1980s and is still very active. The Australian machine design has also been exported to APT programs elsewhere, including China and the United States. The last major program dating back to this period is that of France's Roads and Bridges Research Center (Laboratoire Central des

Ponts et Chaussées in Nantes—LCPC). The LCPC program, highly successful with extensive research studies and strong interaction through partnering with industry, is still active.

Currently, APT programs are globally distributed, providing a sound basis for cooperation in analysis and synthesis. These programs vary from small efforts that have focused on specific topics to comprehensive multifaceted ones. The latter are multiyear programs with strategic plans that cover a wide range of topics. In 1999, an international conference on APT was held in Reno, Nevada, which provided a platform for debate and communication on a wide range of aspects of the various APT programs. Mahoney (1999) gave an overview of the historical development of APT in his keynote address. At the close, Hugo (1999) presented a synthesis of the conference and a perspective that provided some insight into the wide-ranging scope of the APT programs. Substantial detail about the different aspects of the respective programs was presented, which was helpful in structuring this synthesis report.

It is important to understand that APT is a facet of pavement engineering that generates knowledge over a wide spectrum. Figure 1 places APT programs in context to the broad basis of pavement engineering.

APT is an activity that can stand alone and provide some insight into the performance of a pavement. However, to gain full benefit, APT programs must be supplemented with laboratory testing programs. The extent of this varies in scope, depending on the nature of the respective APT programs. In addition, environmental conditions prevalent during APT are of paramount importance, because the behavior of the materials that are being tested may be significantly influenced by the conditions prevailing during the tests. Not surprisingly, APT programs pay close attention to this aspect, particularly when the environment is not controlled.

In general, a very detailed record is kept of environmental conditions during testing. This is a necessary ingredient for analyzing the performance of a pavement. Another important aspect is the nature of the device used for testing. *NCHRP Synthesis of Highway Practice 235* (Metcalf 1996) includes an in-depth review of the devices that were in use throughout the world at that time. This provided a sound knowledge base for APT users. With this information already documented, detailed discussion was

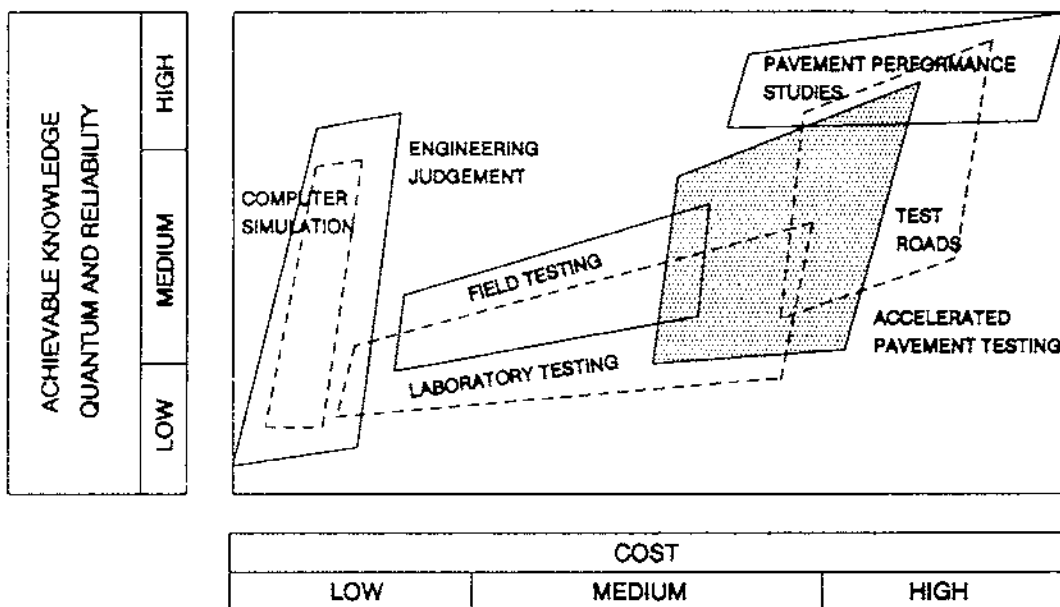


FIGURE 1 Interrelationship between pavement engineering facets that collectively and individually contribute to knowledge (Hugo et al. 1991).

not considered necessary on most of the devices that had been used by the programs reviewed in this study.

Most of the information about devices commissioned after the publication of the earlier synthesis was collected as part of this study and relevant details are provided elsewhere in this synthesis report.

A similar study is currently underway in Europe under the acronym COST 347, the Co-operative Science and Technology study program of the European Community (Hildebrand et al. 2001). There is some overlap between COST 347 and this synthesis study. However, the scope of COST 347 is broader; for example, it includes scaled APT. It was apparent that there was scope for cooperation and indeed collaboration to warrant linkage between the two programs. Accordingly, APT users in the European community were encouraged by COST 347 to respond to the questionnaires that had been made available globally.

SCOPE OF THE STUDY

The scope of this study was designed to capture significant findings from full-scale APT, which is defined as the application of wheel loading, close to or above the legal load limit(s) to a prototype or actual, layered, structural pavement system (Metcalf 1996). The intent of the APT is to determine pavement response and performance under a controlled, accelerated accumulation of damage in a compressed time period. Accordingly, full-scale test tracks and roads, for example, the Minnesota Road Research Project (Mn/ROAD) were

included. However, experimental road sections such as those from the LTPP studies were excluded, except where they form an integrated part of an APT program.

The objective was to document and summarize the significant findings from the various experimental activities associated with full-scale accelerated pavement tests. More specifically, the focus was on reported findings and their application to research and practice.

This synthesis includes an overview of the nature of APT as described by the various APT users. It also discusses the various applications that have been reported, with comments on factors that affect pavement performance under APT.

The synthesis includes a review of the wide range of ancillary tests that have been used in conjunction with APT, both in the laboratory and in the field. The singular prerequisite was that such testing had been done as an integral part of the full-scale APT program. It is apparent that this covers a wide range of tests, including Strategic Highway Research Program (SHRP) testing and a wide variety of laboratory tests. It also includes trafficking and wheel tracking tests, but only insofar as such tests have been used in conjunction with full-scale APT.

INFORMATION COLLECTION

The proceedings of the 1999 conference in Reno, Nevada, on APT (International Conference on APT 1999) served as a point of departure for a comprehensive literature review.

A variety of other sources of information were explored, especially the bibliography contained in *NCHRP Synthesis of Highway Practice 235* (Metcalf 1996). An extensive questionnaire was used to capture detail that was unpublished. It also provided an avenue for obtaining first-hand responses to questions relating to operational matters and viewpoints on significant findings.

The questionnaire was initially distributed in North America and, shortly thereafter, internationally, to capture the APT scene as widely as possible. It was drafted to provide information at three levels, with the intent of allowing the respondents the freedom of deciding to what depth they were able and willing to respond to the questionnaires. The full questionnaire is contained in Appendix A.

Figure A1 in Appendix A sets out the framework that was used to develop the synthesis report. The relationship between the various elements is also shown. In essence, the primary objective was indicated to be the improvement of performance and economics of pavements.

ANALYSIS OF THE QUESTIONNAIRES

The response to the questionnaire was very satisfactory, both nationally and internationally. A list of the respondents is included in Appendix B.

The questionnaires contributed significantly toward the synthesis as a result of the detail of the respective responses, which provided invaluable information on a variety of aspects of the APT programs. This information was reviewed, analyzed, categorized, and incorporated into the report in the following ways:

- Graphical presentations reflecting answers to pertinent questions,
- A summary of views of APT users on significant findings from their programs, and
- Compilation of a categorized bibliography on the topics related to the significant findings.

Graphical presentations on the response to specific questions are shown in Appendix C. The graphs have been structured to convey the information gathered in two ways. In the first instance the responses have been stacked in bar chart form to give an indication of the extent of the response to each question. At the same time, acronyms have been included as an integral part of the respective bars in the graphs to identify the respondents, providing insight into the geographic distribution of the responses. It also serves as a contact point for further communication on a personal basis, if required. The summaries of views of the respondents were compiled relative to the following topics:

- Evaluation, Validation, and Improvement of Structural Designs;
- Vehicle–Pavement–Environment Interactions;
- Evaluation of Materials and Tests;
- Enhancement of Modeling in Pavement Engineering;
- Development and Validation of Rehabilitation, Construction, and Maintenance Strategies;
- Pavement Engineering Applications and Issues; and
- Improvement of Pavement Economics and Management Through APT Applications.

These views were considered to be important, because they are related to the direct experience of the users and their application and use of significant findings. The questionnaires also contained categorized references submitted by the respondents, which were used to compile an annotated bibliography (this is discussed further in chapter seven). Where appropriate, responses to the questionnaire have been included in the body of the report.

The following general observations on APT programs were made from the analyses of the questionnaire. It should be noted that this should be read in conjunction with all of the components that have been included in Appendix B.

- A total of 48 responses were received, 35 from the United States. The others were from Europe, South Africa, New Zealand, Australia, and China.
- Twenty-eight of the programs reported that they were active, with 15 of these in the United States. Seven facilities are understood to be active elsewhere internationally, but no survey responses were received from them.
- The nature of the APT programs is such that they cover all aspects of pavement engineering. This is not surprising, particularly because as was indicated earlier, the APT programs invariably are linked to both field and laboratory/ancillary testing. It is also evident that software development is taking place in conjunction with APT programs, specifically as far as it pertains to modeling (see Figure C2 and chapter five).
- Although many of the APT machines are mobile, by far the largest number of tests take place at fixed sites (as can be seen in Figure C3). Furthermore, the tests are normally conducted on specially constructed test pads.
- The majority of the devices can traffic unidirectionally and bidirectionally. A small number of the devices can only traffic unidirectionally.
- Figure C5 shows the extent of the programs. It can be seen that each of the seven programs reported having tested more than 50 sections.

As mentioned earlier, details about recently commissioned APT programs were obtained through responses to

the questionnaire and, in some cases, personal contact. This information is presented in the next section.

ACCELERATED PAVEMENT TESTING PROGRAMS INTRODUCED SINCE 1996

In this section, a brief overview is given of APT facilities that have been commissioned since 1996. Of these new facilities, 90% use linear trafficking devices. Salient features and test capabilities of the new APT facilities are summarized in tabular form in Appendix E. More information, including test capabilities, can be found on the websites that are cited in Appendix B.

Federal Aviation Administration, New Jersey

The establishment of the Cooperative Research and Development Agreement between the Federal Aviation Administration (FAA) and Boeing in 1999 is an excellent example of partnering. It resulted in the construction of the National Airport Pavement Test Facility (NAPTF). This facility allows for the testing of rigid and flexible pavements by simulated undercarriages of aircraft weighing up to 591 000 kg. The 5340 kN Pavement Testing Machine spans two sets of railway tracks that are 23.2 m apart. The vehicle has adjustable dual-wheel loading modules. The load is applied to the wheels on the modules through a hydraulic system.

The design of the NAPTF was primarily based on the newly developed pavement design procedures for the latest generation of large civil transport aircraft. Of particular concern was the interaction between the loads of the multiple wheels and the close spacing of wheel bogies (trucks) that will be used on these aircraft. This has a direct impact on the subgrade in flexible pavements. Test sections vary in size depending on the test plan. A number of initial tests have been conducted since the inauguration of the facility in 1999 and these will be discussed later.

Florida Department of Transportation

Florida's Accelerated Pavement Testing and Research program was established in 1999 to test highway pavements. It is located in a new state-owned research park in Gainesville. The loading facility is a Heavy Vehicle Simulator (HVS) Mark IV model, with an automated transverse laser profiler. The load can be varied sinusoidally to simulate dynamic loading. During testing, the pavement temperature can be controlled within the range of ambient to 70°C to simulate in-service loading conditions. The current test site has 8 linear lanes, each being 45 m long and 3.6 m wide. Two additional test lanes have been designed with water table control capability within the supporting base and subgrade layers.

Kansas State University Facility

The Kansas State University facility was established in 1997 and is financed through contributions to the Midwest States Accelerated Pavement Testing Pooled Fund from the departments of transportation (DOTs) of Iowa, Kansas, Missouri, and Nebraska. The facility consists of a test frame in which a bogie with dual wheels can move forward and backwards while a load is applied by means of two main longitudinal girders. The frame span is approximately 12.8 m long. At the end of the travel distance, an energy absorption and release system transforms the kinetic energy of the carriage into potential energy in the springs; the springs are used to launch the bogie in the opposite direction. The wheel assembly consists of a tandem axle with air suspension bags. The wheel assembly is an actual bogie from a standard truck. Loading of the axle is achieved by varying pressure in the suspension system. It is possible to achieve simulated one-way traffic through a hydraulic pump that can lift the wheels off the pavement surface.

Tests can be conducted on two test pits. The wheel paths are fixed with widths depending on the selected wheel configuration. The temperature of the pavement can be controlled within the range of -10°C to 45°C .

Ohio Research Institute for Transportation and the Environment

The Ohio facility was constructed in 1997 as a joint venture between Ohio University and Ohio State University, through a grant from the Ohio Board of Regents. The facility has a rolling wheel load mechanism operating between two suspended steel girders spanning along the length of the test pit. It can be positioned at any selected transverse position for testing with optional random lateral wander.

The facility contains a test bed 13.7 m long \times 11.6 m wide \times 2.4 m deep. This is equivalent to two standard highway lanes with 1.2 m and 2.4 m shoulders. The pavements that can be constructed in the pit can be tested with dual or single wide-base tires at loads of 134 kN under controlled environmental conditions. The test pit and wheel load apparatus are enclosed in a room where the temperature can be maintained between -12°C and 54°C . Large doors allow for standard construction equipment to be used to build the test pavements in the pit.

Test Track of the National Center for Asphalt Technology, Alabama

The National Center for Asphalt Technology (NCAT) test track is another prime example of partnering between industry and government for the purpose of improving the

quality of flexible pavement performance. Apart from state and federal partners, industrial partners included material and equipment suppliers. A unique approach was adopted for financing the test pavements, with each of the individual sections being sold to a user agency. The main purpose of the facility is to test pavements by using conventional truck trafficking without any environmental control. The project was launched in 1996.

In the first phase of the program 10 million equivalent single-axle loads (ESALs) were applied in 24 months, with rutting as the expected form of distress.

The closed oval loop test track has two standard 3.4 m lanes and inside and outside shoulders of 1.2 m and 2.4 m, respectively. The outside lane was trafficked, although the inside lane has been reserved for control purposes and APT-related testing. The 46 test sections were trafficked by four conventional manned trucks, each towing triple trailers. The trailers were previously used in the WesTrack test system in Nevada. Each train consists of a lead single-axle semi-trailer followed by two single-axle trailers providing a total of 10.3 ESALs per pass. Each axle of the vehicle train is loaded to 89 kN except for the front axle of the tractor, which has a load of 53.4 kN. An alignment schedule was developed to counter the effect of perpetually right-directed tangential accelerations caused by track geometry.

Trafficking was completed on December 17, 2002. None of the 46 sections tested developed ruts greater than 12 mm despite the expectation that some would occur during 2002. Some minor overlay work was done in the western loop for safety reasons.

The individual axle load of the trucks was limited to 88 kN, while the gross vehicle weight was approximately 69 t. Truck and equipment maintenance was done once a week when trafficking was stopped. Rut depths were captured with a laser profiler and smoothness and surface texture were measured weekly in each wheel path. Structural integrity was measured by a Falling Weight Deflectometer (FWD). Compaction was monitored using a nuclear density gauge and an impedance density gauge.

University of Illinois/Advanced Transportation Research and Engineering Laboratory

In 2000, the Advanced Transportation Research and Engineering Laboratory developed the Accelerated Transportation Loading System (ATLaS) with funding from the Illinois DOT and the state of Illinois to evaluate multiple transportation support systems.

The wheelcarriage of ATLaS can be fitted with single or dual wheels used for highway trucks, an aircraft wheel, or

a single-axle rail bogie. The structural gantry is mounted on four crawler tracks to facilitate positioning of the device. The ATLaS transmits load to the pavement structure through a hydraulic ram attached to the wheel carriage. Loading can be unidirectional or bidirectional. A movable structure is used to protect the ATLaS from the environment, which also minimizes environmental effects (temperature and moisture) on the pavement.

The ATLaS is long enough to extend over six joints of a jointed concrete pavement test section. The initial test program for the ATLaS concerns continuously reinforced concrete pavements.

U.S. Army Corps of Engineers Research and Development Center—Cold Regions Research and Engineering Laboratory, New Hampshire

The test device at the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (ERDC–CRREL) is a modified HVS Mark III. The modifications include increased speed capability, automatic and manual controls, and an electric motor to drive the test carriage. The modified device, referred to as the HVS Mark IV, was acquired in 1997, and can accommodate dual truck tires, a single truck tire, or a C141 aircraft tire. The load can vary between 20 kN and 111 kN on super singles or duals and up to 200 kN on C141 tires. Speeds can reach 13 km/h, which yields 700 load applications per hour in a unidirectional trafficking mode. The wheels wander up to 900 mm in increments of 50 mm. The transverse load distribution can be programmed as desired. The maximum lateral wander is 1 m. The study is funded by the FHWA.

The facility is housed in an environmentally controlled building with a battery of test cells, each of which is 6.5 m wide × 7.6 m wide × 3.7 m deep. The water table can be varied in the test cells, and the ambient air temperature can be controlled. Six freeze–thaw cycles can be simulated in a calendar year. Test sections are 6.1 m long and 1.8 m wide.

U.S. Army Corps of Engineers Research and Development Center—Geotechnical and Structures Laboratory, Mississippi

An accelerated trafficking device to simulate vehicle and aircraft trafficking on pavement sections was inaugurated at the U.S. Army Engineer Research and Development Center—Geotechnical and Structures Laboratory (ERDC–GSL) site in December 1998. The mobile and automated device is a HVS–aircraft Mark 5, and has been nicknamed Bigfoot. Simulated trafficking ranging from single and

dual vehicle tires to single to twin aircraft tires can be applied. The load range is 45 to 445 kN.

The trafficking device is self-propelled (mobile), allowing movement between adjacent test sections, and portable, allowing transport to field sites. An environmental chamber can be fitted to control pavement temperature from -5°C to 45°C . Trafficking can be uni- or bidirectional, with up to 15,000 passes per day in the bidirectional mode. Test sections are $3\text{ m} \times 12\text{ m}$. Trafficking can be channelized or normally distributed.

Technical Research Center of Finland, the Finnish National Road Administration, and the Swedish National Road and Transport Research Institute (HVS–Nordic), Sweden, and Finland

Finland and Sweden have a joint APT program operating a HVS Mark IV. The device is jointly owned by the Technical Research Center of Finland, the Finnish National Road Administration, and the Swedish National Road and Transport Research Institute (VTI). The Swedish National Road Administration provides support to VTI to cover its share of the capital cost. The HVS–Nordic (a linear full-scale accelerated pavement testing machine) was initially located in Finland in 1997 and 1998, and then in Sweden from 1998 through 2000. In Finland the machine is located at the Technical Research Center and in Sweden at VTI. The budget for the period from 1994 through 2001 was set at a value of FIM 45 million [approximately \$17 million US (1994)]. The loading wheels of the HVS–Nordic can be dual or single with standard or wide-based tires. The lateral movement is $\pm 750\text{ mm}$ and the wheel load can be varied between 20 kN and 110 kN with speeds up to 15 km/h. The HVS–Nordic is unique in that it is mobile with full temperature control and the loading can be varied dynamically $\pm 20\%$ sinusoidally.

CLOSING REMARKS

It was clear that the different time frames within which the various programs were operational would affect the study. There are programs that have matured greatly, and these provided an extensive source of information for this synthesis study. On the other hand, there are programs that are just currently coming on line and these have not yet produced extensive or necessarily implementable results. Nevertheless, some information on these programs has been included in the report in chapter nine for future updates.

During the last decade, there has been a sharp increase in the number of APT programs launched in the United States. In many instances, the latest programs are being developed to enable cooperative and collaborative efforts to use the various facilities that were being operated around the world.

For any agency involved in APT this report will provide insight into

- Research initiatives—ways and means of using APT facilities to enhance research into all aspects of pavement engineering, and
- Practical applications that have been successfully applied in practice toward enhancing APT or pavement engineering design and construction.

This report is not intended to provide a comprehensive review of all APT research, although it does cover a substantial portion of that research. The intent is rather to gain useful information from lessons learned and successful applications of APT findings. An index has been included to enhance the ability of readers to access this information. Readers are also encouraged to consult the extensive topical bibliography provided at the end of the report or to visit websites that have been included in Appendix B.

CHAPTER TWO

EVALUATION, VALIDATION, AND IMPROVEMENT OF STRUCTURAL DESIGNS

INTRODUCTION

This chapter discusses APT research to enhance the structural design of pavements. In structural design, the stiffness and thickness of the pavement layers are selected to ensure an adequate support structure such that the bearing capacity of the underlying subgrade is not exceeded. The chapter cites studies that were selected to present a generic overview of APT practice and research on pavement structural designs.

Structural designs form the core of pavement engineering. It is therefore not surprising that APT programs focus strongly on this topic. However, as is well known, design cannot be considered in isolation. This is because of its strong interaction with other fields of pavement engineering, such as materials and vehicle–pavement–environment interaction. The net result is that discussions on the topic must take into account the total system, and the process is often iterative to account for changes that take place over time, particularly in the case of materials. The same can be said of changes that take place in vehicle configuration. When considering designs, pavements are normally classified into two broad categories, flexible and rigid (AASHTO 1993). Conventional flexible pavements generally have a composite layered structure with some form of asphaltic material in the upper layers. Full-depth flexible pavements have one or more layers of asphalt directly on the subgrade. Nonasphaltic base and subbase courses generally consist of some type of natural material or crushed stone that may or may not be stabilized. Rigid pavements consist primarily of a layer(s) of concrete separated from the subgrade by a base course layer.

This chapter will consider the various aspects of structural design in relation to the composition of the pavement, namely AC, portland cement concrete (PCC), and composite materials. [For this synthesis, hot-mix asphalt (HMA) was considered to be a synonym for AC. Accordingly, the acronyms HMA and AC should be read as synonyms throughout the report, as appropriate.] The discussion will focus on guidelines for evaluating, validating, and improving designs with notes on possible negative features. Unconventional structures such as block pavers will be considered in chapter seven, as will ancillary aspects of pavement design.

The results from the survey questionnaire will be presented before discussing the wide variety of applications that were found in the literature.

QUESTIONNAIRE SURVEY

The responses to Questions 2.1 to 2.12 on structural composition are reflected in Figures C15 to C26 in Appendix C. This section of the questionnaire was seen as an opportunity for owners and managers to indicate how the capacity of their facilities was being deployed for APT studies. The responses were synthesized and the results are contained in the following list. The respondents' views on structural composition are presented in Table D2 in Appendix D.

- APT programs are focused on the structural performance of the pavements, as well as functional performance in a ratio of about two to one (Figure C15).
- Most of the APT work thus far has been focused on the asphaltic component in the pavement structure. This is not surprising as this material lends itself to APT. However, of equal importance, is that APT has been conducted on granular layers and concrete pavements (Figure C16).
- Figure C17 indicates that tests have focused on all forms of distress that occur in surface seals.
- Evaluation of performance of pavements with clayey, sandy, and granular materials has focused on permanent deformation (Figures C18 and C19).
- The primary and not unexpected focus in APT programs on stabilized pavements has been on cracking (Figure C20).
- In contrast, Figure C21 shows that the two major forms of distress of interest in asphalt pavements are rutting and fatigue. A few programs have also been focusing on two other important issues, namely moisture damage and stripping and aging; however, it is apparent that not much work has been done in these fields.
- Cracking is the primary form of distress examined in jointed concrete pavements in APT. Joint failure and load transfer have only been investigated to a limited extent (Figure C22).
- Four forms of distress of composite pavements have been investigated; rutting, fatigue, cracking, and debonding (Figure C23).
- For functional performance, safety and roughness were the two aspects studied most (Figure C24).
- Rutting, skid resistance, and roughness were featured most prominently in the studies on safety (Figure C25).

- Very few respondents reported studies on environmental aspects; two had studied noise and one dust pollution (Figure C26).

APPLICATIONS OF ACCELERATED PAVEMENT TESTING TO ASPHALT PAVEMENT DESIGNS

Odéon et al. (1997) reported on LCPC APT tests in which different asphalt base pavements were evaluated in terms of fatigue performance. The pavements were constructed on a fairly weak subgrade [California bearing ratio (CBR) between 5% and 10%] and a subbase consisting of 400 mm of well-graded, untreated granular material. Conventional and modified (BB), improved (GB), and high modulus (EME) AC were used for the base materials. (It should be noted that in this report “stiffness” has been used as a generic term. It should be read as a synonym for modulus and stiffness modulus.) These high-modulus ACs are typically constructed on very stiff subbases, and the researchers found that the high-modulus asphalt mix, in particular, was very sensitive to thickness, especially when placed on a deformable subbase. Increasing the thickness of the EME from 90 to 110 mm increases the fatigue life 2.5 times; however, rapid degradation of the EME base was apparent with the onset of cracking. Under carousel (circular) loading, modified base pavements outperformed conventional pavements.

Harvey et al. (2000) tested pavements conforming to California DOT (Caltrans) specifications. Pavements tested included those with Asphalt-Treated Permeable Base (ATPB), termed “drained” pavements, and those with standard aggregate bases, termed “undrained.” HVS tests have confirmed that the total pavement thickness developed using the Caltrans pavement design procedure is generally adequate to prevent rutting through permanent deformation of the subgrade and unbound granular layers. Fatigue cracking of pavements for higher traffic levels with weaker subgrades is a concern. They point out that innovative pavement designs such as the “rich bottom” (high binder content) concept or the use of modified binders significantly improve fatigue performance of pavements compared with conventional designs. The use of higher binder contents in the lower structure of the pavement is deemed feasible given that deformations and stress levels under loading are greatly reduced with depth. Rut resistant mixes must be used in the “critical zone” for rutting, found to be within 100 to 150 mm of the pavement surface (Harvey et al. 1999).

The use of drainage layers (ATPB) in pavements has led to stripping incidents where water may remain trapped within the pavement system because of faulty edge and transverse drains. As an alternative to ATPB, Harvey et al. (2000) recommended that standard asphalt base layers be used. In addition, they emphasized the need for adequate compaction (less than 8% voids in the mix after construc-

tion) to reduce permeability. They also proposed that the thickness of these layers be increased to delay the initiation and propagation of cracking. This approach may be further improved by the use of a rich bottom layer. They noted, however, that drainage layers may still be required to remove water seeping into the pavement from the subgrade. If ATPB layers are required, then the California researchers suggest the use of higher binder content, modified binders such as asphalt rubber, and additives such as lime or anti-stripping agents. Geotextile filters should be used to prevent clogging of the ATPB layer and maintenance practices for cleaning edge and transverse drains should be in place. They further recommended raising the “gravel factor” for ATPB from the current 1.4 to 2.

Kekwick et al. (1999) outlined the influence of the SA–HVS program on pavement design philosophy. In South Africa, HVS testing has been used to validate the performance of well-balanced, deep pavement structures. These pavements are constructed with materials such that there is a gradual decrease in stiffness with depth in relation to the bearing capacity of the respective layers. HVS testing has demonstrated that poorly balanced, shallow pavements, where most of the stiffness of the structure is concentrated at the top of the pavement, are normally load sensitive. These types of pavements may appear to have adequate bearing capacity but deteriorate rapidly under overloaded conditions. However, they warn against increasing the test wheel load to levels far above those of the standard design load. This may induce failure mechanisms that will never manifest under normal traffic loading conditions, especially in the case of bound layers.

The SA–HVS testing program has been instrumental in the development of the South African Mechanistic Design Method for Pavements (Theyse et al. 1996). It is an example of how APT can benefit pavement engineering overall. They discuss how HVS test results were used to develop transfer functions for the mechanistic–empirical modeling of the permanent deformation of unbound pavement layers in pavements with asphalt and granular base layers as well as granular and stabilized subbase layers. This method was applied to establish standard pavement structures for use in different climatic regions of South Africa and different levels of design traffic. These standard pavement structures are cataloged in manuals for implementation by the road industry and have, over the years, been validated and refined in the field using HVS testing. The significant amount of data collected during HVS testing of numerous types of pavement structures has allowed confidence limits to be established to assess the reliability of design methodologies (*Structural Design of Interurban and Rural Road Pavements* 1980, 1985, 1996).

Sharp et al. (1999a) reported Accelerated Loading Facility (ALF) tests on a test section with a high bitumen content

(0.5% above optimum) mix in the lower base that did not show excessive deformation in that material. This indicated that these layers could be used in thinner asphalt structures than previously thought necessary and/or that the addition of more bitumen was possible to further improve fatigue life. ALF testing was used to validate fatigue transfer functions for asphalt and cement-treated crushed rock (CTCR) in the Austroads Pavement Design Guide (Austroads, formerly NAASRA—the National Association of Australian State Road Authorities). These are primarily based on empirical relationships derived from overseas data (e.g., Shell) and field-performance data.

Hugo et al. (1999c) reported on Texas Mobile Load Simulator (TxMLS) tests completed in Victoria, Texas, to evaluate the widely used district pavement design using local siliceous river gravel flexbase with thin asphalt surfacing. They reported that high construction variability and high asphalt void content led to early fatigue failure of the AC in the test sections. Stabilizing subgrade layers enhanced the structural capacity of the pavement. Deep-seated variability in the pavement foundation, however, influenced its performance, and lenses of poor materials affected the pavement surface profile.

Bhairo et al. (1998a,b) reported on LINTRACK (a full-scale HVS for APT) experiments that evaluated the fatigue performance of two full-depth asphalt pavements with varying asphalt thickness on a sand subgrade. One of the structures had a total asphalt thickness of 150 mm consisting of two layers, an 80-mm bottom layer and a 70-mm top layer. The second structure had a single 75 mm layer. For the thinner structure, LINTRACK loading led to structural fatigue cracking in the asphalt (bottom-to-top) and surface cracking (top-to-bottom). The researchers concluded that the Shell subgrade strain criterion appeared to be very applicable for subgrade sands as used in The Netherlands.

Addis (1989) reported on trials undertaken in the Pavement Test Facility at the TRL to evaluate the relative performance of dense bitumen macadam (DBM) and heavy duty macadam (HDM). In general in Great Britain, macadam consists of a high-quality aggregate with large, single-sized particles (37–53 mm), which is stabilized by filling the voids with a suitable material. Typically, the macadam is defined more specifically in relation to the material used for filling the voids; for example, waterbound macadam has a filler of natural material with a low plasticity, whereas slurry-bound macadam has a filling of slurry. The research team reported that the results of the accelerated tests showed little difference in the overall performance of the two materials. The initial rate of rutting of the materials was different, that of the HDM being lower than the conventional DBM. The team found, however, that the HDM generally weakened more under the influence of very heavy wheel loads. They concluded that both the ob-

served and measured variability in the compacted quality of the bituminous materials, in particular that associated with the HDM, could have been a major contributor to some of the later life performance differences.

APPLICATIONS OF ACCELERATED PAVEMENT TESTING TO CONCRETE PAVEMENTS

Caltrans testing of concrete pavements (Harvey et al. 2000) has indicated the importance of the use of dowels and non-erodable bases for heavily trafficked, jointed concrete pavements. The Caltrans researchers point out that dowels are effective in restricting the curling of concrete slabs along transverse joints. In the same way, tie bars were found to be useful in restricting curling along longitudinal joints. They suggest seeking higher than currently required flexural strengths together with material having low coefficients of thermal expansion to reduce the thickness of concrete slabs.

Harvey et al. (2000) further stated that shorter slab lengths are required for high-shrinkage hydraulic cement to prevent premature top-to-bottom cracking in the slabs. Furthermore, they suggest that joint spacing requirements be made a function of climate. According to Roesler (1998), joint spacing should be less than 4 m for a slab thickness of 200 mm. From the same test program, Roesler et al. (1999) reported that the performance of fast-setting hydraulic cement concrete (FSHCC) pavements was very similar to that observed for PCC pavements.

Vuong et al. (2001) reported on plain concrete pavements tested using the ALF at Goulburn, New South Wales in Australia. Four pavements were tested to assess fatigue performance, and five pavement sections were tested to assess erosion performance. The site chosen had a high diurnal temperature change, on the order of 20°C, which produced significant interaction of loading and slab curl. The influence of dowels, shoulder ties, and slab thickness (150 mm, 175 mm, and 200 mm), as well as erosion of unbound and bound subbases, was investigated. Erosion was investigated by wetting of the pavement before and during trafficking. Because of the effect of the shading of the pavement under the ALF on curling of the concrete slabs, conventional (rigid) trucks were also used to evaluate loading response. The following findings are relevant to structural design:

- No fatigue failure had been induced in the concrete slab after 170,000 load applications of an 80-kN ALF axle load.
- When a slab 150 mm thick with undoweled transverse joints was tested with ALF 40-kN, 60-kN, and 80-kN dual-wheel loads, the movement at the center of the slab was the same for all three wheel loads.

However, when an 80-kN standard axle was introduced using a rigid truck, movement at the slab center was six times greater than that produced by ALF. This reflects the importance of slab curl, and the effects of pavement shading and loading configuration.

- Deflection data showed that slabs lost support at the corners and edges during the night and at the center of the slab in daytime because of curling.
- The presence of tied shoulders significantly reduced the curling behavior of the slab during the night (up to 80%).
- The presence of dowels in transverse joints significantly reduced curling behavior, which raised slab centers during the daytime and hence loading deflections (up to 47%); however, the dowels allowed higher movement at corners without a shoulder during the night.
- Increasing slab thickness reduced curling of the slab during the daytime and hence reduced bending stresses.
- Deflections under load increase rapidly for a slab in a curled state until contact is made between the base and subbase, whereupon there is little further increase.
- For slabs with and without dowels, erosion occurred in the subbase of unbound granular material. This material is unsuitable for subbases under plain concrete pavements subjected to heavy loading.
- A very small amount of erosion occurred in a heavily bound subbase of a concrete pavement without PCC pavement dowels.
- Erosion did not occur with a lean mix concrete subbase, and there was no clear evidence of erosion in a heavily bound subbase with dowels. Lean mix concrete subbase and heavily bound subbase with dowels may be suitable for plain concrete pavements subjected to heavy loading.

Vuong et al. (2001) emphasized that for APT testing of concrete pavements consideration must be given to long-term environmental effects and the possibility of fines moving between the base and subbase, which may change loading stresses arising with slab curl. Draining of this interface is considered essential. They concluded and recommended that

- Tied shoulders need to be retained in pavement design,
- A minimum slab thickness to reduce curling and the effects of curling on pavement performance needs to be specified for pavements subject to heavy loading, and
- Unbound subbases are unsuitable under plain concrete pavements subject to heavy loading.

Balay et al. (1992) reported on LCPC APT tests on concrete pavements aimed at validating the thickness designs

in the French design catalogue of new pavement structures. The goal was to determine whether three concrete pavement structures proposed in the French design catalogue were equivalent with regard to their performance under traffic. The following three structures from the catalog were tested:

- Short slabs with dowels built on a treated subbase,
- Short slabs without dowels built on a treated subbase, and
- Short slabs built on an untreated subbase.

For the third structure, slabs with normal and lean concrete (300 kg/m^3 cement vs. 140 kg/m^3) were tested. A comprehensive paper on the numerical analysis of the test track was presented by Balay and Goux (1994). They concluded that the APT results accurately reproduced modes of functioning and distress of actual concrete pavements. They found that the functioning of the pavements was reproduced sufficiently realistically through their Finite Element (FE) analysis to be useful.

Failure of the pavements was characterized by cracking, joint failures, and pumping of fines. As expected, the slabs with dowels built on the treated subbase performed the best. The lean concrete slabs on the untreated subbase failed completely halfway through completion of the tests, necessitating repair. Strengthening of the subbase significantly improved the performance of the concrete pavements. The researchers found that the thickness of some standard designs could be reduced slightly when the sub-surface conditions were favorable. This required good efficient drainage with a nonerodible soil surface under the concrete slab. Paved shoulders were also considered necessary.

A number of tests have been completed at the NAPTF facility in Atlantic City, New Jersey. Guo and Marsey (2002) presented some important details relating to the effect of curling of the slabs that need to be taken in to account during APT.

- Measured deflections at the center of the slab remained effectively constant, whereas the deflections at the joints and corners varied significantly during testing.
- Deflections at joints and corners are significantly larger in winter compared with summer. Joint load transfer capability was also lower in winter.
- Analysis indicated that slabs were always curled up in winter and this was more significant on a stronger subgrade.
- The sum of deflections on both sides of joints, remain almost unchanged when traffic direction is reversed. However, sides of joints vary significantly from summer to winter.

APPLICATIONS OF ACCELERATED PAVEMENT TESTING TO COMPOSITE STRUCTURES

HVS testing has been instrumental in validating the effectiveness of inverted pavement structures, which are now used extensively throughout South Africa. These structures incorporate stabilized or lightly cemented (<4%) subbase layers that provide support to granular or asphaltic base layers. The stiffness of these stabilized subbase layers, while intact, are higher than that of the base layers. This allows adequate compaction of the base layer, and in the case of asphaltic base layers, reduces the development of horizontal tensile strains beneath the layer, hence extending the fatigue performance of the pavement structure. In the case of high-quality granular bases, the stiff subbase layer confines the base, and this “sandwich” effect has been shown to significantly increase the shear strength of high-quality granular bases. The influence of climate as well as traffic level is accounted for in the structural design of pavements.

Further validation of this phenomenon was reported by Gramsammer et al. (1999) in France and Harvey et al. (2000). The APT tests at LCPC in France were done to determine the optimum thickness of the unbound granular material on top of a cemented subbase and below the asphalt surfacing layers. A specific optimum thickness was not reported.

The Australian Road Research Board (ARRB) (Sharp et al. 1999a) reported on ALF tests aimed at the evaluation and improvement of structural designs. Testing included trials to investigate the influence of thickness on the performance of CTCR pavements constructed to similar standards. Pavements with CTCR layers of 200 mm and 300 mm were tested. These experiments were complemented by the testing of similar pavements with and without a bitumen heavy-cure coat interlayer and a section constructed in one lift instead of the usual two or three lifts. ALF testing confirmed that the typical failure mode was the result of the debonding of the CTCR base layers, followed by the ingress of water at the interfaces and the subsequent erosion of the bottom of the upper layer, leading to a failure of the top layer. As a result of these tests, construction practice was changed to allow the construction of cement-treated bases in single layers rather than in multiple lifts.

ALF testing programs were undertaken to evaluate the in situ stabilization of marginal sandstone material. The importance of curing stabilized materials was emphasized. A lack of curing, especially of the slag/lime material, resulted in some drying out of the top of the bound material, and a considerable number of shrinkage cracks were observed before the application of the prime and asphalt surfacing. Crushing of the bound material was apparent under ALF loading, which led to erosion of the base and subsequent pumping of fines. In view of the results, the re-

searchers recommended that stabilized pavements required 7 days moist curing or that they be sealed immediately with an approved curing compound. Alternatively, the next layer of the pavement should be constructed to prevent excessive drying of the stabilized surface that may lead to cracking.

De Beer (1990) and De Beer et al. (1991) also reported on the performance of cemented base and subbase layers under APT. The program covered a period of 6 years. Specific failure mechanisms were identified and guidelines were developed for the use of cementitious layers in pavement structures.

Sharp et al. (1999a) reported on ARRB–ALF tests conducted to evaluate geotextile-reinforced seal pavements. Geotextiles were used to strengthen pavements with clay subgrades in regions where gravels are scarce and of low quality. They indicated that the geotextile-reinforced pavements performed satisfactorily, with little distress observed after the design traffic loading had been applied, even when testing was conducted near the edge of the pavement adjacent to a filled dam. Guidelines for the design, construction, maintenance, and management of geotextile-reinforced seal pavements were prepared and issued.

Sharp et al. (1999b) discussed ALF trials undertaken to validate the ERDC (formerly USACE Waterways Experiment Station) tentative classification scheme for lateritic gravels for road and airfield pavement construction. For these trials the APT test objectives included

- Establishing the performance of gap-graded ridge gravels and a relative measure of the performance of “good” and “poor” lateritic gravels,
- Comparing the performance of the lateritic gravels when they are constructed to two compaction levels, and
- Comparing the performance of lateritic gravels when they were constructed “full depth” (300 mm in two layers on a clay subgrade) and 150 mm in one layer on a cement-treated subbase (CTSB).

ALF testing indicated that in a dry state there was not a significant difference between the performance of the good and poor lateritic gravels. In addition, the APT testing indicated that the level of compaction was not a major factor affecting the performance of the lateritic gravels. The performance of the two full-depth lateritic layers compared with the thinner layer on a CTSB was similar. Higher deflections were apparent in the full-depth lateritic layers; however, it was suggested that this was acceptable given the cost savings inherent in constructing an unbound subbase layer rather than a CTSB.

Kadar et al. (1989) reported extensively on the performance of slag road bases under APT. Their findings indi-

cated that the blast furnace slag could be used in the place of high-quality, crushed-rock road bases. The slag and stabilized slag materials proved suitable for use as base material provided they are protected from excessive tensile stresses. The findings of the APT tests provided a sound basis for developing guidelines for the design of pavement structures with this type of material. In particular, they gave insight into the manner in which the structural behavior changes as the material characteristics change. The importance of the uniformity of the mixing of stabilized materials was again demonstrated. The researchers suggested increasing the content of the binder (blends of granulated slag and lime) used for stabilizing to improve the uniformity of the mix. The increase was not needed for strength purposes. Another problem that was identified was the negative effect that thin leveling layers had on the performance of the pavement. It was emphasized that these should be avoided under any circumstances, because they lead to delamination.

Vuong et al. (1996) reported on the Beerburum II ALF trials, which contributed to the state of the art for the design and construction of stabilized and unstabilized granular pavements. These trials consisted of 34 experiments completed in Australia, where 3 million light-load cycles were applied to each of 10 pavement types. They found that pavements with high-quality crushed-rock base layers benefit significantly from increased compaction because of the reduced influence of moisture. It was found that the degree of saturation is of paramount importance. For granular materials with low plasticity, the degree of saturation is considered to be a better indicator than optimum moisture content of the aggregate. In situ stabilization using 2% bitumen and 2% cement was found to be more effective than other treatments that had been explored as replacements for the sandstone and high-quality crushed rock. This included stabilization with bitumen only and different proportions of bitumen and cement.

Saarelainen et al. (1999) report HVS–Nordic tests done to evaluate a thawing and frost-susceptible subgrade. Three pavement structures were tested, each consisting of a thin asphalt surfacing (50 mm), a base layer of crushed rock (200 mm), and a subbase layer of sand (250 mm). In one of the structures, a reinforcing steel mesh was installed in the base layer. The subgrade was constructed using natural lean clay, referred to locally as dry crust clay. The pavement was cooled by exposure to atmospheric frost temperatures until there was a frost penetration of approximately 1.2 m. The pore pressure development was monitored. The resulting frost heave was typically about 50 to 70 mm. Before HVS testing, the pavement was thawed to a depth of 0.9 m. The decrease in pavement stiffness with thawing was confirmed using FWD testing. It was found that, with the development of rutting in the reinforced pavement, the steel mesh significantly increased

the strength of the base layer and ultimately the performance of this pavement. The moving test wheel caused fast stress pulses to the soil and this resulted in increased pore pressure.

Ruiz and Romero (1999) outlined the Spanish CEDEX APT program, the main objective of which is to improve pavement structures detailed in a pavement design catalogue. The catalogue lists pavement options depending on subgrade quality and traffic level, including flexible, semirigid (flexible with some stabilized or bound layers in the composite structure), and rigid pavements. These structures were determined based on experience and analytical design approaches. The APT facility is being used as a tool for validating the pavements in the catalogue, but also to evaluate the performance of the pavements in the Spanish road network.

The first CEDEX test evaluated two pavement options for traffic levels of 50 to 200 trucks per day and subgrades with a CBR of between 10% and 20%. One of the sections consisted of a 150-mm asphalt surfacing and base over 500 mm of granular material. The other section consisted of 180 mm of asphalt over 250 mm of granular material. The influence of thickness variations of the asphalt and granular materials were investigated. CEDEX APT testing, together with an analysis of the performance of in-service pavements, led to the elimination of the second section (180 mm) asphalt from the design catalogue. These pavements did not perform as expected. An equivalency between granular materials and asphalt mixtures was established (10 mm of asphalt mixture being equivalent to 30 mm of granular material). Subsequent testing was done to evaluate additional catalog pavement structures with different types of base materials; that is, granular, soil–cement, and gravel–cement. The influence of subgrade strength was also investigated. CEDEX testing validated the performance of the catalogue designs; all the pavements performed adequately under the conditions considered in the design. The flexible pavements exhibited cracking after trafficking was continued beyond the level to which in-service pavements would have been subjected. Pavements with cement-treated layers did not crack during the tests and performed better than flexible pavements. Pavements with soil–cement bases performed similarly to the pavements with gravel–cement layers. This was unexpected and contrary to results of the analytical design of these pavements.

Metcalf et al. (1999) discussed ALF testing done in Louisiana to evaluate nine different soil–cement base courses under accelerated loading to failure. In-place cement-stabilized select soils are the primary base material for the vast majority of noninterstate pavements constructed in Louisiana. Such pavements are usually surfaced with 90 mm of AC. Metcalf points out that factors influ-

encing the performance of these base types are nonuniform cement distribution, inadequate mixing of the cement and soil, and the high probability of shrinkage cracking. This leads to nonuniform support of the pavement, which results in isolated pavement failures and marked variability of the pavement performance. Cracking of the cement-stabilized bases generally results in block cracks at the pavement surface, which allows moisture to infiltrate the pavement structure and negates the rideability and performance. The following findings were found to be relevant:

- The crushed-stone base structure outperformed the soil–cement structure.
- All stabilized base structures failed because of softening and erosion of the materials and loss of support under the asphalt layer. Shrinkage cracks in the stabilized base generated reflection cracks in the asphalt surface layer.
- The higher cement content (10%) in the in-plant-mixed soil–cement only slightly increased the life of the structure when compared with the low cement content (4%) of the in-plant-mixed stabilized base.
- In-place-mixed soil–cement performs similar to the in-plant-mixed soil–cement.
- Plastic fibers do not significantly improve the performance of the soil–cement base.
- At the same cement content, increasing the thickness of the soil–cement improves the performance of the road structure.
- Under high moisture conditions, an inverted pavement outperforms the soil–cement base pavement, as well as the conventional flexible pavement.

Based on the findings, Metcalf et al. (1999) concluded that consideration should be given to

- The use of an AASHTO layer coefficient of 0.10 for stone-stabilized base,
- The use of the inverted pavement configuration,
- The use of thicker cement-stabilized bases with lower cement contents, and
- Ending the use of fiber reinforcement in cement-stabilized layers and of geogrids in unbound bases.

Meng et al. (1999) reported on ALF testing in China to evaluate stabilized base pavement options for heavy design traffic. The options included cement-stabilized soil, lime-stabilized soil, cement-stabilized crushed-stone, fly ash, and lime-stabilized crushed-stone bases. The stabilized base pavements tested were found to fail because of the disintegration of the surface–base interface and not from fatigue cracking of the bases. The performance of the fly ash gravel base pavement was considerably better than the pavements with cement-stabilized crushed-stone and cement-stabilized soil bases. The researchers reported that a relative thick asphalt surface over a stabilized base can

significantly improve the pavement rutting resistance. Based on these findings, they recommended that the quality of the materials and the selection of the layers be considered in the pavement design stage to alleviate the erosion of the stabilized base at the interface of the asphalt and base layers. They suggested using a waterproofing layer between the asphalt surface and the stabilized base to alleviate the effect of water on pavement failure. Furthermore, special consideration should be given to enhancing the bond between surfacing and base layers.

Núñez et al. (1999) report on APT research in Brazil on weathered basalts to reduce the costs of low-volume roads. Tests were done on pavements with weathered basalts as base and/or subbase layers. In some of the tests only weathered basalts were used as aggregate, whereas in others densely graded, sound crushed stone was included as the base layer over the basalt subbase. Two distress mechanisms that affect weathered basalts were identified; crushing in weaker aggregates and lateral displacement in stronger ones. They concluded that weathered basalts may be used as base layers for pavements of low-volume roads.

Lynch et al. (1999) discussed APT research by the USACE in Vicksburg, Mississippi. The original California Highway Department design curves for light and medium-heavy highway traffic were used as a basis for airfield design curves. The first of these curves were for 31-kN and 53.4-kN single-wheel aircraft loads. Subsequently, design curves were established for 890-kN single-wheel loads with tire pressures up to 1378 kPa. The concept of an equivalent single-wheel load also stems from this research. Accelerated tests conducted to investigate environmental effects led to refinement of the CBR design procedure to include thaw weakening.

Gramsammer et al. (1999) reported on LCPC APT tests in France to evaluate a foam-bound aggregate-graded course (cold mix) inserted between two high-modulus asphalt courses. After the application of 4.3 million 13-t axle loads, no deterioration was visible on the surface, although core boring revealed a horizontal crack within the foam-bound course a few centimeters above the bottom of this layer. Gramsammer reported that the horizontal crack was the result of shear fatigue rather than flexural fatigue.

Corte et al. (1997) reported on LCPC APT experiments designed to evaluate the fatigue performance of pavement structures incorporating hot and cold mixes. The purpose of the program was to study the behavior of cold mixes on a deformable (flexible) base. The experiments were initialized to evaluate a newly developed emulsion-bound granular material using a modified binder and a “double-coated” cold mix. Tests were also done on conventional hot-mix asphalt and an emulsion-bound material, both serving as

reference or benchmarks to compare the relative performance of the experimental materials. The bituminous materials were compacted to a thickness of 100 mm on top of a 300-mm, untreated, well-graded crushed-aggregate subbase, purposely designed to allow deformation in the base.

No rutting was observed in the cold mixes after completion of the testing. Each of the bituminous materials tested cracked, although the cracking of the cold mixes was described as being finer than that found in the hot mix. Major debonding was observed on the conventional emulsion-bound granular material and, to a lesser extent, on the emulsion-bound granular material with the modified binder. The double-coated cold mix did not debond. Gramsamer et al. (1999) concluded that for cold mixes the nonlinearity of these materials must be taken into account during mechanistic analysis and that the cold mixes manifested less cracking.

SUMMARY

This chapter has covered a number of issues related to the structural design of pavements. Structural designs are typically tested at fixed-site test facilities, whereas rehabilitation designs are usually evaluated in the field, although in a few cases rehabilitation designs are evaluated on fixed-site lanes that had previously been tested to failure.

For asphalt pavements, APT has demonstrated the benefits of using very stiff, high-modulus asphalt for bases, rut-resistant mixes in the upper structure of the pavement, and “rich bottom” layers to increase fatigue resistance, and has shown the importance of well-balanced, deep-structure pavements. For concrete pavements, the influence of thickness, dowels, and tie bars has been investigated, as well as the influence of subgrade support and curling and warping. For composite structures, the effectiveness of inverted structures has been illustrated. APT has contributed to advances in the field of stabilization of marginal materials to strengthen pavements and the use of geofabrics for reinforcement.

APT has also been instrumental in validating and refining agency structural design guidelines. In addition, improvements in structural design have been brought about by the insight gained on the effect of a number of factors on pavement performance, including

- The influence of concrete slab configuration,
- The influence of support under concrete slabs,
- The influence of water on performance and related failure mechanisms,
- The importance of bond between layers and the quantification of the effect, and
- The interaction between structural composition and material characteristics.

CHAPTER THREE

VEHICLE–PAVEMENT–ENVIRONMENT INTERACTION**INTRODUCTION**

The topic of vehicle–pavement–environment interaction is complex and probably one of the most controversial aspects of APT. Croney and Croney (1991) noted that age strengthening appears to be a major factor in the performance of well-designed pavements. Nunn (1997) also reported on this phenomenon. These effects were found to be the result of changes in the asphalt over time, which lent support to the statement by Croney and Croney (1991) that the environmental limitations placed APT in jeopardy. Differences between loading used during APT studies and conventional traffic have also led to questioning of the applicability of APT findings to the performance of conventional in-service highways.

However, during the last decade, advances have been made toward a better understanding of these phenomena. The results from research by a number of APT programs will provide evidence of this. Naturally, there are differences in the extent to which the various programs include these issues in their test plans. In subsequent chapters some case studies will be presented to illustrate how this affects design and construction, which should help APT users at large and DOTs to gain confidence in using and applying the various findings from APT programs.

Before discussing the wide variety of applications and relevant issues that were found in the literature, the results from a synthesis of the questionnaire survey is presented here.

QUESTIONNAIRE SURVEY

The responses to Questions 3.1 to 3.4 on loading and environment are shown in Figures C27 to C30 in Appendix C. These responses were synthesized, and the results are contained in the following list:

- The primary load characteristic to which performance is related is the wheel load and whether it is applied with or without lateral wander (Figure C27).
- Of almost equal importance to load is tire pressure.
- Temperature (both pavement and air) is the primary environmental element that has been related to performance (Figure C28).
- The environmental condition that is controlled most is pavement and air temperature (Figure C29).

- Of almost equal frequency of control is the subgrade moisture with related factors such as the water table and drainage.
- Most tests were conducted at moderate temperatures ($>10^{\circ}\text{C}$ and $<40^{\circ}\text{C}$) (Figure C30).

Views of respondents to the survey on loading and environment are presented in Table D3 in Appendix D.

ELEMENTS OF THE VEHICLE–PAVEMENT–ENVIRONMENT SYSTEM

The structural configuration of the pavement system is normally fixed by design or policy, including the materials that are to be used. The structural system is then subjected to the impact of traffic loading under the prevailing environmental conditions that affect its performance.

The response and performance of the pavement system is therefore subject to an array of influential factors that have variable levels of control and are time dependent to a greater or lesser degree. The following need to be considered:

- Pavement materials;
- Trafficking comprising
 - wheel loads that can be single axle or multiple axle,
 - wheel load(s) that can be static or dynamic,
 - wheel loads that wander laterally,
 - suspension systems,
 - tire pressure/contact stress,
 - tire type, and
 - speed;
- Environmental impact of
 - wind and radiation,
 - temperature, and
 - water in a variety of forms.

Clearly, the performance of the pavement is dependent on the interaction of these factors. APT programs have proven to be invaluable because of the ability to partially or fully control these factors. The synthesis of the findings from the various APT programs provides valuable insight and some useful applications, which will be considered in terms of the respective factors. The effect of materials will be considered in conjunction with the respective factors pertaining to traffic and the environment, where appropriate.

Chapter four discusses the relationship between APT and materials and tests comprehensively.

TRAFFICKING

APT programs have used both conventional trucks and a variety of vehicles for simulating conventional trafficking of pavements. The wheel loads are applied at selected static levels that may be varied according to the needs of the experiment, with or without some type of suspension. In some cases the suspension or even the undercarriage is the same as that used in conventional trucks. In addition, the devices have used wheel loads that vary from the conventional truck wheel loading to aircraft loading. The tire pressures have also been varied to accommodate both conventional and extraordinary tire pressures to explore the impact of this variable. Because of the range of variables, the findings from the different programs need to be carefully scrutinized to determine to what extent the results are comparable. Some protocols have been established and these have provided a means of limited comparison of the respective test programs.

Details of the respective APT trafficking devices in use through the mid-1990s can be found in *NCHRP Synthesis of Highway Practice 235* (Metcalf 1996). It provides an excellent overview of the trafficking devices that had been used up to that time. Some details of the latest additions to the APT scene, such as trafficking systems, mechanical functioning, loading characteristics, and test plans, are given in chapters one and eight and in Appendix E of this synthesis. In this section, the focus will be on aspects of APT trafficking that affected the performance of the pavements in experimental and related analytical studies.

Wheel Load Intensity and Load Equivalency

Wheel load intensity has by far the most profound effect on pavement performance and yet it is, to a large extent, an uncontrolled variable in real traffic. This explains the interest in the well-known “fourth power law” that dates back to the AASHO road test (AASHO 1961). Understandably, APT programs are increasingly focusing on this aspect as test capabilities improve in their sophistication. It had been reported that the relationship of load with performance was neither constant nor linear. The so-called fourth power law was found to be exponential and highly dependent on the thickness and configuration of the layer(s). In addition, it depends on whether the axle has a suspension, on the type of suspension, and on the degree of smoothness of the pavement surface. Some relevant studies are discussed here.

In 1989, the Organization for Economic Cooperation and Development (OECD) undertook a full-scale pave-

ment test in France at the circular fatigue test track of the LCPC in Nantes. The primary purpose of the test was to assess the relative damage of the maximum legal axle loads of 15 European countries, in comparison with the 11.5-t axle load that was to be the future standard axle load in the European Union (Gramsammer et al. 1999). Because of the many factors that affect performance, Gramsammer et al. (1999) are of the opinion that APT was the only means of coming to a quantitative solution that would be acceptable to all parties concerned.

A report on the joint test program that became known internationally as the FORCE project was published in 1991 (OECD 1991a,b). The findings were also discussed at a 1991 conference in La Baule, France (OECD 1992). For the analysis of the comparison of the 10- and 11.5-t axle loads, relative damaging effects were calculated in terms of cracking and rutting performance, and on the basis of response measurements. The damage exponent was determined separately for rutting and cracking. The report concluded that the fourth power law constitutes only a general description and approximation of relative damage owing to axle loads.

For the rutting, the thin asphalt (67 mm) flexible pavement had an exponent of 5.74. The value for the thick asphalt (140 mm) pavement was 2.88 and the semi-rigid pavement (170-mm cement-treated gravel base with a 63-mm surface layer of asphalt) had a value of 1.47. The exponent decreased with increasing stiffness and the thickness of the bituminous layer.

The cracking evaluation was limited to the flexible pavements because of the lack of deterioration in the cement-treated pavement structure. The exponent varied between 1.8 and 9 depending on the degree of deterioration, the criterion used for comparison, and the condition of the pavement at the time of comparison based on cracking of the thin asphalt section. The exponent increased linearly with the degree of cracking up to a level of 400,000 load applications. Thereafter, the rate of increase gradually reduced. Crack distress was defined as crack length per 100 m (linear) of pavement. The report points out that 25% to 30% of cracking at the FORCE experiment yields an exponent varying between 2.7 and 4.3 on the basis of 60–100 m/100 linear meters of an in-service pavement. The necessity of qualifying the degree of cracking in the pavement is apparent. It should be noted that there was little deterioration in the cement-treated pavement structure for the number of axle load applications that had been applied at the time. Nor was there any significant cracking in the thick asphalt. The exponent applicable to the semi-rigid pavement structure was expected to change as the layer deteriorates if and when further trafficking is applied.

A number of participating countries with APT facilities such as the United States, Spain, Switzerland, and Finland,

undertook studies that would serve as “cross-tests” for the tests that were conducted at the LCPC track in France. The purpose of the cross-tests was to promote international cooperation toward more effective use of large and expensive facilities. The intent was, among others, to conduct the tests on the basis of the specifications and procedures used for the tests in France. Axle loads of 10 t and 11.5 t were used with single and dual tires. The results of the various cross-tests did not correspond directly with the findings from the LCPC test track. This was ascribed to differences in pavement configuration, material characteristics, subgrade strength, climatic conditions, and the type of test. Some examples are discussed here.

Kenis and Lord (1992) reported on FHWA participation in a cross-test. The performance of the FHWA ALF test differed significantly from that in France in terms of both rutting and cracking. Furthermore, the findings were not consistent. In the case of the thin asphalt, the OECD pavement performed poorly when compared with the FHWA test, whereas the reverse was found in the case of the thick asphalt. In a cross-test conducted in Finland (Pihlajamäki 1992), the thick asphalt and semi-rigid pavements were tested to 7 million applications of a 25-kN single-wheel load without serious distress. Thereafter, subgrade conditions were artificially changed to accelerate distress by adjusting the water table. The first cracks manifested after 11 million applications. Distress was primarily in the form of rutting. The performance was better than the test at the LCPC track, which was terminated after 13.5 million load applications. In Switzerland (Scazziga et al. 1992), the thin asphalt pavement performed as well as the thick asphalt pavement at the LCPC track. One reason for this was thought to be the difference in subgrade bearing capacity. Romero et al. (1992) reported on a cross-test in Spain. The cracking and rutting damage exponents from this cross-test once again differed from the LCPC test results for the thick asphalt pavement test. For example, in the case of the 11.5-t versus the 13-t axle loads, the exponents were greater than 12. In the light of these findings it is understandable why it was concluded in the report that cross-tests were misnomers and that they were more correctly *comparative tests on a qualitative basis* (OECD 1991).

Núñez et al. (1999) reported on APT studies of sound, weathered-basalt gravel base pavements with thin surfacings in Brazil. The Load Damage Equivalency exponent was found to be four. Soil moisture was monitored with jet-fill tensiometers. This provided valuable information on the variance of subgrade modulus. This topic is discussed at greater length later in this report.

Hugo et al. (1997) reported on tests with the TxMLS in which the damage exponent in terms of rutting of a pavement comprising 75 mm of asphalt on a 150-mm cement-treated siliceous gravel base course was found to be as

high as 7. Freeme (1984) reported damage exponents that had been determined for rutting in the SA–HVS program for different pavement structures. For pavements with granular layers, the values varied between 2 and 4. For thick asphalt layers, the exponent was 4. Overall, the loading exponent varied between 2 and 6, depending on the relative stiffnesses of the pavement layers and the respective pavement layer thicknesses. The findings lead to the identification and subsequent validation by HVS testing of the concept of strength-balance of a pavement structure in terms of depth (Kleyn et al. 1985, 1989). This enhanced the understanding of pavement behavior relative to structural composition and provided a basis for selecting layer composition and configuration when designing pavements.

Vuong et al. (1994) reported on Australian studies pertaining to performance of subgrade and base course layers using fine-grained marginal material under accelerated loading. They concluded that excessive deformation of poor sandstone base course caused the loading exponent with respect to differing wheel loads to increase to a value of 7 to 8. As a result, they noted that there was a need to revise the Austroads subgrade critical strain criterion to improve the prediction of pavement life.

Suspension/Dynamic Load

The fourth power law of load equivalence was derived from experiments in which the applied wheel forces were dynamic (AASHO 1961). However, performance models for asphalt pavement generally included the effects of traffic loading on the basis of static wheel loads and numbers of applications; vehicle dynamic effects are not explicitly taken into account. Pidwerbesky et al. (1997b) pointed out that Sweatman (1983) had deduced that there was a degree of spatial repeatability in the dynamic loads that occur under wheel loads. As a result, the damage at peak load locations would be the critical factor in pavement performance. This was validated through a study of the influence of dynamic axle loads on pavement response and deterioration at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) (Pidwerbesky et al. 1997b). In this study, the effect of three types of suspension, steel multi-leaf, twin parabolic spring, and air suspension, on pavement deterioration was investigated in two tests. The wheel loads were identical statically, but quite different dynamically. Analysis ranked the suspensions from worst to best as steel, parabolic, and air.

In the first test it was found that there was a good correlation between the dynamic wheel forces and pavement distress. The results also showed that using a suspension system that is not designed for the load it is carrying could have significant impact on the distress in the pavement. The second test was part of the OECD DIVINE (Dynamic

Interaction between Vehicles and Infrastructure Experiment) project (OECD 1998). Two suspensions, a steel multi-leaf and a dual air suspension, were compared. The modes and level of pavement distress proved to be dependent on the particular suspension characteristics. The air suspension generated dynamic loads less than half those generated by the steel suspension. Surface rutting and longitudinal profiles, as well as surface distress, were monitored and analyzed. The difference in pavement condition led the researchers to conclude that the steel spring suspension caused an increase in deterioration rate compared with the airbag suspension.

The mean vehicle speed was 45 km/h with the inner and outer Simulated Loading and Vehicle Emulator (SLAVE) units traveling at 43.0 km/h and 47.0 km/h, respectively, on the inner and outer circles. This slight difference between the speeds was not considered to be of concern.

Single wide-base tires were used, and the amount of lateral vehicle wander was limited to ± 100 mm to maximize the separation between the vehicles. Pavement failure was defined as maximum rut depth exceeding 25 mm or surface cracking exceeding 5 m/m^2 over 50% of the trafficked area.

Steven et al. (1999) reported that the two different types of vehicle suspensions (dual air suspension and multi-leaf steel spring) in the CAPTIF tests produced no significant difference in the mean level of pavement wear in terms of surface roughness. However, the variability in the wear is quite different, with higher dynamic wheel loads producing greater variability. Similarly, the average wheel load was the same, but the response of the suspensions differed considerably. The authors noted that the findings have important implications for pavement maintenance requirements. In the same vein, the benefit of a smooth, uniform pavement structure is apparent.

As stated by Steven and Pidwerbesky (1997)

This research provided the first real insights into the effect of suspensions and dynamic loading on pavement life and performance; only an accelerated loading facility could provide an affordable means of obtaining the results in controlled experimental conditions within a reasonable time frame. The pavement condition and response changed with increased numbers of applied loads, and varied between the different suspensions. The effect of dynamic loading was clearly demonstrated by severe depressions in the pavement at intervals relating to the dynamic characteristics of the different suspension types.

Kenis and Wang (1999) focused on one important aspect of the OECD's DIVINE program in New Zealand. The goal was to investigate whether it was possible to distinguish between the development of pavement distresses resulting from initial variations in material properties and layer thicknesses, and those resulting from variations in the

dynamic wheel forces imposed on pavements due to tire-suspension dynamics. Research was conducted to determine if such differences in the level of these two phenomena, that is, the effects of pavement structural variability and dynamic wheel force on pavement performance, were detectable. They concluded that it was. They found that the change in mean Vertical Surface Deformation in both wheel paths with trafficking was similar, thus confirming theoretical assumptions that dynamic loading had no effect on the accumulation of mean surface deformation. However, they did find that there was about a 27% greater standard deviation of the Vertical Surface Deformation in the outer wheel path than the inner wheel path. This was probably because of the increase in the dynamic load in the outer wheel path. Cross-correlation analysis showed that the initial profile had little influence on the final profile of the pavement regardless of the type of suspension.

The reliability analysis by Kenis and Wang (1999) revealed that reducing structural variability of the pavement because of variability of pavement materials or nonuniformity of pavement construction increased the reliability of pavement service life. It is apparent that this improved understanding of the vehicle pavement has important pavement economic consequences, because it affects such factors as construction quality control and the long-term performance of the pavement structure.

In contrast to the CAPTIF facility, the LCPC carousel maintains a constant load to minimize the dynamic effect. This is the case for most facilities. Recently the HVS IV was put into operation in Florida, with some limited capability to simulate dynamic loads; however, test results have not yet been reported (Steyn et al. 1999). Gautrans Province in South Africa also acquired an HVS IV+ with enhanced capacity for dynamic loading. It can apply a sinusoidal load pattern along the length of the test section with a varying wavelength. The load amplitude can vary $\pm 20\%$. The TxMLS (Hugo et al. 1991) was also designed to have some dynamic load effect, but thus far this aspect has not been used except for trial purposes. Test facilities using regular truck trafficking also apply dynamic loads and the performance of the pavements reflects this. For example, in the case of WesTrack (Sime and Ashmore 2000), it was possible to gain insight into the effect on user cost of measurable changes in surface smoothness. This is discussed in more detail in chapter eight.

Unidirectional/Bidirectional Loading

Contradictory findings have been reported on the effects of unidirectional versus bidirectional trafficking. Tests in the United Kingdom (Brown and Brodrick 1999) reported that the bidirectional trafficking system is more severe in terms

of relative performance. In one case (50 mm of asphalt on a 160-mm granular base), the rutting more than doubled for two-way traffic. In contrast, Huhtala and Pihlajamaki (2000) reported that Finnish researchers found no difference in performance. Theoretical analyses have clearly indicated that a difference in performance should be expected because of residual stresses (Yandell and Behzadi 1999). Galal and White (1999) have also commented on this aspect. In general, trafficking with the Indiana DOT/Purdue-APT was done unidirectionally. In a single comparative test, White (T.D. White, personal communication, 2002) found that unidirectional trafficking exhibited less deformation than bidirectional trafficking. No follow-up tests have yet been conducted. The reason(s) for this apparent anomaly in the findings is not clear, and further research is needed to address this issue.

Lateral Wander During Traffic Loading

This topic has a bearing on the number of load applications that cause the damage affecting performance. Most devices have the capability to apply lateral wander, but in the interest of increased rates of load application on the center of the wheel path, it is often not applied. The effect of such an approach needs to be considered because it affects the relationship between distress and load applications at transverse positions in the wheel path.

Epps et al. (2001) reported on the effect of lateral wander on a number of the test sections at WesTrack. The researchers found that the HMA had moved laterally during trafficking and there was evidence that the material could be shoved upwards when the mix was shear susceptible at high temperature. This phenomenon was also observed by Hand (1999). As a result, the rut depth could be reduced at a specific lateral position with an increase in the number of load applications. Accordingly, Epps et al. (2001) concluded that the effect of this phenomenon had to be taken into account when quantifying the rutting performance under APT trafficking.

Chen et al. (1999) and Chen and Lin (1999) compared the typical wheel path rut profiles on a number of highways in Texas to the wheel path profiles generated by the TxMLS during testing to relate the performance under APT to actual traffic on the highways. They determined an adjustment factor based on the respective wheel path widths.

White et al. (1999) also reported on the effect of lateral wander. Their extensive tests showed significant reduction in rut depth and upward heave when the load applications were applied with lateral wander. For example, in a specific case, the rut depth and upward heave were respectively 10 mm and 5 mm with wander, compared with 15 mm and 14 mm without wander. In general, they reported

reductions of between 30% and 40% in rut depth when lateral wander normally distributed over a width of 250 mm was introduced. They also showed that FE analysis and modeling could be used to quantitatively predict the APT rutting with wander from single wheel path rutting. This has an advantage over fitting regression curves to data and extrapolating. The latter is purely empirical and relates only to the data collected. Extrapolation may be inappropriate

On the basis of these reports, it is apparent that lateral wander has an important influence on the rutting performance of pavements.

Tire Characteristics and Related Contact Stresses

Recent developments in the field of vehicle-pavement interaction have provided users of APT programs with important insights into the performance of pavements. It has become clear that the tire-pavement interface has a major impact on the performance of the upper layer(s), especially for flexible pavements.

De Beer et al. (1997) described the quantification of three-dimensional (3-D) tire/pavement contact stresses for vehicle tires using the Vehicle-Road Surface Pressure Transducer Array (VRSPTA) system (Figure 2). The system was developed to measure actual contact stresses under a moving tire; that is, Stress-In-Motion as an ancillary device for use in conjunction with the South African APT facilities. The contact stresses were found to be nonuniform and were considered to be a primary cause of surface cracking. Researchers have shown conclusively that the contact pressure is not uniform over the contact surface. Contact pressure varies between the center of the contact area and the outer edge, depending on the tire pressure and the nature of the tire; that is, whether it is a radial ply tire or not. Measured peak contact stresses were up to 100% higher than the inflation pressure (De Beer et al. 1997). Blab (1999) also found that tire inflation pressure, load,



FIGURE 2 The VRSPTA on the pavement under the HVS with a 315/80 R22.5 tire (De Beer et al. 1997).

and tire type are the dominant factors affecting the 3-D vehicle–pavement contact stresses. He concluded that high tire edge vertical contact stresses are the principal factors responsible for surface rutting and cracking.

Bonaquist (1992a,b) also reported on work that had been done to assess the impact of wide-based single tires. The comparison between dual and wide-based single tires was done in terms of response and performance relative to fatigue and rutting damage potential. Two thicknesses of AC, 89 and 178 mm, over a 305-mm crushed aggregate base, were trafficked. There was a near linear increase in gross contact area for increasing loads for both tire types. For compression within the AC, tire pressure was found more important than load. However, the tensile strain at the bottom of the asphalt layer and the compressive strain at the base and subgrade level were affected more by the load. This was a good example of Saint Venant's principle, which states that the stress in the depth of the pavement is solely dependent on the size of the load and not the contact stress. Overall it was found that the wide-based single tire generated 1.0 to 2.4 times more rutting than the dual tires with the majority of the rutting occurring in the crushed aggregate base layer. The observed damage in terms of fatigue cracking was approximately four times greater with the single tire compared with the dual tire in terms of measured crack lengths.

These values compared well with theoretical predictions based on the following damage models:

$$\text{Fatigue Damage} \quad \frac{I}{N_f} = a(\epsilon_t)^b \quad (1)$$

$$\text{Layer Rutting} \quad \Delta_p = \Delta_r c N^d \quad (2)$$

where

- N_f = fatigue life,
- ϵ_t = tensile strain at the bottom of the AC layer,
- Δ_p = layer permanent deformation,
- Δ_r = resilient layer compression, and
- a, b, c, d = material coefficients.

The expected relative damage according to the models was between 3.5 and 4.3 times greater for fatigue damage, and between 1.1 and 1.5 times greater for rutting damage.

Corté et al. (1997) reported on results from experiments on the LCPC test track in France to determine the aggressiveness of wide-based single tires. It was found that the aggressiveness of the axles with wide-based single wheels is greater than that of the dual wheels. For the sensitive mixes, the magnitude of the ruts formed by the wide-based single tires was 50% more than those of the standard dual

tires. In subsequent tests with rut resisting mixes, this difference in rutting performance was reduced to 20%. It was therefore concluded that this effect depended on the nature of the asphalt. The more sensitive the asphalt mix was to rutting, the more pronounced was the effect. The relative effect of a tandem axle with wide-based single tires does not appear significantly different to two isolated wide-based single wheels. However, this observation was made for rather low test temperatures and was therefore not favorable for determining differences in rutting performance.

Gramsammer et al. (1999) reported that LCPC had also tested new 5.3-t extra-wide single tires currently being developed. As always, the tests were related back to reference materials with known performance to serve as a benchmark. The tests involved sponsors from the industry, which resulted in fast-tracking the findings into field application by the industrial partners, thus expediting economic benefits.

Increase in tire pressure affects rutting in APT. Both Gramsammer et al. (1999) and Hugo (2000) found the increase in rutting of the asphalt layers to be proportional to the increase in tire pressure.

De Beer et al. (1997) reported that tire inflation pressure predominantly controls the vertical contact stresses on the pavement at the tire center, whereas the tire load controls those at the tire edges. Their analysis indicated that during instantaneous overloading/underinflated conditions, the maximum strain energy of distortion (SED) in the asphalt surfacing occurs close to tire edges. Under instantaneous uniform vertical stress conditions, the SED is within the asphalt surfacing at the tire center.

In a recent Australian study by Foley and Sharp (2001), pavement deformation beneath wide-based radial and conventional radial tires was compared under ALF trafficking. A nominal 75-mm-thick asphalt mix of 25-mm maximum aggregate size, exhibited five times more rutting under the wide-based radial tire than under the dual radial tire at an equal vertical loading. It was concluded that the transverse tensile contact stress developed across individual tread ribs causes a reduction in shear strength because of a reduction in confinement of the material. As a result, the deformation was adversely affected. It was concluded that the contact stresses beneath wide-based radial tires needed to be investigated further. Similarly, the ability of models to simulate these conditions should also be explored further. FE methods were considered to be the most useful for these investigations.

Sideways shear or shear forces (stresses) that may develop under a condition of cornering were investigated. In South African experiments, the HVS test tire was sheared

over the surface of the VRSPTA by moving the tire during testing toward one side of the VRSPTA at an angle of 7.5 to 8 degrees. The test results indicated that the transverse stress increases by approximately 30 kPa/degree for conventional Type IV tires and approximately 50 kPa/degree for the wide-based tires. In terms of the ratio of maximum stresses, the transverse ratio increases to a range of between 2.6 and 3.61 (De Beer et al. 1997 and Figure 2).

Woodside et al. (1999) also reported on a study of tire-pavement interaction in Northern Ireland. They used a multifunctional wheel tracking device known as TRACKER. Test specimens were tracked by a truck (lorry) tire, at a speed of 2.7 km/h. The stress induced by the tire was varied by altering the tire inflation pressure and the loading. A test platform was used to measure dynamic contact stress by means of 12 specially designed, inverted T-shaped transducers positioned across the width of the contact patch. Surface texture was simulated by varying the extent to which the T-shaped transducers protrude above the cover plate. The researchers reported that contact stresses increased with tire load, inflation pressure, and surface roughness (texture depth); contact stress distribution is not uniform, but rather increases toward the tire edge. In dynamic stress models, vertical stresses are of higher magnitude than lateral or horizontal stresses. They also showed that mathematical models were ideal for analysis of dynamic contact stress.

A quantitative model was developed by Groenendijk et al. (1997) to describe the contact stress distribution measured under tires of LINTRACK in tests in South Africa. This model distinguishes between the edge (2 times 20%) and center (60%) zones of the tire width. The vertical stress level in the center zone is mainly determined by the tire pressure and the edge zone level is mainly determined by the wheel load. In follow-up work, Groenendijk (1998) concluded that the measurement of tire/pavement contact stresses with the VRSPTA had improved the estimation of the vertical, transverse, and longitudinal forces; that is, stresses under slow-moving pneumatic tires. He also pointed out that the surface stresses primarily affect the upper 100 mm of the pavement contributing to surface distress.

De Beer et al. (1997) reported on an investigation into some effects of the actual tire pressures on thin asphalt surfacings. They concluded that the design and analysis of flexible pavements with thin surfacing (<50 mm) were affected by surface stresses. The results are significantly different compared with those used in conventional design and analysis methods.

The ability to evaluate the tire pavement interface in such detail under accelerated pavement test devices could be an important reason why APT programs have become

more popular for determining how pavements respond and ultimately perform under traffic. In this regard, the computer analysis of Stress-in-Motion using the VRSPTA system is a powerful tool for enhancing pavement load modeling for both design and analysis.

Trafficking Speed (Speed of Load Application)

The effect of trafficking speed has not received as much attention as other pavement interaction factors. This is probably because most of the APT systems are either not able to test over a wide range of speeds or are not designed to measure dynamic deflections during trafficking. Nevertheless, some findings have been reported. Corté et al. (1997) noted that, as a first approximation, the trend is that in the range of speeds of 40 to 50 km/h, an increase in speed of 15% reduces rutting by 20% to 35%. They mention that there may have been a veering effect of the wheels during circular trafficking. This value becomes more variable with stiff asphalt (small deformation). Also, when the ruts are small (2–4 mm), it is difficult to quantify the influence of speed. Steven et al. (1999) reported that the dynamic load coefficient, as measured with the CAPTIF device, doubled when a parabolic spring suspension was used and the speed was increased from 20 km/h to 45 km/h. The effect was minimal with a multi-leaf spring suspension.

Lourens (1995) measured both static and dynamic deflections under wheel loads on in-service highways to relate these to deflections measured under the HVS. Figure 3 shows the results on a pavement consisting of 60-mm asphalt surfacing, 210 mm high-quality crushed-stone aggregate base, and 150 mm of cement-treated subbase. He obtained similar results with a pavement that had 100-mm asphalt surfacing, but a slightly weaker support structure. The results show how the deflection reduces dramatically within the speed range of 0 to 20 km/h. Because of the relationship between elastic and plastic strain this would lead to a similar reduction in deformation of the asphalt. The experiments were done with different axle loads and on a range of pavement structures. The range of strain measurements taken in five different pavement structures under 11.5-t axle loads during the FORCE project (OECD 1991) were very similar to those shown in Figure 3. White et al. (1999) demonstrated the effect of speed on rutting with the FE analysis that had been developed in their APT program. They found that the rutting would be halved when the speed is increased to 100 km/h from creep speed. These findings demonstrate why frequency of load application is important when comparing deformation under different trafficking patterns as was done by Epps et al. (2001).

It is clear that speed of loading has to be carefully considered in judging results from APT trafficking, especially

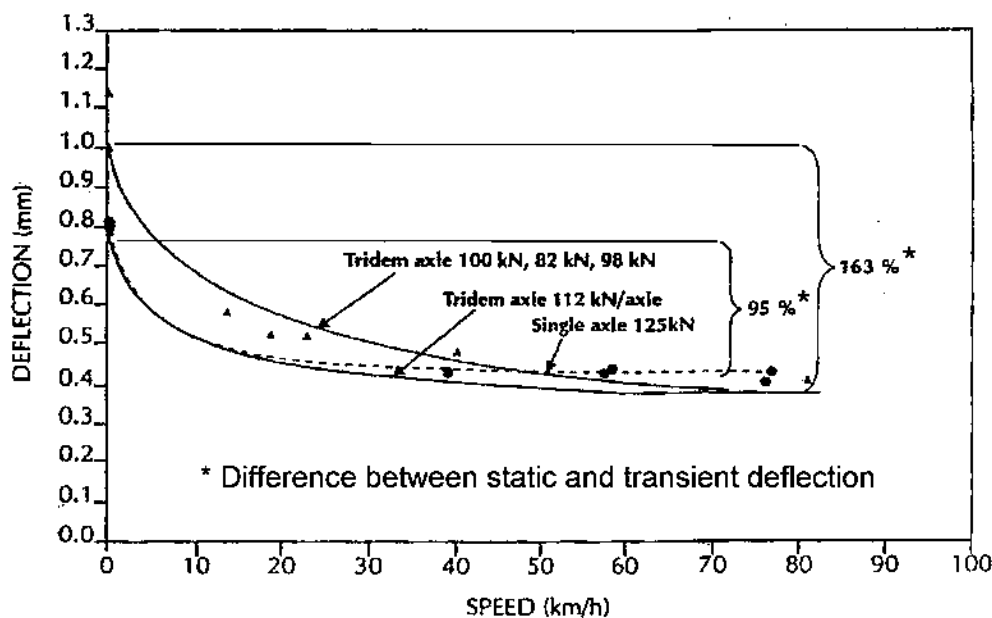


FIGURE 3 Effect of speed on pavement deflection (Lourens 1995).

when a substantial layer of asphalt is present in the structure. On the other hand, it is apparent that the wide range of variants that have to be considered in pavement performance can most probably only be investigated with any degree of success by using APT. In this regard, Gramsammer et al. (1999) reported the following in their presentation on research at the LCPC test facility during the 1999 Reno conference:

The Carousel made it possible to optimize the inverted pavement structure quickly. . . Could the hierarchical organization of anti-rutting qualities of the materials have been worked out as easily (without the use of APT)? How could the traffic, the speed, and the temperature conditions have been as rigorously guaranteed with another testing facility?

LOAD COMPOSITION AND CONFIGURATION (SINGLE OR MULTIPLE AXLES)

According to LCPC reports, the effect of multiple axles has not been excessively detrimental (Gramsammer et al. 1999). The phenomenon is however receiving specific attention at the Mn/ROAD project (Newcomb et al. 1999). At this facility, a range of vehicle loads, axle configurations, and vehicle speeds are being applied to instrumented pavement sections. The results were successfully used to develop a mechanistic-empirical design process that takes actual load repetitions into account (see the summary at the end of this chapter).

By reviewing HVS test data from actual constructed pavements, Wolff (1992) was able to determine the effect of molding (post-construction consolidation) of a pavement structure due to wheel load applications. This had previously been postulated and verified by Kleyn et al. (1985). Wolff found that the application of different load

sequences on the pavement structure affected the performance. It appeared, from the limited data that were available, that the stress path influenced the final performance.

The extensive nature of the impact of tire-pavement interaction explains why more APT programs are incorporating this factor in their test plans. The same applies to the attempts at simulating dynamic effects of truck trafficking through APT devices.

ENVIRONMENTAL IMPACT

As mentioned earlier, environmental impact is essentially caused by physical and chemical action related to temperature, water, wind, and radiation. It was found that the impact of temperature and water on pavement structures had been investigated by a number of APT programs, and a wide variety of pavement structures and materials had been tested. As far as could be ascertained, wind and radiation have not been featured to any extent in APT studies.

In considering the effects of temperature and water it was apparent from the literature and the responses to the questionnaire that it was necessary to differentiate between short-term and long-term conditions. In addition, non-traffic effects had to be considered, especially in the case of temperature. This portion of the synthesis, on applications and significant findings relative to environmental impacts, was therefore compiled with due regard to these influence factors.

During the course of events, test protocols have been developed, and these have provided a means of comparison between the findings of the various test programs.

Environmental Impact Factors

Both non-traffic and traffic-related findings will be discussed in this section.

Aging of asphaltic materials, caused by time-related exposure to heat, oxygen, radiation, and wind, is one of the primary non-traffic-related effects that have to be considered. Surrogate tests have provided useful laboratory insight into the effect of such aging on pavement performance. However, to capture all aspects of this phenomenon, the actual effect of aging on pavement performance, a long-term study at a dedicated site(s) is needed. Thus far, no formal study has been undertaken specifically for this purpose by any APT program. Epps et al. (2001) did consider the effect of aging in their analysis of the findings from the MMLS3 (one-third scale mobile load simulator) study at WesTrack. It has also been recognized by Hand (1999) as a factor that needs to be considered in the analysis of APT performance. As expected, rutting was reduced because of the hardening of the aged binder. In addition, artificial accelerated aging has been used to simulate natural aging of asphalt in APT studies (Hugo et al. 1987; Van der Merwe et al. 1992).

Van der Merwe et al. (1992) aged two HMA test sections through heating, at 100°C for 7 days and 28 days, respectively. They found a dramatic increase in the rut resistance after the artificial aging. However, at the same time, the resistance to cracking had decreased, because surface cracking was experienced much earlier. Shift factors relating the respective performance parameters (rutting and cracking) before and after aging were 1:1.5 (rutting) and 5:1 (cracking). It was clear that aging had affected performance both positively and negatively. Unfortunately, the study was not taken any further, but it was apparent that the entire issue of aging needed additional research. In the second study, Hugo et al. (1987) reported on testing of similarly aged material at low temperature (−10°C). Aging again resulted in more extensive cracking distress. It was found that cracking depends on the interrelationship between the increase in modulus and tensile strength. A proposal for investigating the effect of the environment was put forward by Hugo (1999). It entails a method for quantifying the effect of the environment over a period of several years with the aid of a structured APT study. The primary goal would be to develop procedures for determining the possible changes in the intrinsic life of a pavement due to environmental impact.

The remainder of the discussion in this section focuses on the various findings that have come about from APT programs that have addressed the influence of temperature and water in their testing of pavement structures without specific attention being paid to the effect of aging.

Impact of Temperature on Performance

Performance of pavements is affected by the full temperature range that occurs during its life cycle. During earlier APT studies tests were simply conducted at ambient temperature, while monitoring and recording the actual conditions during testing. However, recently, many facilities have provided some means to control the temperature of the pavement. These programs are identified in Appendix F.

Test temperature capabilities vary, with the upper limit reported as high as 76°C (Harvey et al. 2000). The LCPC system was adapted to heat one of the sections artificially (Corté et al. 1997). A total of 36 tungsten–halogen projectors, of 1,000 W unit output, were installed on the inside of the track, 0.5 m from the wheel path at a height of 1.5 m above the ground over a length of 25 m. This enabled the pavement temperature to be increased by 10°C to 14°C above the ambient air temperature. The power needed for this was a little over 2 kW/m² for testing speeds limited to 40 km/h. It is of interest to note that the power required to maintain a test temperature of 50°C under the MMLS3 on in-service pavements was the same, but was dependent on the ambient conditions (Epps et al. 2001). The difference with the MMLS3 was possible because the device is well insulated, thus minimizing loss of heat. For the initial heating prior to starting an experiment, 6 kW/m² or more was needed to bring the pavement to a test temperature of 60°C when the ambient temperature was near freezing. The heaters used with the ARRB–ALF system have a maximum capacity of 2.8 kW/m² (Johnson-Clarke and Fossey 1996). A number of facilities have also acquired the capability to cool the pavement system and test at a controlled low temperature level. In some cases this can be below 0°C. However, this requires specially equipped facilities such as HVS–CRREL and a limited number of others identified in Appendix F.

Because the reports on the application of APT under different temperature ranges focus on dissimilar phenomena, the related discussions are considered in separate subsections by means of case studies.

APT Tests at Ambient and Elevated Temperatures

Corté et al. (1997) discussed in detail the effect of temperature on rutting. They reported that there is a threshold temperature above which asphalts show susceptibility to rutting. For the reference asphalt mix in the LCPC facility, this threshold temperature was 40°C to 45°C. When the temperature was below this, there was a marked reduction in the rate of rutting, as well as the extent of rutting, with deformation very low or even indeed nonexistent. This threshold value appears to be close to the Ring and Ball

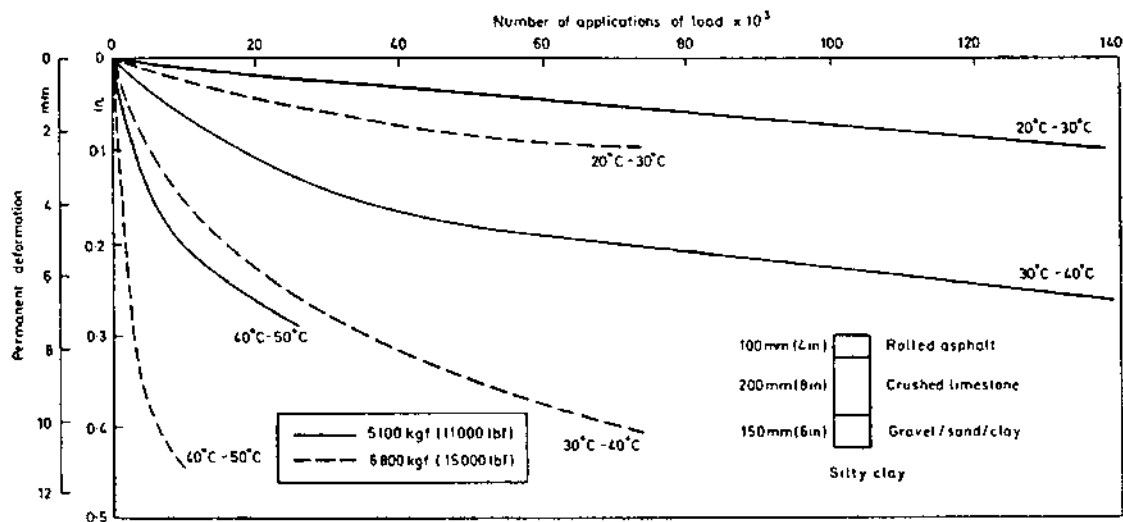


FIGURE 4 Effects of wheel load and temperature on permanent deformation.

softening point temperature of the binder. [The Ring and Ball test is used to determine the temperature at which bitumen (asphalt) reaches a certain degree of softness. This is arbitrarily defined in terms of a test to determine when bitumen changes from solid to liquid. The test is carried out as follows: The bitumen is melted and poured into a standard brass ring placed on a plate; when cool, a standard-sized steel ball is placed on the bitumen and the ring suspended in a water bath, the temperature of which is raised at the rate of 5°C per minute. The temperature at which the bitumen softens sufficiently to allow the ball to pass through the ring and touch the lower plate—a distance of 25 mm—is called the softening point.] For this reason, the thermal history of a pavement plays an important role in the development of rutting and the related performance. Lister reported this in 1972 (Lister 1972 and Metcalf 1996) in one of the very early APT studies in the United Kingdom (see Figure 4). From this figure, the dramatic effect of a 10°C or 20°C change in temperature on deformation can be seen. The results reported by Lister show a similar trend toward a threshold temperature at 40°C, as that reported by Corté et al. (1997).

This explains why temperature is a major factor in the performance of asphalt pavements. The same is true of concrete pavements, albeit for different reasons, such as curling of slabs. The temperature effect is both short and long term.

Maccarrone et al. (1997) found that the sensitivity of the deformation rate with increase in temperature is markedly reduced with each of the two ethylene vinyl acetate (EVA)-modified binders that were evaluated. They compared their performance to that of a conventional AC-30 binder (Class 320 Australian binder classification). In all cases, the comparative mixes were continuously graded asphalt with 10 mm nominal aggregate and 5.1% binder. The rate of de-

formation approximately doubled for every 4°C increase in temperature for the Class 320 mix, compared with every 7°C for the two modified binders. Modified binders were found to significantly reduce permanent deformation in asphalt pavements at elevated temperatures. At pavement temperatures of 60°C, it was found that the two tested, modified binders could reduce the rate of deformation by factors of approximately five and eight times, respectively, when compared with conventional AC-30 binder.

Galal and White (1999) investigated the effects of different constituents of asphalt mixtures on permanent pavement deformation using APT. The investigation was also used to study the effect of lateral wander on rutting, which is discussed elsewhere in detail in this chapter. The researchers considered aggregate type, percentage of crushed gravel, and percentage of natural versus crushed sand and binder. Thirty-two mixtures were evaluated at a temperature of 38°C (±1°C) and a trafficking speed of 8 km/h. The elevated temperature and the slow speed enabled definitive conclusions to be drawn. The researchers found that the aggregate type has a significant effect on rutting; slag and limestone mixtures rutted 50% less than gravel mixtures. They also found that an increase of 0.25% in the binder content resulted in as much as a 40% increase in rutting of the gravel mixtures.

Harvey et al. (1999) reported on two pavements that were constructed in 1995. One pavement was a Caltrans “undrained” structure consisting of prepared subgrade, an aggregate subbase and base layers, and an AC surface. The second pavement was a Caltrans “drained” structure, in which a 75-mm-thick layer of ATPB was placed beneath the AC, replacing a portion of aggregate base. They reported partial verification that rutting of HMA primarily

occurs in the upper 100 mm of pavements. The speed of loading during the rutting tests averaged 7.6 km/h, while the nominal surface temperature was 55°C. Once again the slow speed and the elevated temperature yielded definitive results. It was found that 48% to 68% of the observed surface rutting was the result of the deformation of the asphalt layers and that the plastic deformation in the subgrade was minimal. The aggregate base and subbase layers contributed 22% to 50% of the total permanent vertical deformation.

Gramsammer et al. (1999) pointed out that rutting experiments require fewer load cycles. Testing with the carousel at LCPC requires applying 100,000 to 200,000 load applications on four radii of gyration at speeds of 38 to 48 km/h depending on the radius. Because rut tests require high temperatures, such tests are systematically conducted in midsummer (July and August) when the temperature reaches 30°C within the wearing courses (between 9 h and 18 h solar time). The rutting tests are conducted on a specific site equipped with a subbase course resisting deformation, so that rutting measured on the surface is really the result of the plastic deformation of the wearing courses and not of the subsurface layers.

Sharp et al. (1999b) also reported that deformation at high temperature was confined primarily to the upper asphalt layer, indicating that only the upper layer needed to be replaced with a more rut-resistant product to effectively repair temperature-related deformed pavement surfaces. They concluded that the current Austroads design method needed to be revised to reflect the plastic-related deformation in the asphalt layers together with limiting subgrade strain. In that study, a test section incorporating a high bitumen content mix in the layer base course showed only limited rutting. This was similar to findings reported by Harvey et al. (1999) in support of the rich-bottom design. Sharp et al. (1999b) concluded that testing at an elevated temperature at 40°C was too low for typical Australian in-service pavements, and suggested 50°C instead.

APT Tests at Low Temperatures

Low temperature cracking is a phenomenon that has been addressed primarily through improved binder specifications. APT studies in regions with low winter temperatures and no environmental control presented the opportunity to evaluate the success of this approach. In the case of WesTrack, no distress of this nature occurred, thus validating the design strategy (Epps et al. 1999). At Mn/ROAD, the occurrence of low temperature cracking owing to the natural environment is also being monitored (Newcomb et al. 1999).

When the pavement is subjected to temperatures below 0°C water becomes an important factor, because it freezes and the freeze–thaw phenomenon has to be considered. It

becomes an interactive process between temperature and water. Few of the facilities take this into consideration. The Mn/ROAD is one site that was especially designed to investigate the problem. The proposed design methodology that was implemented to address this is reportedly successful (Newcomb et al. 1999). The HVS–CRREL facility is also equipped to investigate this, and Janoo et al. (1999) have reported on a study that was conducted with their HVS.

Zhang and Macdonald (1999) reported on full-scale APT testing of a pavement structure at low temperature with the Road Testing Machine in Denmark. The purpose was to investigate the effect of freeze–thaw cycles on the response and performance of a pavement that had already been subjected to 150,000 load applications at 25°C with only very limited deterioration. Trafficking included 50,000 load repetitions at dual-wheel loads of 40 kN, 50 kN, and 60 kN each. The International Roughness Index (IRI) had increased to 1.50 m/km from zero with a rut depth of 10 mm.

In the freeze–thaw tests, the pavement was frozen to a depth of 1.2 m, which included the top three of nine clayey silty sand subgrade layers. The freezing was achieved by maintaining –10°C in the climate chamber surrounding the pavement section. Once this condition had stabilized, freezing was stopped and profiles measured. During freezing, the surface heaved upwards from 6 to 26 mm, in different locations, because of ice formation. The temperature was slowly raised to 25°C and the pavement was allowed to thaw. Pore pressures (soil suction) were measured with tensiometers during thawing using a blend of water and anti-freeze. Temperatures were also monitored. A dual 60-kN wheel load was applied at a rate of 150 load cycles per day. The pavement response and pavement profiles were measured at regular intervals.

After 1,800 load repetitions, freezing was resumed and a second cycle started. The frost heave was again recorded. During the second thawing period, 3,000 dual-load repetitions were applied. The IRI increased to 4.4 m/km, whereas the rut increased to 22 mm. A stress–strain model was developed that closely predicted the permanent strain in the subgrade for a subsequent test.

The comparison between measured and calculated pavement responses proved satisfactory. Models for estimating plastic strains at the top of the subgrade and the permanent deformation of the subgrade were also developed and found to be satisfactory. It was observed that

- Some 60% to 70% of the total increase in plastic strain occurred during the early stages of thaw loading.
- Dynamic transient (elastic) stresses and strains increased by up to 40% during thaw loading over those measured before the freeze–thaw.

A model for the IRI was also developed to reflect the permanent deformation at the surface.

A number of conclusions were drawn from the study.

- It is important to measure pore pressures in the subgrade before and during thawing.
- The subgrade permanent strain model closely predicted the permanent deformation (rutting), but underpredicted the permanent strain in the subgrade.
- Freeze-thaw experiments are time consuming. It took 2 months of continuously applied freezing temperatures at -10°C for a single cycle. The experiment took 11 months to complete.

Impact of Water on Performance

The impact of water on pavement performance has been explored in a number of APT programs. In general, the effect of water ingress into the structure is dramatic. The importance of this is endorsed in the questionnaire response from CAPTIF, which states that the exclusion of environmental factors such as moisture greatly increases pavement life when compared to the expected design life (see Appendix D, Table D3).

As much as feasible, the discussion will differentiate between the effect of surface infiltration of water and subsurface ingress of water. However, as was shown in the case of temperature, water also has an effect that is non-traffic-related, at least until it causes distress that affects interaction with traffic. A major factor in this regard is chemical distress, which

is primarily the result of chemical disintegration of material(s) or deterioration of layers. It is another form of non-traffic-related impact. The study by Roesler on alkali-silica reaction (ASR) attack on PCC in conjunction with the CAL/APT program in Palmdale, California, is an example of this (Roesler 1998; Roesler et al. 1999).

South Africa's testing of cement-stabilized gravel that is deteriorating because of carbonation and/or crushing (Steyn et al. 1997) is another example of how APT has provided insight into the application of distress mechanisms and remedial measures. Similarly, the diagnostic study of the distress that the N2 National Road section in the Western Cape province of South Africa has suffered because of alkaline reaction is a good example of how extensive the impact of this form of distress can be and how APT was used to provide parameters for evaluating optimum solutions for the rehabilitation. This is discussed in chapter six of this report (Strauss et al. 1988; Strauss and Van der Walt 1990).

Infiltration of Surface Water

In his study of the deformation of unbound bases, Maree et al. (1982) found that the ingress of water into the pavement structure had a major impact on the deformation. This is vividly demonstrated in Figure 5, which shows how rain and the subsequent artificial spraying of water onto a 30 mm surface under HVS testing in South Africa led to a dramatic increase in the deformation. The researchers report that this does not occur when the pavement is properly maintained, for example, by crack sealing. They also report

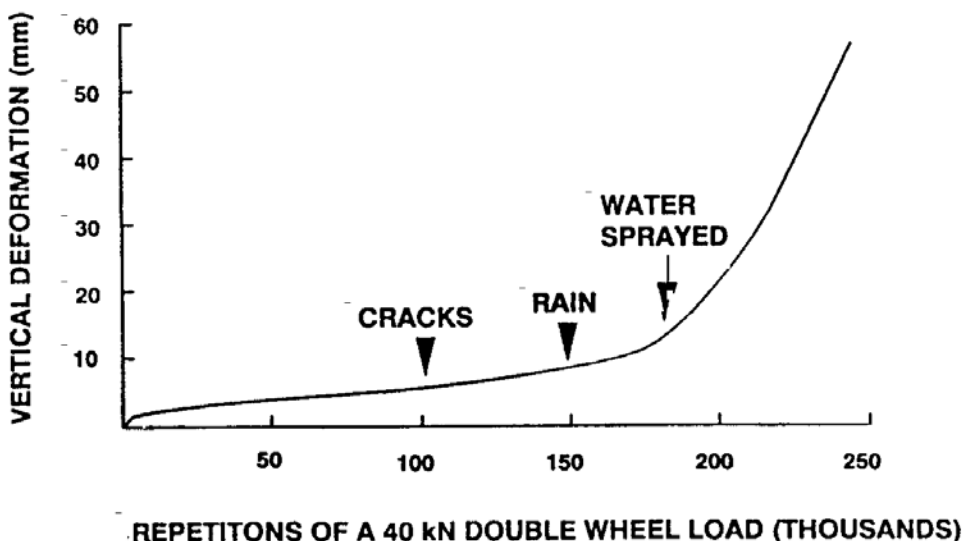


FIGURE 5 Rutting performance of a pavement with a granular base layer during HVS testing (Maree et al. 1982).

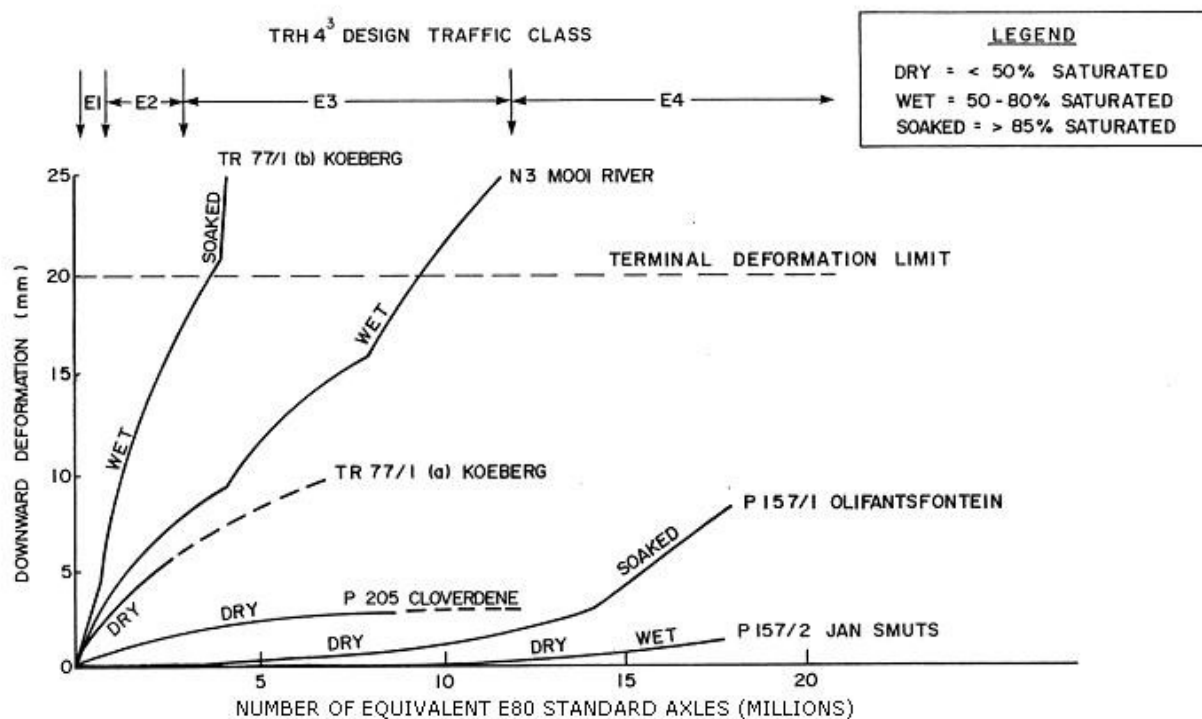


FIGURE 6 Comparison of the pavement deformation induced in various crushed-stone base pavements by HVS trafficking (using $n = 3$) (Walker 1985).

that the rate of rutting is reduced significantly when the pavement is allowed to dry out after the wetting phase.

Water affects pavement performance when it gains access to the pavement structure. During trafficking pore water pressures develop, causing a loss of shear strength and even disintegration, depending on the nature and quality of the asphalt or other pavement materials. Sharp et al. (1999b) reported on APT that had been done on gravel base courses in Australia. Time Domain Reflectometry (TDR) gauges developed by the Council for Scientific and Industrial Research Organisation (CSIRO) were used successfully to monitor moisture in the subgrade. The lateritic soil was found to be very susceptible to moisture, and field road performance correlated well with the moisture variation in the wheel path.

Walker (1985) discussed the impact of moisture on pavement performance and used data that had been obtained from various HVS tests on South African field pavements to show how the effect differs depending on the type of pavement and the degree of saturation. Figure 6 (Walker 1985) shows the deformation relative to equivalent 80-kN standard axles using $n = 3$ in the load equivalency formula. Highway P 157/1 (see Figure 6) was subsequently investigated in 1996 (Jooste et al. 1997) to evaluate how it had performed since the initial HVS testing (see chapter seven).

Walubita et al. (2000) reported on studies that were conducted on Texas US-281 with the MMLS3 in conjunction with the TxMLS. The goal was to investigate whether moisture damage of the asphalt mixtures would occur as a result of the wet trafficking. The MMLS3 tests were conducted on the pavement adjacent to the TxMLS with a sheet of water flowing over the surface during trafficking. The most important finding was a significant drop in modulus of elasticity measured by spectral analysis of surface waves (SASW) owing to wet trafficking. This was in contrast to an increase in SASW modulus of elasticity because of trafficking under warm conditions (38°C). There was also a significant reduction in the indirect tensile fatigue life of the wet trafficked asphalt. This reduction was attributed to microfracturing, which would indicate that the test under the TxMLS that had been trafficked dry was less severe than the test with the scaled device.

This meant that a much lighter wheel load was causing more damage to the pavement through wet trafficking than the full-scale trafficking could achieve under dry conditions; the apparent remaining life appeared to have been reduced to 20% to 40% of that in the dry trafficked areas. Related findings by (Pidwerbersky et al. 1997a) and others indicated that the impact of water during trafficking on remaining life and performance can be significant.

Surface and Subsurface Water

In an APT study on the performance of subgrade and base course layers of marginal quality, Vuong et al. (1994) reported on the importance of moisture content, making the following noteworthy points:

- Back calculation of layer moduli from FWD deflection data provides information on the effect of moisture content. The variation in back-calculated moduli with time was a useful tool for determining the relative effects of seasonal environmental conditions.
 - Under dry conditions the sandstone had adequate stiffness (at say 50% of optimum moisture content). The material behaved nonlinearly, with the stiffness increasing as the load increased. However, the negative effect of wetting the sandstone was also clearly demonstrated (see Figures 7 and 8). As a result of this finding it was apparent that the modulus had to be adjusted to account for seasonal moisture variations, because it could significantly impact the performance of low-cost pavements.
 - The Regression Rut Depth Model was used to analyze the performance data from ALF tests when load and environmental conditions vary. It was also used to derive the power law in the load damage relationship. The model is illustrated in Figure 9. The 40-kN load applications are progressively adjusted to be equivalent to 80 kN by varying the exponent value. The best-fit regression indicates the applicable damage exponent.
- The effect of heavy rain in a concentrated short period of time needs to be considered in the adjudication of performance, because it can override the good results over a long period of time. Granular materials that are sensitive to moisture do not dry back quickly and the prevention of ingress of water and the possible increase in moisture content within the material is critical. When the subgrade has adequate strength to support traffic, the main function of unbound marginal material is to carry the surface seal rather than support the load.
 - The relative effect of the environment can be expressed in terms of an environmental equivalency factor or an environmental damage exponent (EDE). The EDE is defined by the ratio between rut depth and the number of load repetitions on a log-log basis. EDE values of 6 to 10 were obtained from the trials indicating that the environmental effects could be more significant than the loading effects.

The Australian roads subgrade strain model overpredicted the lives of granular pavements because it did not

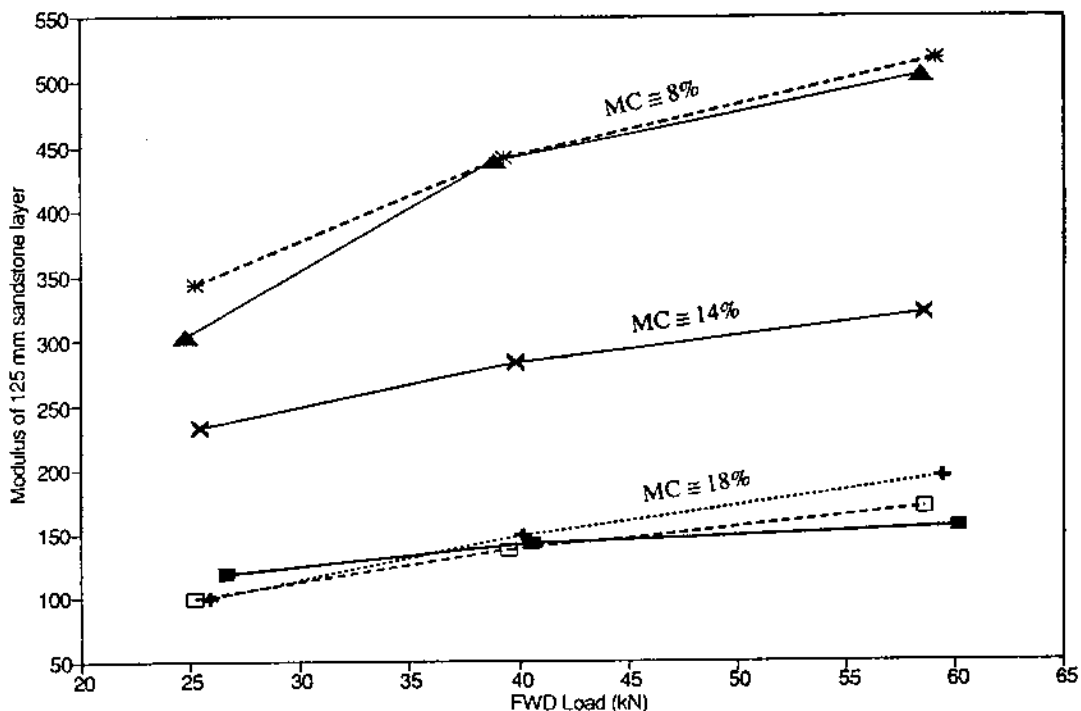
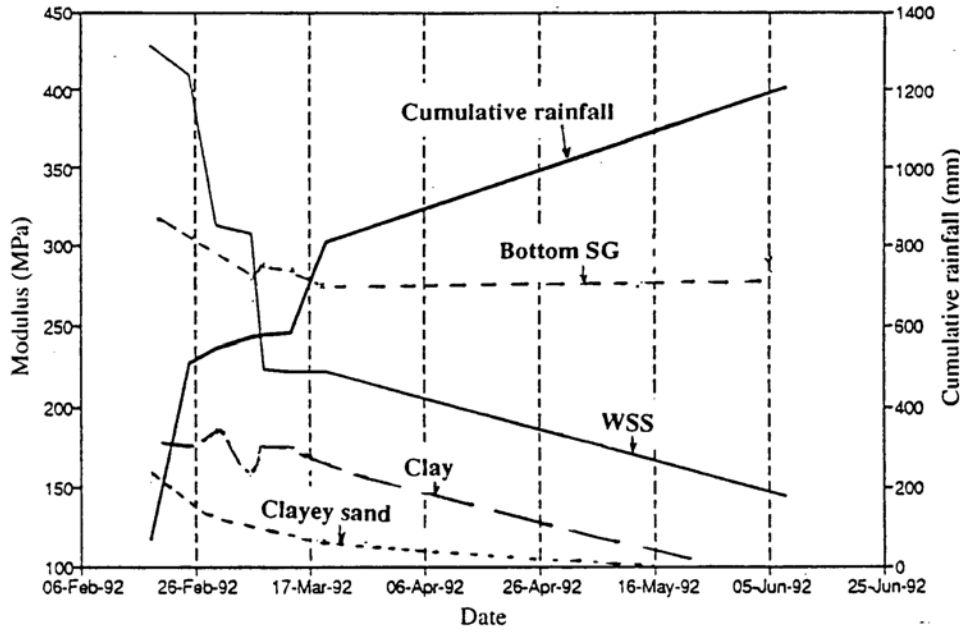


FIGURE 7 Variation in sandstone layer modulus with different loads and moisture conditions (Vuong et al. 1994).



Mean Value E1 - Data includes Moduli during trafficking b/w 1/3/91 and 20/3/92

FIGURE 8 Comparison of average layer moduli in site C and cumulative rainfall over time (Vuong et al. 1994).

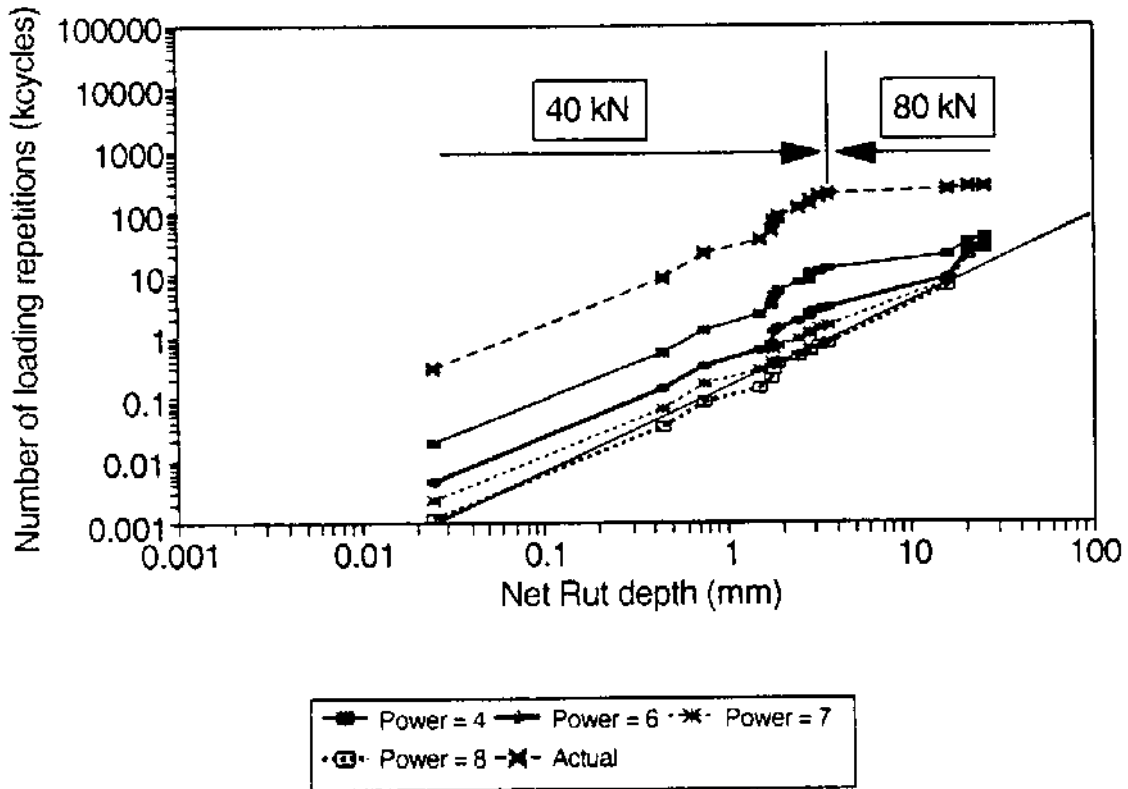


FIGURE 9 Comparison of net rut depth with 80-kN load repetitions (site C) (Vuong et al. 1994).

take into account the deformation of granular pavement layers that are sensitive to moisture and compaction levels.

Freeme (1984) had previously reported a damage exponent that varied between 2 and 6 in studies with the HVS.

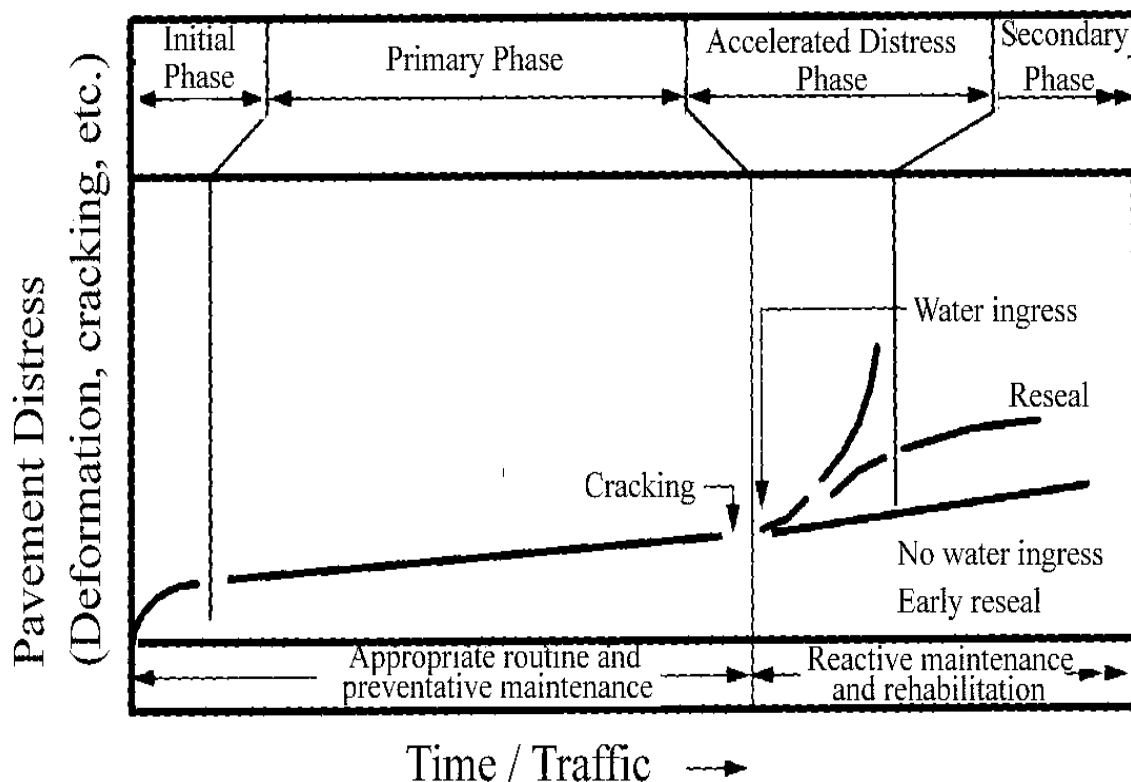


FIGURE 10 Impact of water ingress on pavement performance (Rust et al. 1997).

Vuong and Sharp (1999) reported that the typical construction of 95% of sealed roads in Australia is unbound crushed-stone/gravel bases with sprayed seals or thin HMA. As a result, the ALF program in Australia has focused heavily on this type of pavement structure. This is evidence of the appropriateness of APT as a tool for investigating a wide range of pavement structures and configurations. The same is true of several other programs such as SA-HVS (Rust et al. 1997) and CEDEX in Spain (Ruiz and Romero 1999).

Meng et al. (1999) reported from their tests on a highway in China that rainfall is one of the major environmental factors that can accelerate pavement deterioration. They also commented that the damage is primarily the result of pumping and erosion at the underside of the asphalt layer.

Rust et al. (1997) pointed out that extensive studies have been undertaken to explore the impact of water on the performance of the pavement. Figure 10 shows the deformation performance schematically.

Odermatt et al. (1999) completed accelerated testing on two subgrade soils at two moisture contents. The structures included 76 mm HMA, 229 mm gravel base, and 3 m subgrade. They investigated the effect of increasing the moisture content in the subgrade and mathematically modeled

this in terms of a power function relating accumulated permanent strain in the subgrade and rut depth (see chapter five). From the study it was found that stresses and strains increased rapidly during the early loading cycles and the rate then tended to slow down. Either the dynamic or permanent strain could be used to relate to surface rutting. The use of the ϵ -mu coil system proved to be very successful. This method of measuring strain uses a signal conditioner system for collecting and decoding signals generated between two coils placed in the pavement layer system. It requires a good low-pass filter system to remove excessive noise from the dynamic output signal. Further validation was planned to include other soils and moisture contents.

Under freeze-thaw conditions, the effect of water is greatly increased because of the development of pore pressures. The result was a dramatic reduction in subgrade strength. The topic was discussed earlier in this chapter in the section on the influence of low temperature on the pavement structure.

Artificial Wetting of the Pavement Structure

Several innovative ways have been used to simulate the ingress of water into the pavement structure to study the effect of water and/or moisture. These include trafficking

with water on the surface (Walubita et al. 2000). In the SA–HVS program the researchers spray water onto the surface to apply wet trafficking. In addition, they inject water through drilled pipes into one or more of the pavement layers under 1 to 2 m positive static pressure (Maree et al. 1982; Rust et al. 1997).

Kadar and Walter (1989) give details of a procedure that was used to weaken the subgrade to achieve acceleration of distress. In essence, this entailed among other procedures

- Using a longitudinal gradient for the test pad at 1% fall,
- Constructing the drainage layer above ground (for positive drainage),
- Allowing positive drainage flow into the structure, and
- Constructing impermeable barriers between layers and between test layers.

Moisture in the Pavement Structure During Freeze–Thaw Cycles

The effect of moisture in the pavement structure is well known. A number of APT programs have studied this phenomenon and some valuable findings have been reported.

Newcomb et al. (1999) extensively discussed the impact of moisture in the pavement structure, particularly as it affects the pavement during the freeze–thaw period of the year. They noted that at the moment when the soil becomes unfrozen and there is excess water in the base course, the soil weakens to its lowest point. This affects the stiffness of the layers and hence the pavement design and operational requirements.

Saarelainen et al. (1999) reported on full-scale APT of a pavement on thawing, frost-susceptible subgrade using the HVS–Nordic with environmentally controlled conditions. The objective was to simulate natural thaw weakening in pavement subgrades. The pavement consisted of an HMA (50 mm), on a crushed-rock base layer (200 mm), and a subbase layer of sand (250 mm). The structure was constructed on six subgrade layers of lean clay. The tests were conducted by freezing the pavement to a depth of 1.2 m and testing with the HVS–Nordic once the thaw depth had reached 0.9 m, with the temperature kept constant at 10°C. Pressure cells and strain gauges were installed and pore pressures were measured. It was found that the APT cyclic loading increased the state of static pore pressure. The time between two load pulses was approximately 7 s. The main purpose of the test was to determine a reference limit for the deflection of the pavement during thawing to ensure a predetermined rut depth limit (see chapter four for a further discussion). The dramatic impact of thawing on the subgrade support was evident. Tests to evaluate this have been

reported by Zhang and MacDonald (1999). These were discussed in the section on APT at low temperature earlier in this chapter.

MINNESOTA ROAD RESEARCH PROJECT—A COMPREHENSIVE CASE STUDY OF VEHICLE–PAVEMENT–ENVIRONMENT INTERACTION

Mn/ROAD was intended to provide a full-scale test facility where the complex interaction between climate, materials, and traffic could be studied relative to the design and performance of the pavements. Forty pavement sections were constructed consisting of concrete-, asphalt-, and aggregate-surfaced structures. Both low- and high-volume traffic were considered. Climatic conditions are such that the frost-susceptible silty clay subgrade would provide insight into the environmental impact on the pavement structure. Provision was made to allow for nonfrost-susceptible material to allow for comparison. The results have been very good and have provided the basis for developing the mechanistic–empirical design system. In addition, it was possible to determine the effect of the spring thaw on the pavement structure, and this provided the basis for structuring guidelines for restricting truck loads in the state during the critical period of the year. The analytical model and the transfer functions, as well as seasonal changes in material properties, provided the basis for the systematic development of the procedure.

The system comprises a computerized design procedure called ROADENT, which is an interactive, user-friendly, flexible pavement-thickness design program. WESLEA (Waterways Experiment Station Layered Elastic Analysis) is the analytical model used in ROADENT for calculating strains in critical locations. Strains at the bottom of the asphalt layer in a variety of pavement structures in six instrumented flexible pavement sections in the Interstate portion of Mn/ROAD were used to confirm the reasonableness of WESLEA calculations (Chadborn et al. 1997).

It is important to note the close collaboration with other entities that provided input into the system, such as the USACE and the state of Washington. Another aspect that received attention was the determination of vehicle load damage. As could be expected, material characterization and instrumentation formed a major part of the program. A variety of other concerns are being addressed, such as ultra-thin white topping, drainage characteristics, and low-volume roads. An integral part of the design system is the use of Monte Carlo simulation. This enables the design to take care of input variability in terms of moduli and thicknesses of the layers. The computer program Evercalc was employed to accomplish back-calculation. In the analysis a stiff layer is used to accommodate the relatively high water

table. Changes in the moduli during the year were monitored and used for the design system. Miner's hypothesis was used to define the state of damage. Also investigated was the use of air temperature as an indicator of thawing following the research done in Washington. Revised reference temperatures were determined for calculating a cumulative degree days thawing index. The onset of thawing could be predicted from measurements of actual in situ air temperature. This information was subsequently used to revise Minnesota DOT policy on the application of spring load restrictions.

SUMMARY

The studies cited show the importance of vehicle–pavement–environment interaction. A wide range of factors that affect this interaction were discussed. Through the application of APT, it was possible to gain insight that has benefited pavement engineering in general. As an example, it has been found that the damage exponent in terms of rutting and cracking varies depending on the degree of deterioration, the criterion used for comparison, the pavement structure, material characteristics, and the condition of the pavement at the time of comparison. The range extends from as low as 1.7 to as high as 10 and even more. Simi-

larly, the impact of suspension type on the extent of damage owing to wheel load is now well understood.

However, it was also apparent that there was a need to address several knowledge gaps, particularly in terms of the impact of the environment on pavement performance. A failure to properly incorporate environmental effects was the one factor that could jeopardize the broader application of APT in the field of pavement engineering. Nevertheless, there were several important case studies available to serve as guidelines for the best way to approach this problem. The extent of APT work that is needed became clear through the synthesis of all of the experimental studies. Some of the topics that need further attention are

- Lateral wander,
- Unidirectional versus bidirectional trafficking,
- The effect of surface shear,
- The effect of speed,
- The impact of wet trafficking, and
- The effect of soil moisture.

It was apparent that there is a need to formulate and conduct a comprehensive collaborative APT program to develop guidelines to account for environmental effects on vehicle–pavement interaction.

CHAPTER FOUR

EVALUATION OF MATERIALS AND TESTS**INTRODUCTION**

Full-scale APT programs worldwide have produced significant findings comparing and evaluating pavement material response and performance. The primary goal of most programs is to evaluate new, innovative, recycled, materials, with validation of traditional materials as a secondary goal. Another primary goal of many programs is to validate laboratory material characterization through comparison with response under full-scale loading, recognizing that a strategic approach that incorporates APT, laboratory testing, long-term field evaluation, and modeling or analysis, produces meaningful results that allow for the consideration of material, loading, and environmental variability. This chapter presents the current knowledge base in these two areas in general, recognizing that the results are not specifically comparable because of differences between programs in terms of loading and environmental conditions, measurement and analysis techniques, and failure definitions. These differences are expected, given the high cost of operating full-scale APT devices and the corresponding necessity to produce goal-specific results that advance the understanding of pavement materials and behavior for the conditions most relevant to the funding agency for a particular program. Because of the substantial resources required and a focus on multiple goals, experiments that use APT technology in conjunction with laboratory testing and analysis have not provided as many results specific to materials evaluation when compared with experiments that use only laboratory testing. This highlights the importance of sharing significant findings and underscores the potential for substantial gain through cooperation and coordination of multiple APT programs.

Significant findings from applying full-scale APT technology to evaluating materials and tests are organized in this chapter by pavement layer, with the discussion presented by material type. Following an overview of field and laboratory material characterization used in different APT programs, general response and performance results are presented without describing specific instrumentation, the comparison of different measurement techniques, or specific parameters that were monitored and analyzed. All of these results must be qualified in recognition that differences between full-scale APT loading and environmental conditions and those under full-scale traffic in service do exist. Separation of the materials evaluation results from the discussions of design considerations in chapter two and

maintenance and rehabilitation techniques in chapter six is incomplete because of the synergy between material selection and structural design. Unconventional pavement materials, including block pavers and ultra-thin whitetopping, and performance not related to primary forms of distress, including drainage effects and curling and warping of concrete pavements, are discussed subsequently in chapters six and seven.

Before discussing the wide variety of applications that were found in the literature, the results from a synthesis of the questionnaire survey is presented.

QUESTIONNAIRE SURVEY

The responses to Questions 4.1 to 4.9 on materials and tests are reflected in Figures C31 to C38 in Appendix C. These responses were synthesized and the results are contained here.

- Asphalt Pavements
 - HMA was tested the most frequently, followed by granular materials and stabilized materials. There is far less focus on other materials.
 - In terms of mix type, continuously graded or dense-graded mixes have been tested the most frequently, both for surfacing and base courses.
 - Asphalt parameters most frequently measured include density, gradation, binder content, and stiffness.
 - Special materials such as geogrids have also been tested.
 - In the laboratory, the indirect tensile test is the test most frequently used to evaluate the strength of asphalt materials.
 - Sample preparation was either by gyratory compaction or by Marshall compaction.
 - There were essentially two binder tests that were being used, the Dynamic Shear Rheometer and Penetration and Softening Point. The bending beam rheometer and rotational viscometer were also used frequently.
- Concrete Pavements
 - Jointed concrete pavements were the most common rigid structures tested.
 - PCC was the primary material tested in jointed concrete pavements.
 - In the laboratory, cylinder compressive tests were the most frequently used.

- Flexural strength and stiffness, together with compressive strength, were the primary items that were evaluated for the purposes of controlling the concrete materials.
- In the field, the FWD was the primary tool used to gain insight into the characteristics of the pavement structure. Density and moisture measurements also featured prominently. Other supplementary tests were ground penetrating radar and the dynamic cone penetrometer. Deflection measurements were also done with the Benkelman beam.

Views of the respondents to the survey on materials and tests are presented in Table D4 in Appendix D.

MATERIAL CHARACTERIZATION

Most APT programs use both field and laboratory material characterization to assess pavement response and performance under full-scale APT loading. Performance monitoring at the APT test section generally involves measurement of transverse and longitudinal profiles, deflection and deformation at the surface or with depth in response to a moving load or falling weight, in situ density, environmental conditions including moisture and temperature with depth, visual surface distress, and in situ stresses and strains. For concrete pavements, relative joint movement is also usually monitored. Other field characterization used in some APT programs included SASW to determine stiffnesses (elastic moduli) and detect damage prior to visual distress identification (Lee et al. 1997), in situ permeability testing, trenching after failure, and measurement of the relative shear resistance of unbound materials. Surface friction or skid resistance is also monitored in some programs. In other programs a scaled APT device was used on a section adjacent to the section tested by the full-scale device to aid in evaluating the effects of different environmental conditions including moisture and elevated temperatures.

Laboratory characterization varies widely from program to program depending on the goals, experience, and available equipment. Stiffness measured by resilient modulus and density of field cores and each layered material are determined as part of most APT tests. Shear stiffness measurements in frequency sweeps and indirect tensile testing of asphalt materials are also common. Triaxial testing of unbound materials through the use of standard or modified equipment is common. Permeability tests on these materials in the laboratory have also been completed. Technology and analysis systems for asphalt materials developed during SHRP were used in a number of APT tests. Many studies included AC mixture tests to determine resistance to fatigue cracking in third point flexural fatigue tests and

resistance to rutting in either repeated or simple shear tests. One APT program also included AC mixture testing to ensure adequate resistance to thermal cracking (Epps et al. 1999). Resistance of these materials to rutting is also commonly assessed through the use of wheel-tracking devices or creep tests. In addition, traditional and SHRP performance grade binder tests are used to characterize asphalt binders and their contribution to both fatigue and rutting performance. Indirect tensile fatigue tests and semi-circular bending tests are also occasionally employed to characterize AC. Moisture susceptibility testing of AC through the use of retained indirect tensile strength ratios before and after wet conditioning also contributed to the assessment of APT results. Direct tension testing of both asphalt and concrete materials has also been used, although less frequently. Common characterization for concrete materials includes determination of compressive and flexural strength and stiffness. Other performance indicators for these materials, for example, sulfate resistance and ASR potential, are also measured in some APT tests, for example, CAL/APT (California Accelerated Pavement Testing) (Harvey et al. 2000).

Metcalf (1996) and others provided detailed descriptions of instrumentation used to obtain these field and laboratory measurements. These measurements are then analyzed using a number of different procedures to determine pavement performance in terms of primary forms of load-related distress. The possible effects of environmental conditions were then assessed through the use of laboratory characterization and modeling or analysis. A summary of these general performance results related to the evaluation of materials and tests follows.

Surface

To date the majority of APT tests have been conducted using AC or a bituminous chip seal as the surface pavement layer. For many of the AC surfaces, modified binders were included and exhibited enhanced performance in terms of resistance to rutting and/or fatigue cracking. The ALF program in Australia reported this enhanced performance for AC mixtures with a range of modified binders used in rehabilitation treatments (Kadar 1991; Sharp et al. 1999a). The improved fatigue performance and adequate rutting performance of a rich bottom AC layer; that is, a layer with a high binder content, was also demonstrated. Laboratory fatigue and dynamic creep testing of mixtures to examine performance highlighted a need for standardized test methods.

The ALF program in Australia also explored the use of modified binders to increase AC mixture resistance to permanent deformation (Oliver 1994; Sharp et al. 1999a). Stone matrix asphalt (SMA) mixtures that incorporated full-scale loading under the ALF and extensive laboratory

testing were also included in this study. Conventional mixtures with two different filler contents and five different binders, including one modified with styrene butadiene styrene (SBS) polymer and one modified with EVA polymer, were evaluated, along with a recently developed rut resistant mixture with a conventional binder and an SMA mixture. Laboratory testing included dynamic creep testing, resilient modulus determination, laboratory wheel-track testing, and measurement of the Superpave binder rutting parameter $G^*/\sin\delta$. Mixture creep and resilient modulus testing revealed a significant effect of filler content. Creep test results of field core specimens measured at a representative ALF trafficking temperature were also able to identify a significant effect of binder type; however, these results could not distinguish between mixtures with different aggregate gradations (filler content). Mixture creep properties of field-core specimens measured at elevated temperatures did not correctly rank rutting performance under full-scale loading. Laboratory wheel-track results at 60°C (using the Australian wheel-tracking device) correlated with field performance under the ALF at 50°C and served as an indicator of mixture resistance to rutting. The binder parameter $G^*/\sin\delta$ was also invalid as an indicator of rutting performance for the modified mixtures. Mixtures incorporating the SBS-modified binder and a multigrade binder exhibited reduced temperature susceptibility and an increased resistance to rutting when compared with the other mixtures.

The CAPTIF program in New Zealand also investigated the effects on performance of modified binders in AC surface layers constructed on nominally identical pavement structures (Pidwerbesky 1995b). The performance of a thicker AC layer with a conventional binder was equivalent to that of thinner layers containing either a high-stiffness unmodified binder or binders modified with a plastomer or one of three different elastomers. At the conclusion of the APT tests, all of the structures exhibited minimal surface distress and negligible structural deterioration.

The CAL/APT program found that a gap-graded, crumb-rubber-modified AC overlay outperformed a dense-graded mixture with a conventional binder in terms of permanent deformation when the structure is adequate to preclude permanent deformation of the underlying layers (Harvey et al. 2000). Both overlays, discussed as rehabilitation measures in chapter six, also exhibited substantial resistance to reflective cracking from the underlying failed AC layer. This program also demonstrated the use of the flexural fatigue test for AC mixture design and analysis developed during SHRP. Use of the repeated simple shear test at constant height, also developed during SHRP, was recommended for modified AC mixtures.

The SA-HVS program also investigated the use of bitumen-rubber asphalt in a relatively thin, open-graded AC

overlay of a cracked concrete pavement (Viljoen et al. 1987). This overlay exhibited good performance in terms of reflection cracking when compared with many other rehabilitation overlays, including those with different types of interlayers, as discussed in chapter six.

The LA ALF program also examined crumb-rubber-modified AC in a surface layer and found no significant improvement in mixture rutting performance as compared with conventional AC (Mohammad et al. 2000). This finding was consistent with laboratory mixture characterization, including indirect tensile strength and resilient modulus, indirect and axial creep results, and Superpave shear tests.

Modified asphalt binders were also used at the LCPC facility in France in two experiments aimed at determining the binder effect on both rutting and fatigue of AC (Corté et al. 1994, 1997; De la Roche and Rivièrè 1997). For the rutting tests, surface layers with seven different binders were placed on nominally identical pavement structures. The binders evaluated included one conventional unmodified material, two with low-temperature susceptibilities, one modified with SBS elastomer, one modified with EVA plastomer, one hard binder (20/30 Pen), and one modified with low-density polyethylene waste. The hard binder was used in a high-modulus mixture that had an additional very thin AC layer at the surface. When compared with the conventional mixture, mixtures with modified binders exhibited increased resistance to rutting in laboratory wheel-tracking tests with the French device. In addition, all mixtures incorporating new and innovative materials exhibited better rutting performance under full-scale loading. The high-modulus mixture with its very thin AC surface layer also retained surface texture under trafficking. Other laboratory mixture test results, including those from repeated triaxial and static and dynamic creep tests, provided performance rankings equivalent to those based on performance under full-scale loading or in laboratory wheel-tracking tests.

For the LCPC fatigue tests, surface layers with five different binders and three thicknesses were constructed on nominally identical pavement structures (De la Roche et al. 1994). These binders included two conventional unmodified materials of the same grade, but obtained from different sources; two hard binders (20/30 Pen) of the same grade from different sources used in a high-modulus mixture and one binder modified with SBS polymer. For one of three experiments included in this study, very thin AC surface layers were used; these thin surface layers were omitted from the other experiments. The two mixtures with conventional binders from different sources exhibited similar fatigue performance under full-scale loading, but very different fatigue behavior was measured in the laboratory. When compared with a conventional mixture, the high-modulus mixture is expected to increase fatigue life, but

this material must be used on relatively stiff supporting layers. On a deformable supporting layer, this type of mixture in a thin layer offered no improvement in performance, but performance benefits increased rapidly with thickness. When properly used, a high-modulus mixture can offer performance benefits in terms of resistance to both fatigue cracking and rutting. The polymer-modified mixture also increased fatigue life, but only slightly. As part of this study, extensive laboratory fatigue testing was also completed. Laboratory test results indicated that relative fatigue performance depends on the specific test, the presence or absence of rest periods, and the testing mode. Relative behavior of the mixtures evaluated in this study was successfully predicted using controlled-stress fatigue testing in the laboratory.

Modified asphalt binders were also evaluated as part of the FHWA ALF program to validate Superpave binder parameters controlling rutting and fatigue cracking of AC (Stuart et al. 1995, 2000; Stuart and Mogawer 1997; Romero et al. 1998, 2000; Sherwood et al. 1998, 1999). For the rutting tests, surface layers with two aggregate gradations and maximum sizes and five different binders, including one modified with low-density polyethylene and one modified with styrene-butadiene polymer, were placed on nominally identical pavement structures. When compared with conventional binder mixtures, modified binder mixtures exhibited more resistance to rutting as measured under full-scale loading and indicated by high binder $G^*/\sin\delta$ values. Mixtures with larger nominal maximum size aggregate also exhibited decreased susceptibility to permanent deformation. The Superpave binder specification test results correlated well with rutting performance in the APT tests for conventional mixtures, as did test results with three laboratory wheel-tracking devices. Modified mixture performance was less sensitive to the binder parameter $G^*/\sin\delta$, and this parameter did not successfully predict the performance of these mixtures under the ALF or in laboratory wheel-tracking tests. This study highlights the need for additional characterization of modified binders and mixture testing of modified mixtures to capture their improved performance. As part of this same study, laboratory shear testing and wheel-tracking tests of two unmodified mixtures were not able to capture the effect of aggregate gradation on rutting performance, although they were able to capture the effect of the binder on rutting performance.

For the FHWA ALF fatigue tests, surface layers with two thicknesses and five different binders, including one modified with low-density polyethylene and one modified with styrene-butadiene polymer, were placed on nominally identical pavement structures. The Superpave binder specification test results correlated with fatigue performance in the APT tests only for the thin AC layers when binder testing was conducted at a higher frequency (Sherwood et al. 1999). This behavior is expected because flexibility in thin

layers increases fatigue life, and the Superpave specification sets a maximum $G^*/\sin\delta$ value at intermediate temperatures. This parameter was derived for strain-controlled conditions in thin AC layers, and thus the specification only applies to thin layers where these conditions are appropriate (Stuart et al. 2000). The binder effect on fatigue performance also reflected this dependence on AC layer thickness. Mixtures whose binders have high $G^*/\sin\delta$ values exhibited increased resistance to fatigue cracking in thin layers and decreased resistance in thick layers. These effects are also expected for mixtures with polymer-modified binders with anticipated high $G^*/\sin\delta$ values. As part of this same study, flexural fatigue testing of AC mixtures was conducted. When comparing mixtures with different binders, results from the laboratory were in agreement with the full-scale APT results. The flexural fatigue test was recommended to determine relative fatigue performance; however, its limitations when used as a stand-alone test to account for pavement structure and representative temperature fluctuations were recognized (Romero et al. 2000). As developed in the SHRP program, this test must be used as part of a design and analysis system.

The Texas DOT program evaluated a thin AC surface layer and found early fatigue failure resulting from high air void contents and construction variability (Hugo et al. 1997). Early and unexpected rutting failure occurred in coarse-graded AC mixtures at WesTrack (Epps 1998; Epps et al. 1999). In this APT program, coarse- and fine-graded AC mixtures at three air void contents and three binder contents were placed on nominally identical pavement structures, and performance was monitored toward development of performance-related specifications for AC and field verification of Superpave volumetric mix design. Materials evaluation involved both field performance in terms of fatigue cracking, rutting, moisture damage, and thermal cracking, and corresponding mixture characterization tests in the laboratory. Coarse- and fine-graded mixtures performed differently in both field and laboratory conditions. Moisture sensitivity was indicated for one-half of the mixtures according to laboratory determination of the ratio of indirect tensile strength before and after moisture conditioning; however, moisture damage was not detected under full-scale loading as designed. This result highlights the need to reevaluate this laboratory testing process and the correspondence of laboratory results with field performance.

All mixtures were also designed to preclude thermal cracking. Laboratory test results and field performance both indicated adequate resistance to this form of distress. Similar results in both the laboratory and field performance were also demonstrated with the flexural fatigue test and corresponding fatigue cracking. As expected, mixtures with lower air void contents and higher binder contents exhibited increased resistance to fatigue. These effects were

amplified for coarse-graded mixtures. For rutting performance, field and laboratory mixture assessment again agreed in terms of the effects of air void content, binder content, temperature, and gradation. Laboratory assessment included the use of repeated shear tests, shear frequency sweeps, laboratory wheel-tracking devices, and a scaled APT device (Ruiz and Romero 1999; Williams and Prowell 1999; Epps et al. 2002). The unexpected rutting performance displayed during this APT test highlighted the need for including a mixture performance test at a critical high temperature in the Superpave mix design process. Other recommendations for improving the design of these mixtures are discussed in chapter five.

Coarse-graded Superpave AC mixtures also exhibited less resistance to permanent deformation when compared with fine-graded mixtures during APT tests conducted as part of the Indiana DOT/Purdue program (Galal and White 1999; White et al. 1999). Laboratory characterization using a scaled wheel-tracking device and shear frequency sweeps validated these results under full-scale loading. In a separate warranty study, a Superpave AC mixture demonstrated improved rutting performance compared with a conventional mixture. A third study in the Indiana DOT/Purdue program emphasized the need for a minimum percentage of crushed aggregate to ensure adequate rutting performance of AC mixtures. This study also examined the effect of coarse aggregate type on rutting performance and found that slag and limestone aggregates that are traditionally crushed produced mixtures with rutting performance substantially better than mixtures with more rounded, uncrushed gravel aggregate.

To validate Superpave mixtures for implementation in Kansas, the Kansas Accelerated Testing Laboratory (K-ATL) program used the agency's APT facility to traffic two fine-graded Superpave mixtures with two different percentages of natural sand (Wu et al. 2000). These mixtures were constructed on nominally identical pavement structures. Both mixtures exhibited severe rutting after relatively few load applications, from shear flow of the mixture with a high natural sand content and from consolidation of the other mixture. At this point, no visible fatigue cracking was present in either mixture. Flexural fatigue testing in the laboratory indicated that the mixture with a lower natural sand content is expected to exhibit better resistance to fatigue cracking; however, this result was not validated under full-scale loading as a result of the rutting failure. This program also found that a Superpave mixture provides better rutting performance as an overlay of concrete pavement, when compared with a commonly used mixture designed by the more traditional Marshall method.

Based on relatively few full-scale load applications, the HVS-NORDIC program in Finland estimated the relative performance of a traditional AC structure with an SMA

surface layer and a conventional AC base and an innovative structure with a stiff AC surface layer and a flexible, fatigue-resistant AC base layer (Huhtala et al. 1999). The innovative structure was estimated to substantially increase fatigue life based on pavement response data measured in terms of strain at the bottom of the AC layers and laboratory stiffness and fatigue testing.

The Texas DOT program reported on the comparison of two rehabilitation processes under APT (Hugo et al. 1999a,b; Smit et al. 1999; Walubita et al. 2000, 2002). The tests are also discussed in chapter six. It was found that the recycling of a thicker layer of lightweight aggregate asphalt concrete (LWAC) resulted in improved rutting performance and decreased layer deflections as compared with the recycling of a thinner layer of the same material in situ and overlaying with a new AC mixture. Details of the pavement and rehab structure are shown in Figure 11

Both surface layers exhibited substantial resistance to permanent deformation, but the remaining underlying LWAC was less resistant to rutting and susceptible to moisture damage. The process that involved recycling of the thinner layer in situ and placement of an overlay was also more susceptible to moisture damage; however, these materials exhibited improved fatigue performance under hot and dry conditions. Both sections showed reduced fatigue lives after wet trafficking based on indirect tensile fatigue testing. These results highlighted the importance of considering degradation and deterioration that are the result of the combined effects of trafficking and moisture. Use of seismic analysis of surface waves to detect decreasing stiffness during wet trafficking was also demonstrated (Walubita et al. 2002). Material evaluation results for this type of APT test are difficult to assess without the extensive use of laboratory characterization because the original pavement structures play a large role in performance, as discussed in chapter six. In this case, the underlying LWAC lay on a stiff structure, and therefore pavement performance was controlled by the rehabilitated layers and the underlying LWAC.

AC overlays of nominally identical pavement structures were also evaluated in the SA-HVS program (Kong Kam Wa et al. 1997). This APT program has traditionally tested in-service pavements, and therefore the evaluation of rehabilitation techniques, as discussed subsequently in chapter six is common. The performance of a dense-graded AC mixture with a conventional unmodified binder was compared with that of a more open-graded mixture containing styrene-butadiene-rubber binder. Two different overlay thicknesses were examined for each mixture, with smaller values used for the polymer-modified mixture with the expectation of equivalent or improved performance. Improved fatigue performance of the modified mixtures was demonstrated in flexural fatigue tests in the laboratory.

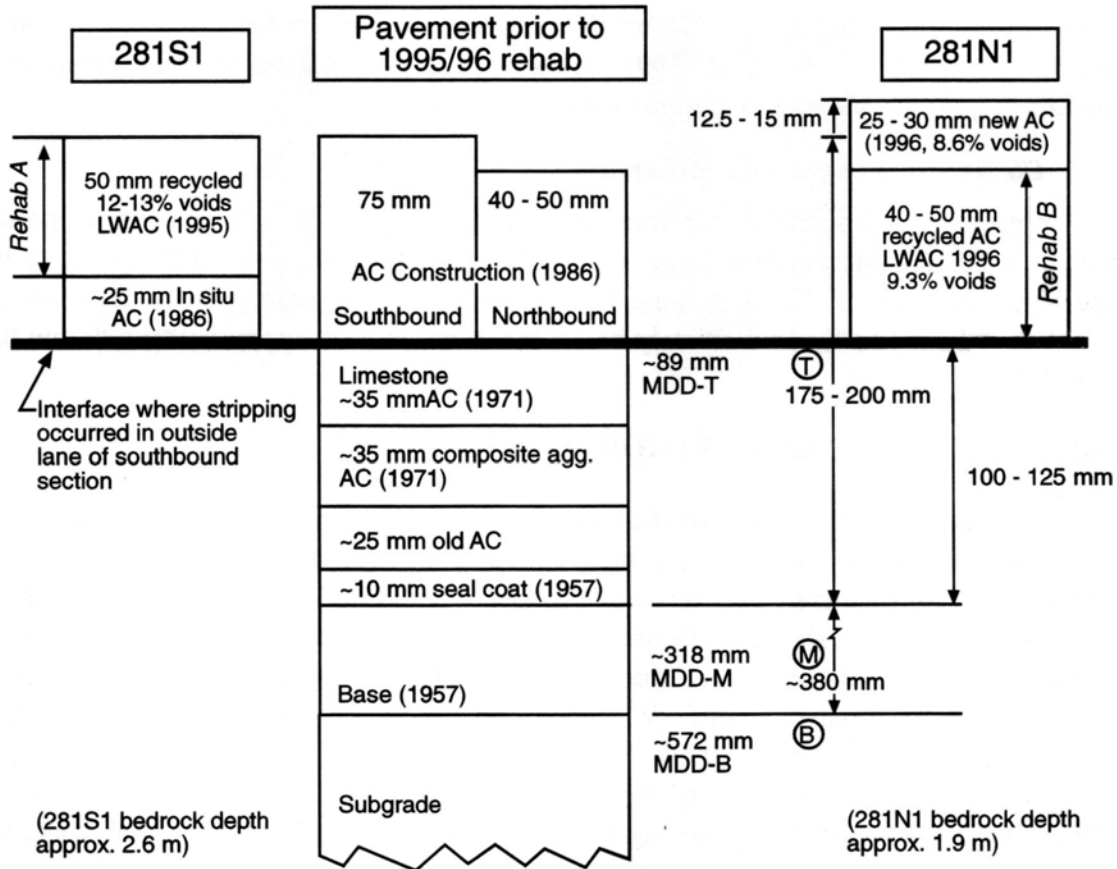


FIGURE 11 Texas US-281 pavement structures tested with the TxMLS and the MMLS3 (Walubita et al. 2002).

Traditional stiffness prediction methods were not applicable to the modified mixtures; these methods could not predict stiffness values measured in indirect tensile testing and determined from deflection values measured by layer.

APT has also been used to evaluate bituminous materials other than AC as surface layers, but less frequently. The ALF program in Australia demonstrated adequate performance of geotextile-reinforced chip seals over clay subgrades for low-volume roads (Sharp et al. 1999a). This result validated the use of local materials that produced cost savings by removing the need to import higher quality materials. The ALF was also used to evaluate deep-lift, in situ recycling (Sharp et al. 1999a). Slag/lime binder was used at three different recycling depths and performance was compared with an unbound granular material. Adequate fatigue performance was obtained for all stabilized sections. Modulus and unconfined compressive strength values of laboratory-compacted specimens and field cores did not match because of differences in preparation techniques.

Recently, interest has revived for using APT to evaluate concrete materials. The CAL/APT program examined FSHCC in a jointed concrete pavement (Roesler et al. 1999;

Harvey et al. 2000). The fatigue of this material was similar to ordinary type II PCC tested in the laboratory. Recommendations included enhanced laboratory characterization of the sulfate resistance and ASR potential of these concrete materials to improve performance prediction. These were based on laboratory tests to study those aspects that were run to complement the accelerated load testing. The use of a nonerodable, flexible support material to ensure adequate performance was also suggested. According to the questionnaire survey, the K-ATL program found no improvement in performance from fiber reinforcement of a plain concrete overlay without dowels. As discussed earlier in chapter two, the ALF program in Australia recently completed APT tests of plain concrete pavements to quantify the effects of different design elements (Vuong et al. 2001).

Base/Subbase

Numerous APT tests have been conducted to examine the performance of unbound and stabilized granular materials used as base or subbase pavement layers. These studies are particularly prevalent in international APT programs because of the role and importance of these layers in many

low-volume road networks. On these networks, thin AC layers or chip seals are usually only providing a surface that waterproofs the underlying base and/or subbases.

The first APT test in the CAPTIF program in New Zealand validated the use of well-compacted, dense-graded, crushed, and unbound materials as base layers beneath chip seal surface layers (Pidwerbesky 1995b). The first APT test in the Australian ALF program investigated the performance of unbound and stabilized base materials beneath a thin surface seal (Kadar and Walter 1989). The use of base materials stabilized with slag in place of high-quality crushed rock was validated under full-scale loading when adequate support from the subgrade and protection from a surface layer are provided. The second ALF test verified adequate performance of crushed rock pavements surfaced with chip seals, provided that the seal is kept intact (Sharp et al. 1999a). The third ALF test demonstrated that deterioration of a CTCR base could be duplicated under ALF loading (Kadar et al. 1989; Sharp et al. 1999a). This material failed by debonding at the interfaces of the multiple lifts placed during construction and by erosion of the bottom of the top layer. These results primarily influenced construction practices as discussed in chapter seven.

The CAPTIF program also investigated the effect of aggregate size and shape in unbound base layers beneath open-graded AC surface layers (Pidwerbesky 1995a). Aggregate shape had the most pronounced effect on performance in terms of deflection and deformation measured at the surface under full-scale loading, validating the aggregate angularity specification for unbound base materials. The more coarse-graded base material did exhibit improved performance when compared with the more fine-graded material. There were also differences in the performance of base materials with the same gradation. Possible reasons for this could be differences in compacted density and the percentage of angular particles in the mix. The higher density appeared to outweigh the effect of the percentage of angular particles, because the former materials had less deformation.

The ALF program in Australia also investigated the use of marginal sandstone by stabilizing in situ with slag/lime or bitumen/cement binders (Sharp et al. 1999a; Yeo et al. 1999). Performance of stabilized sections was compared with that of a section with the same material in an unbound state. All sections had a thin AC surface layer. Both stabilized sections exhibited good performance in terms of fatigue cracking and subgrade deformation. Failures of the thin surface layer were addressed by the placement of a prime coat before constructing this layer and recommendations to seal the stabilized layers to prevent cracking. As for the deep-lift, in situ recycling study, modulus and unconfined compressive strength values of laboratory-compacted specimens and field cores did not agree.

Marginal sandstone was also evaluated in a second study conducted by the ALF program in Australia (Vuong et al. 1996; Sharp et al. 1999a). In this study, performance of a base layer consisting of a high-quality marginal sandstone was compared with that of a more abundant, lower-quality marginal sandstone. In addition, performance of an unbound sandstone base was compared with that of one composed of sandstone stabilized with a bitumen/cement binder. With a stiff underlying subgrade, any of the marginal materials tested exhibited adequate performance in support of a waterproof surface seal. These materials did not add to the pavement structural capacity; permanent deformation manifested in these layers and the surface seal. Reconstructed sandstone bases on these types of subgrades only improved performance up to a specific thickness, resulting in recommendations for thinner structures, as discussed in chapter five. The stabilized base exhibited good performance in terms of increased stiffness, decreased permanent deformation, and resistance to water infiltration. Stabilization with a bitumen/cement binder was also effective in improving the performance of a high-quality reconstructed crushed-rock base.

The Australian ALF program also conducted additional APT tests to establish a simple test to characterize unbound granular materials in terms of resilient modulus and permanent deformation (Sharp et al. 1999a). High-quality crushed-rock bases beneath thin AC surface layers were used in this study and a standardized laboratory repeated load triaxial test method was proposed.

Both good and poor quality lateritic gravels or ferricrete beneath sealed surfaces also performed adequately under dry conditions in another Australian ALF study (Sharp et al. 1999b). After moisture infiltration, both of these materials failed.

As part of the CAPTIF program in New Zealand the performance of lime-stabilized subbase materials was compared with that of unbound crushed aggregate materials in nominally identical pavement structures (Pidwerbesky 1995a). Laboratory testing was used to determine optimum stabilizer content, and the stabilized materials outperformed the unbound materials in terms of deflection and deformation measured at the surface under full-scale loading. Increasing the thickness of the stabilized subbase layer also substantially improved performance. Stiffness values measured in the laboratory and those determined based on deflections measured in the field did not agree because of compaction problems on a weak subgrade.

The SA-HVS program has traditionally tested in-service pavements; therefore, evaluation of rehabilitation techniques as discussed in chapter six is common. In terms of materials evaluation, this program examined the performance of labor-intensively constructed bases under full-

scale loading and in static and dynamic triaxial tests (Theyse 1999). Emulsion-treated natural gravel, waterbound and composite macadams, and an untreated and emulsion-treated ash waste material were compared to a machine-constructed, crushed-stone base. Each base material was supported by a cement-treated sandstone base and either imported sandstone or ferricrete. The crushed-stone base exhibited the best performance under full-scale loading in terms of rate of permanent deformation and bearing capacity (defined as the number of load repetitions to a specific level of permanent deformation). Static triaxial test results produced the opposite results for the ash waste material; however, a valuable link between dynamic triaxial test results and performance under full-scale loading was realized in this study. The best labor-intensively constructed base material was the emulsion-treated natural gravel. Waterbound macadams were also recommended for heavier traffic loads on light pavements, although the ash waste material with adequate compaction is appropriate for lower traffic loads.

The SA-HVS program has also used APT tests in the development of guidelines for the use of new base materials, specifically large aggregate mixes for bases (LAMBs) and granular emulsion mixes (GEMs) (De Beer and Grobler 1993). LAMBs were tested under full-scale loading to validate an extensive laboratory testing program that demonstrated adequate performance of these materials in heavy-duty pavements. Dynamic creep modulus was also correlated with deformation under full-scale loading. The performance of GEMs that upgrade marginal in situ materials was comparable to an imported crushed aggregate base under full-scale loading. Because of reduced transportation and material costs, this finding again directly results in cost savings as discussed in chapter nine.

Other base materials evaluated in the CSIR program in South Africa included roller-compacted concrete, slag, recycled AC, and emulsion-treated recycled granular material (Horak et al. 1992; Rust et al. 1997). Design and usage guidelines for all of these materials were developed based on their performance under full-scale loading. For example, in rehabilitating untreated or cement-treated bases, the addition of cement and lime to emulsion-treatment improves strength and durability. This type of base material exhibited decreased fatigue performance when compared with AC, but resistance to fatigue was greater than for cement-treated bases (Horak and Rust 1992). Guidelines for the stabilization of marginal natural aggregate materials were also developed based on APT test results. High-quality granular materials were also tested under full-scale loading to verify their use in heavy-duty pavements.

The HVS-NORDIC program in Finland tested two crushed-rock base materials of different quality underneath AC surface layers (Huhtala et al. 1999). Definitive results

were not provided in this first study because of abbreviated tests and incomplete analysis; however, performance was better than expected.

The CAL/APT program compared the performance of a high-quality unbound aggregate base to a commonly required ATPB (Harvey et al. 2000). Both pavement structures tested contained a dense-graded AC surface layer, and performance was evaluated in terms of response under full-scale loading and in standard and repeated triaxial testing in the laboratory under dry and saturated conditions. Permeability testing in the field and the laboratory was also conducted. The ATPB layer was determined to be unnecessary if the permeability of the AC surface layer is decreased and the fatigue resistance is increased through adequate compaction, increased binder content, and increased layer thickness. Improved performance in terms of resistance to fatigue and increased structural capacity was demonstrated for the ATPB in comparison to the unbound aggregate base. However, if ATPB layers are used, stripping and intrusion of fines was shown to be likely in the wet condition. To preclude the failure of this layer, recommendations were made for periodic maintenance of the drainage system, increased binder contents and the use of modified binders, geotextile filters, and additives to guard against moisture damage. Moisture sensitivity evaluation of ATPB in the laboratory was also suggested.

The LA ALF program also investigated base and sub-base materials with AC surface layers (Metcalf et al. 1999). Crushed-stone and stabilized soil-cement materials were combined in nine different base/subbase structures and evaluated in terms of performance under full-scale loading. When the stabilized soil cement was used as a base layer, the AC surface layer cracked as a result of reflection shrinkage cracks and top-down cracks. All stabilized base structures failed because of softening and erosion of these materials and subsequent loss of support. The researchers noted that the source material for the soil-cement was silty and prone to erosion. The modes of distress were probably related to the nature of the material. Structures with crushed-stone bases failed owing to permanent deformation of this material. The combination of the two materials with the crushed stone as the base layer in an inverted structure provided improved performance over standard structures containing only one of these materials. In-plant cement mixing and plastic fibers did not improve performance, but improved performance was demonstrated for materials with increased cement content and increased thickness of the stabilized soil-cement layer.

The CEDEX program conducted a third set of APT tests in Spain to examine the performance of base and subbase materials beneath AC surface layers in terms of load-related distress (Romero et al. 1992; Ruiz and Romero 1999). Each structure was designed for the same level of

traffic; therefore, layer thicknesses of the different materials varied. Granular and soil–cement base materials were compared with a third combination of a gravel–cement base with a soil–cement subbase. Two different subgrade materials were also used. Results under full-scale loading indicated that the cement-treated materials provided improved resistance to rutting and exhibited no cracking as compared with the unbound granular material.

An older APT facility at Washington State University examined the fatigue performance of sulfur-modified AC used as a base layer (Mahoney and Terrel 1982). Material performance under full-scale loading and in laboratory wheel-tracking tests indicated that the modified mixture was more sensitive to strain level than a conventional AC mixture. As a result, longer fatigue lives were demonstrated for these modified materials at larger strain levels.

The ALF program in Australia recently completed APT tests to assess erosion of three subbase layers constructed beneath a lean concrete base and a concrete surface layer (Vuong et al. 2001). The performances of unbound and bound crushed granular materials were compared with that of a lean concrete subbase. Results under full-scale loading indicated that unbound subbases provide adequate resistance to erosion.

The SA–HVS program also examined the performance of three rehabilitation options for lightly cemented pavements (LCP) (Steyn et al. 1997). The performance of a double seal, a thin AC overlay, and a crushed-stone base with a double seal surface were compared under full-scale loading to relatively deep and shallow new LCP pavements. The material evaluation results associated with this study included equivalent performance of the rehabilitated and new pavements in terms of permanent deformation at the surface. The rehabilitated pavements failed only in terms of bleeding of the double seal and surface deformation and pumping of fines in the wet condition for the other options. Further results from this study are discussed in related chapters.

The SA–HVS program examined other rehabilitation options through full-scale loading and laboratory characterization of recycled asphalt pavement (RAP) used as a base layer (Servas et al. 1987). Based on the laboratory results, RAP contents from 30% to 70% did not affect performance in terms of indirect tensile strength, resistance to rutting, or resistance to indirect tensile fatigue. Full-scale loading tests confirmed these results and established RAP as a viable material with performance comparable to conventional AC.

Subgrade

Relatively few APT tests have been conducted specifically to evaluate subgrade materials. In chapter two, LINTRACK ex-

periments in The Netherlands on a sand subgrade were discussed (Bhairo et al. 1998a,b). The researchers concluded that the Shell subgrade strain criterion appeared to be applicable for subgrade sands that are prevalent in that country.

One study conducted as part of the HVS–CRREL program used full-scale loading of different pavement structures in developing an understanding of response in terms of subgrade strain as a function of subgrade soil type and moisture content (Lynch et al. 1999; Odermatt et al. 1999). FWD testing during a thawing cycle was conducted to determine stiffness reduction factors for use in design and analysis. The results are discussed in chapter five and elsewhere.

The HVS–NORDIC program also conducted APT tests at a Finnish site during a thawing cycle, with the goal of setting deformation limits for subgrade materials for this critical environmental condition (Saarelainen et al. 1999). Three pavement structures with thin AC surface layers, crushed-rock base layers, and sand subbase layers of equivalent thicknesses were constructed on a frost-susceptible lean clay subgrade. One of the structures contained a reinforcing steel mesh at mid-depth of the base layer. A sand filter layer lay beneath the subgrade layer to control the groundwater level during the thawing cycle. All three structures failed as the result of cracking in the surface layer and permanent deformation from the underlying subgrade layer. The reinforcing steel mesh reduced deformation by 50% in the unbound layer. However, as has been found generally with reinforcement, the pavement first had to deform before the reinforcement became effective.

CURRENT RESEARCH

Ongoing testing at the NCAT test track in Alabama will produce further performance results for AC surface layers (Brown and Powell 2001). Rutting is the expected mode of distress for the 46 mixtures constructed on nominally identical pavement structures. These mixtures include coarse- and fine-graded Superpave mixtures and SMA mixtures. The effects of aggregate type and binder on performance will be evaluated through the use of full-scale loading and performance monitoring and laboratory testing. At the conclusion of the trafficking of phase 1, these mixtures exhibited no visible fatigue cracking and limited, but measurable, permanent deformation. An extensive laboratory mixture testing program to determine the best performance test for assessing rutting performance is also ongoing.

The full-scale trafficking facility at Mn/ROAD has also collected performance monitoring data for AC, concrete, and aggregate surface layers in 40 pavement sections constructed on two different subgrades (Newcomb et al. 1999). This facility uses actual truck trafficking on a mainline fa-

cility and full-scale trucks on a low-volume road. This study focuses on the development of a mechanistic–empirical pavement design procedure and guidelines for truck load restrictions during spring thaws. The impact of material properties on performance is being explored using the same performance data used in achieving the primary goals.

An aircraft load simulator at ERDC–GSL in Atlantic City is also currently being used to verify and validate a 3-D pavement design and evaluation program (Lynch et al. 1999). Data required for reaching this goal can also be used to assess the impact of material properties on performance.

The LA ALF program is currently using full-scale loading to determine the effectiveness of using RAP as a base material in an inverted pavement structure (Metcalf et al. 1999). The performance of the RAP base layer is being compared with that of a crushed-stone base layer in nominally identical pavement structures.

An international cooperative program involving 11 European countries is also ongoing (Hildebrand et al. 2001). This program builds on previous efforts organized under the OECD (Road Transport Research). The new program, organized under the European Cooperation in the Field of Scientific and Technical Research (COST), consists of several tasks aimed at improving pavement research with accelerated load testing. One of these tasks mirrors the efforts of this synthesis to summarize previous and current research in APT. Identification of new and innovative future research is also planned. Evaluation of materials and tests from previous efforts will be documented, and coordination of research in this area among the different APT facilities should produce significant findings.

SUMMARY

The primary objective of many full-scale APT programs is to evaluate pavement material response and performance. APT programs have produced significant findings that allow for validation of existing materials and implementation of new and innovative materials. APT testing programs allow for performance-based evaluation of these materials,

which is often related to material characterization programs and testing in the laboratory. This chapter has emphasized the importance of considering differences between APT and laboratory characterization in terms of loading and environmental conditions, measurement and analysis techniques, and failure definitions.

The following are a selection of lessons learned through APT in the field of materials and tests that provide evidence of the wide scope of applications that were discussed in this chapter.

- Guidelines for the use of marginal base course materials were established. This is a direct result of the application of APT for understanding the mechanisms that affect pavement performance.
- The effect of soil type and moisture on the performance of subgrade under freeze–thaw conditions is being quantified.
- The ability to monitor the change in stiffness of pavement layers by means of SASW during trafficking is being used to evaluate the performance of bound materials in pavements, particularly under wet trafficking conditions. With respect to the latter, the use of scaled APT in conjunction with full-scale APT has been reported to be of value.
- A wide range of materials have been evaluated for use in the various layers of the pavement structure. In the process, information has been collected that will enable the evaluation of newly defined laboratory test guidelines such as Superpave specifications for characterizing materials in terms of performance. The materials include stiff modified binders (SBS and EVA), cement-modified base course, emulsion-treated natural gravel, ATPB, and RAP, to name only a few.
- Conditions conducive to the improved fatigue performance of HMA were identified in several programs, leading to changes in structural configuration.
- There was clear evidence that modified binders outperformed conventional binders in terms of resistance to fatigue and permanent deformation.

The new APT programs that have been initiated are expected to increase the already wide range of applications in materials and tests. These programs should also benefit from the COST 347 study that is underway in Europe.

CHAPTER FIVE

ENHANCEMENT OF MODELING IN PAVEMENT ENGINEERING**INTRODUCTION**

Pavement performance is a measure of the extent to which a pavement fulfills its principal objective. Performance models are tools to predict performance; they may ultimately be used in pavement management systems, in the structural design of pavements, and in the development of performance-related specifications. Jooste et al. (1997) reported that APT provides a *window* on pavement performance, which can possibly be used to predict how the pavement will perform under real traffic. This chapter presents models developed and/or validated through APT for use in the aforementioned applications. APT programs have produced a wide range of models, both theoretically based and empirical, and focus on physical phenomena covering APT processes or related applications of test data. The usefulness and application of the models that have been validated will be explored with due regard to their limitations. Some models that nominally fall outside the scope of the study are also discussed because they provide a basis for further application of APT.

This chapter explores the phenomenological modeling of pavement damage and the generalization of models by making them dimensionless and thus increasing their applicability. Models developed as part of APT research are discussed, including asphalt pavement failure criteria, for example, for subgrade and base layer permanent deformation, asphalt layer permanent deformation, and asphalt fatigue and cracking. Aspects of modeling concrete pavement performance are also addressed. Before discussing the wide variety of applications that were found in the literature, the results from the questionnaire survey will be presented.

QUESTIONNAIRE SURVEY

The responses to Questions 5.1 to 5.5 on modeling are reflected in Figures C39 to C41 in Appendix C. These were synthesized and the results are contained in the following list.

- Models that are most frequently being used with APT are based on elastic layer analysis, as could be expected, but FE analysis is used almost as frequently.
- Stress-strain modeling and deformation modeling are used most frequently; however, as could be expected, deflection modeling and back-calculation of moduli

are used almost as often. Fatigue modeling has also received considerable attention. Load equivalency does not rank as high, probably because the latest computer hardware and software enables designers to cater to very specific selected loads, which allows the designer to select a specific traffic mix for the purpose of designing any load configuration.

- Instrumentation used to gather modeling data most frequently uses strain gauges, although some facilities opted not to use them because of the high rate of loss of such gauges. Displacement gauges, such as the Multi-Depth Deflectometer (MDD), proved to be equally popular. Pressure cells are also used, albeit not as frequently. Subgrade moisture is also frequently being monitored by sensors.

Views of the respondents to the survey on modeling are presented in Table D5 in Appendix D.

MODELING PAVEMENT DAMAGE

Pavement damage occurs as a result of traffic and environmental loading. Molenaar et al. (1999) showed that the phenomenological progression of damage lends itself to modeling using S-shaped curves. Damage, such as asphalt cracking, normally develops slowly during some period of initiation; the rate of damage then accelerates with further loading. Finally, after a certain amount of damage has developed, the rate of progression decreases. This S-shape failure trend may be described using the Weibull distribution, which can be written as

$$F_w(t) = 1 - \exp \left[- \left(\frac{n}{N} \right)^\beta \right] \quad (3)$$

where

- $F_w(t)$ = probability that failure has occurred before time t ,
- n = number of load repetitions at time t ,
- N = number of load repetitions at which a defined failure occurs, and
- β = curvature parameter.

Figure 12 shows examples of Weibull distributions for various values of β (as shown in the legend), using a non-dimensional number of load repetitions scale n/N , to repre-

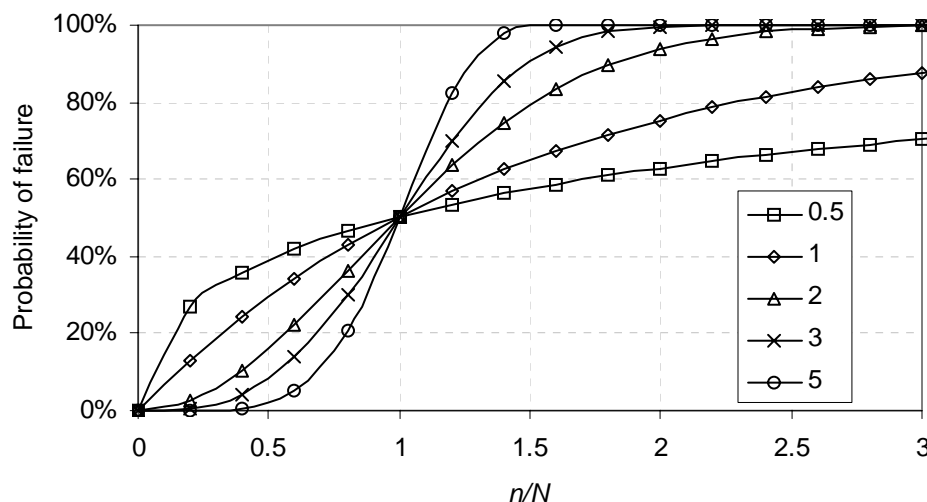


FIGURE 12 Weibull probability of failure distribution for different β -values.

TABLE 1
SOME MATHEMATICAL MODELS USED TO DESCRIBE DAMAGE WITH LOADING

Models	Equation
$y = a + b \cdot N$	Linear
$y = a + b \cdot N + c \cdot N^2$	Quadratic
$y = a + b \cdot N + c \cdot N^2 + d \cdot N^3 + \dots$	Polynomial
$y = a \cdot \exp(b \cdot N)$	Exponential
$y = a + b \cdot \ln N$	Logarithmic
$y = a \cdot N^b$	Power
$y = a \cdot N^{(b \cdot N)}$	Geometric
$y = a^{(1/N)}$	Root
$y = a / (1 + \exp(b - c \cdot N))$	Logistic
$y = a - b \cdot \exp(-c \cdot N^d)$	Weibull
$y = a + b / N$	Hyperbolic
$y = (a + b \cdot N) / (1 + c \cdot N + d \cdot N^2)$	Rational
$y = a \cdot \exp(-(N - b)^2 / (2 \cdot c^2))$	Gaussian

sent the relative damage that occurs with loading over time. When the ratio n/N is equal to 1, the probability of failure is 50%. This may represent a 50% loss in stiffness or a 50% cracked area. With additional loading the rate of deterioration diminishes progressively. Note that similar curves may be established for other failure scenarios.

Molenaar et al. (1999) noted that the complete S curve seldom develops fully in practice, because road authorities

will not allow pavements to deteriorate to such a great extent. This is in contrast to APT tests that may be continued until total failure occurs.

While the Weibull distribution is used to model the probability of pavement failure over time, a variety of mathematical models are used to describe the progression of damage (y) with loading (N) as shown in Table 1. Regression constants are shown as a , b , c , and d .

Multiple (linear or nonlinear) regression analysis may be used to determine regression constants. Regression analysis is a statistical method that uses the relationships between two or more quantitative variables to generate a model that may predict one variable from the other(s). Hand et al. (1999) stated that the term multiple linear regression is employed when a model is a function of more than one predictor variable. The objective behind multiple linear regression is to obtain adequate models, at a selected confidence level, using the available data, while at the same time satisfying the basic assumptions of regression analysis, which include that

- Severe multicollinearity does not exist among predictor variables,
- Influential outliers do not exist in the data, and
- Equal variance exists among residuals (normality).

The objective is accomplished by selecting the model that provides the greatest adjusted coefficient of determination (R^2) and lowest mean-square error for given data.

Turtschy and Sweere (1999) evaluated different models of pavement damage as part of the PARIS (Performance Analysis of Road Infrastructure) project in Europe. Deterioration data were collected from 900 in-service test sections under real traffic and 44 APT-trafficked sections. It was found that power models work well with rutting data, whereas logarithmic models are suited to cracking models. The authors compared failure criteria measured using APT with that measured on the in-service roads under real traffic. They did not model the initial stage of cracking and rutting in APT studies. They reported that one of the main factors affecting this initiation; that is, aging of the AC, does not occur in the short time scale of APT tests. Furthermore, because in-service pavements are repaired before maintenance, damage data collected from these pavements are in an intermediate stage. They concluded that because APT results indicated that the linear functional forms are appropriate for the intermediate stage, the linear form is suitable for modeling the propagation of cracking and rutting under real traffic.

One of the major shortcomings of modeling pavement performance using the mathematical models described above is that the models may have limited applicability and may only be valid for the conditions and sites for which they were established. For this reason, Molenaar et al. (1999) suggested that generalized models be obtained by making them dimensionless. This is done by relating the damage as a relative ratio to the cause of damage, also represented as a relative ratio, in the following form:

$$\frac{d}{D} = \left(\frac{t}{T} \right)^\beta \quad (4)$$

where

- d = amount of damage at the time of inspection t ,
- D = amount of damage at which the pavement is assumed to have reached end of life at time T , and
- β = constant depending on the type of damage and structure.

Molenaar et al. (1999) pointed out that the use of such power models is problematic in cases of damage types for which the exponent β is larger than 1. They reported that such power models do not allow pavement condition predictions to be made in cases where maintenance is already overdue; that is, in cases where the condition is beyond the terminal, condition D .

Numerous computer models have been developed to estimate the displacements, stresses, and strains within simulated pavement systems. Models vary from those using elastic multilayer theory (De Jong et al. 1973; Wardle 1977; Kopperman et al. 1986) to others that account for nonlinearity. The latter include visco-elastic VESYS (Kenis 1978), VEROAD (Hopman 1996), and elasto-plastic models (mechano-lattice). Yandell and Behzadi (1999) have also used the mechano-lattice model to illustrate the influence of loading direction on elasto-plastic pavement response. Residual stresses and strains that accumulate in pavements trafficked in one direction only differ from those when the direction of travel is allowed to reverse. Yandell has also compared the mechano-lattice model to pavement response determined using CIRCLY (Wardle 1977) and VESYS based on ALF-accelerated testing of different pavements. Input parameters define pavement structures, load configurations, and material characteristics. In some cases, the models have been further developed to estimate pavement performance in terms of rutting and fatigue by incorporating appropriate transfer functions (Huang 1993; Chatti et al. 1999a). These models include iterative algorithms to account for seasonal and load variations. The large number of iterations required to characterize the performance of asphalt pavements has led to the use of simplified approaches based on Odemark's layer transformation theory. APT has assisted in the development of these models in that displacement, stress, and strain estimations may be validated using instrumented APT test sites. Furthermore, transfer functions used in the models may be refined based on the results of APT tests.

MODELING OF ACCELERATED PAVEMENT TESTING SUBGRADE RUTTING PERFORMANCE

Modeling of permanent deformation of subgrade materials is usually expressed in terms of (elastic) stresses or strains on top or within the subgrade layer and in its simplest application generally takes the form of the following log-log (power) relationships.

$$\varepsilon_{pz} = \alpha \cdot N^\beta \quad (5)$$

$$\sigma_{pz} = \alpha \cdot N^\beta \quad (6)$$

where

- ε_{pz} = permissible vertical strain on top of subgrade,
- σ_{pz} = permissible vertical stress on top of subgrade,
- N = number of standard axle loads, and
- α, β = regression constants.

These equations may be implemented in mechanistic pavement design and evaluation systems based on linear elastic material properties. The equations indicate that the stresses and strains within subgrades increase quite rapidly during the early loading cycles and then tend to increase at a much slower rate because of shear distortion and densification of the materials.

Odermatt et al. (1999) developed models for predicting surface rut depths resulting from subgrade deformations under HVS trafficking. Strains within the subgrade were measured using the ε -mu coil system. Dynatest soil pressure cells were used to measure the stresses on the surface under the HVS loads. Equation (7) shows the subgrade rutting model developed, expressed in terms of elastic vertical subgrade dynamic strain.

$$RD = 1E - 12 \cdot \varepsilon_v^{3.55} \quad (7)$$

where

- RD = rut depth, mm;
- ε_v = subgrade vertical elastic strain;
- E = elastic modulus;
- with $R^2 = 0.89$.

Odermatt et al. (1999) noted that rutting models based on elastic strains are inaccurate for predicting rutting in wet, soft soils, a condition commonly found during thaw weakening periods. During these periods, there may be no, or only weak, relationships between elastic strains and rut depth. In these cases it is more practical to estimate rutting based on plastic strains. The following equation shows such a relationship developed by Odermatt et al. that also takes the form of the log-log equations indicated previously:

$$RD = 0.0545 \cdot \varepsilon_{vp}^{0.49} \quad (8)$$

where

- RD = rut depth, mm; and
- ε_{vp} = subgrade accumulated permanent strain.

Rut depth may be related to trafficking in the same way that it may be related to subgrade strain. Odermatt et al. (1999) indicated that HVS tests were done at different wheel loads, and they were able to develop a relationship between rut depth and wheel load with trafficking as shown in Equation (9).

$$RD = (0.0117 \cdot P - 0.4816) \cdot N^{0.27} \quad (9)$$

where

- RD = average surface rut depth, mm;
- P = wheel load, kN; and
- N = number of passes.

This equation is similar to Equation (5), indicating that the α constant in that equation is a function of wheel load.

The AASHO Road Test rut depth data were used by Finn et al. (1986) to develop a permanent deformation model for subgrade rutting. They found that the rate of rutting was strongly related not only to traffic and stress on top of the base, but also to surface deflection. Two rutting models were developed for pavements with thin asphalt surfacing layers [less than 150 mm (6 in.) thick] and those with full-depth asphalt. These models are shown in Equations (10) and (11) for thin and thick asphalt layers, respectively.

$$\log RR = -5.617 + 4.343 \log d - 0.167 \log (N18) - 1.118 \log \sigma_c \quad (10)$$

$$\log RR = -1.173 + 0.717 \log d - 0.658 \log (N18) + 0.666 \log \sigma_c \quad (11)$$

where

- RR = rate of rutting in micro-inches per axle repetition,
- d = surface deflection in mils under a load of 40 kN (9,000 lb),
- σ_c = vertical compressive stress at the asphalt-base interface (psi), and
- $N18$ = number of 18-kip single-axle repetitions/100,000.

Chen and Lin (1999) adopted a similar approach to model the permanent deformation of two TxMLS test sites in Texas. They related the rutting to surface deflection measurements determined from FWD tests. The main drawback of this approach is that the models are specific to test sites on which data are collected. Furthermore, one is unable to pinpoint the source of failure and differentiate between the relative rutting in the respective pavement layers.

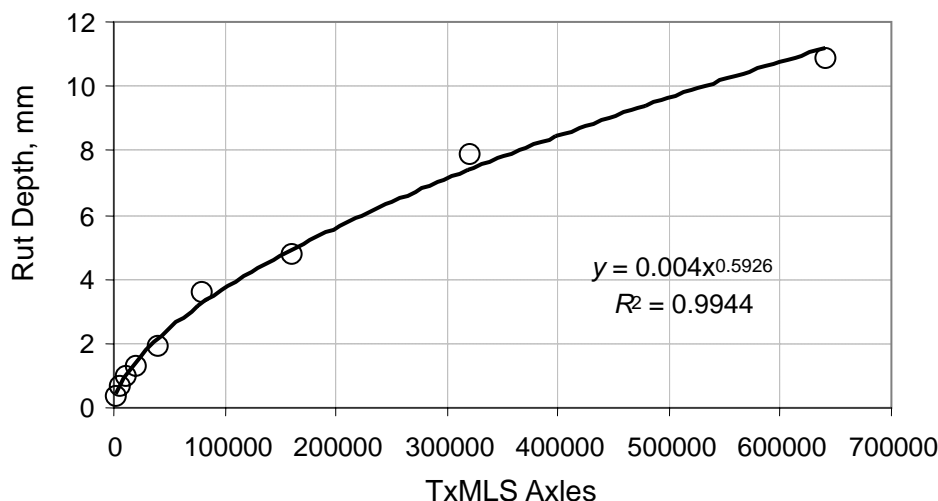


FIGURE 13 Subgrade rutting model of TxMLS tests on Pad F5 in Victoria.

The model shown in Figure 13 was derived relating the rut depth on the surface to applied TxMLS loads for one of the test sections using data provided in the paper by Chen and Lin (1999). The model described by Equation (5) fits the data well.

Theyse (1997) mentioned that two types of data generated during an HVS test are used to develop the permanent deformation models on which the design transfer functions for subgrade deformation are based. These are the in-depth deflection and permanent deformation data obtained from the MDD measurements taken at regular intervals during an HVS test. Test data from a number of HVS tests, selected from the moderate and wet regions in South Africa, were used for the development of the permanent deformation models. A multidimensional conceptual model for permanent deformation was also developed and calibrated with HVS test data for pavement foundation and structural layers of different material qualities. These models provide permanent deformation design transfer functions at different expected performance reliabilities for unbound pavement layers in South Africa.

Elastic moduli were back-calculated from the peak deflection values at the layer interfaces for the HVS test sections under investigation as opposed to the back-calculation of layer moduli from the deflection bowl. The plots of permanent deformation against vertical strain show no clear correlation between these two parameters. The plots of permanent deformation against vertical stress indicate a better correlation between the applied stress and the resulting permanent deformation. This contradicts current design practice, where the permanent deformation of the pavement foundation is usually linked to the vertical strain calculated at the top of the foundation layers. It was therefore decided to develop permanent deformation transfer

functions for the pavement foundation with vertical stress as the critical parameter. The rutting model is given in Equation (12).

$$PD = e^c N^s \left(e^{B\sigma_c} - 1 \right) \quad (12)$$

where

- PD = permanent deformation, mm;
- N = number of repetitions (E80 standard axles);
- σ_c = vertical compressive stress on top of the subgrade, kPa; and
- c, s, B = regression constants.

Theyse (1997) stated that the regression constants c and s in Equation (12) do not change for different material types. Because the HVS tests were done on pavements consisting of different materials, he was able to determine the regression constant B for the different materials. This approach extended the applicability of the performance model.

The SMDM has been used in South Africa for a number of years (Theyse et al. 1996). This is a mechanistic-empirical design method that includes fatigue transfer functions for asphalt surfacing, asphalt base, and lightly cemented layers, as well as permanent deformation transfer functions for unbound structural layers and the roadbed. All of these were developed through the SA-HVS program. The method is based on a critical layer approach whereby the shortest layer life of the individual pavement layers determines the pavement life. This approach may be suited to the fatigue failure of bound layers, but does not allow for each of the pavement layers to contribute to the

total surface rut. Current research is therefore aimed at developing permanent deformation models for individual pavement layers, to enable the designer to predict each layer's contribution to the total permanent deformation of the pavement system.

Ullidtz et al. (1999b) proposed the following three equations (strain, stress, and energy density models, respectively) to model permanent deformation of subgrade materials:

$$\varepsilon_{pz} = A \cdot N^\alpha \cdot \varepsilon_z^B \quad (13)$$

$$\varepsilon_{pz} = A \cdot N^\alpha \cdot \left(\frac{\sigma_z}{p} \right)^B \quad (14)$$

$$\varepsilon_{pz} = A \cdot N^\alpha \cdot \left(\frac{\sigma_z}{2p} \cdot \varepsilon_z \right)^B \quad (15)$$

where

- ε_{pz} = vertical plastic strain in microstrain at depth z ,
- ε_z = vertical resilient strain in micro-strain at depth z ,
- σ_z = vertical compressive stress at depth z ,
- p = a reference stress (atmospheric pressure),
- A, α, β = constants, and
- N = number of load repetitions.

The models were implemented to predict the performance of pavements trafficked using the Danish Road Testing Machine. Strains within the subgrade layer were monitored using Linear Variable Displacement Transformer-based soil strain cells. Strain response monitored using the strain cells was related to mathematical models based on various multi-layer methods, including a simplified approach to elastic layer theory using the Boussinesq equation with Odemark's layer transformation. Ullidtz et al. (1999b) concluded that the models as developed allowed a reasonable estimation of subgrade permanent deformation, although they emphasized that the models simplify the material response and that more sophisticated models are required to better characterize the behavior of real pavement materials.

Newcomb et al. (1999) reported on a subgrade rutting model developed exclusively as part of the Mn/ROAD program that has subsequently been implemented in a pavement design and analysis system. The equation is as follows:

$$N = 5.5 \cdot 10^{15} \cdot \left(\frac{1}{\varepsilon_v} \right)^{3.949} \quad (16)$$

where

- N = number of ESALs to obtain a 12.5 mm rut, and
- ε_v = vertical strain on top of the subgrade.

Epps et al. (1999) used the Asphalt Institute (AI) subgrade rutting criterion shown here.

$$N = 1.05 \cdot 10^{-9} \cdot \varepsilon_v^{-4.484} \quad (17)$$

where

- N = number of ESALs to obtain a 12.5 mm rut, and
- ε_v = vertical strain on top of the subgrade, but modify it to account for rutting accumulation in the pavement structure.

Rut depth (RD) contributed by the unbound layers was assumed to accumulate as follows:

$$RD = d \cdot N^e \quad (18)$$

where d and e are experimentally determined coefficients. Least-squares analyses based on WesTrack APT data suggest that the value for d in Equation (18) may be determined by substituting for N shown in Equation (17) as follows:

$$d = f \cdot (1.05 \cdot 10^{-9} \cdot \varepsilon_v^{-4.484})^e \quad (19)$$

Based on HVS testing of sections with relatively thick asphalt layers (>150 mm), Harvey et al. (1999) reported that the AI subgrade strain criterion as used earlier may be overly conservative for pavement sections with asphalt layers thicker than 150 mm.

Pidwerbesky et al. (1997a), using CAPTIF APT testing of five different asphalt pavements, investigated subgrade rutting criterion for asphalt pavements. Investigations led to the development of a new subgrade strain model that substantially reduced the required thicknesses of overlays.

$$\varepsilon_{cvs} = 0.012 \cdot N^{-0.145} \quad (20)$$

where

- ε_{cvs} = maximum vertical compressive strain on top of the subgrade, and
- N = number of load repetitions.

This criterion was established for pavements having relatively thin asphalt layers (25 to 85 mm) over base and subgrade structures (135 to 350 mm thick) with the

subgrade CBR ranging from 4% to 28%. They pointed out that no single subgrade criterion is appropriate for all conditions. Furthermore, the strain criterion as only a function of the number of axle load repetitions cannot be used alone. The environmental conditions, material properties (especially with respect to the granular base and subbase layers), and construction quality must be considered in the design of new pavements and overlays. The New Zealand researchers argued that because vertical compressive strains in unbound granular layers under thin asphalt surface layers can be equal in magnitude to vertical compressive strains in the subgrade under such pavements and can thus be a significant contributor to fatigue of the surfacing layer and permanent deformation, the unbound granular strains should also be considered in the modeling of thin asphalt pavements. Under a thicker HMA surface layer, the vertical compressive strains in the unbound granular pavement layers are substantially smaller than the vertical compressive strain in the subgrade and may therefore not be significant.

In their investigation, Pidwerbesky et al. (1997a) found that the magnitudes of actual vertical compressive strain measured in the unbound granular layers and subgrade are substantially greater than the levels predicted by the models on which some designs are based. Their conclusion was based on the Shell, Austroads, and old New Zealand Road Board flexible pavement design procedures for the same number of loading repetitions to failure.

The relationship between vertical compressive strains in the materials and the cumulative loading becomes stable after the pavement is compacted under initial trafficking (in the absence of adverse environmental effects). The New Zealand Road Board subgrade criterion placed emphasis on loading history. Using APT the New Zealand researchers found that the effect of cumulative axle loading has substantially less influence on the response and performance of unbound granular pavements than is implied in the pavement models that are the basis of the flexible pavement thickness design procedures. The pavement models have been calibrated to in-service pavements using empirical data from field studies. Hence, environmental factors and construction quality must have a significant influence on the pavement performance, but current flexible pavement design procedures emphasize the effect of load repetitions and only implicitly consider the other two major factors.

Molenaar et al. (1999) identified the following trend in subgrade rutting that may be used in remaining life estimates. Note that this model is dimensionless.

$$\frac{S}{ST} = \left(\frac{n}{N} \right)^b \quad (21)$$

where

- S = rut depth (mm) at time t ,
- ST = rut depth at the end of pavement life = 18 mm,
- n = applied number of load repetitions,
- N = number of load repetitions to a rut depth of 18 mm, and
- b = constant = 0.41 (from LINTRACK APT trials).

The rut depth of 18 mm is considered to be the depth at which maintenance is required (this ensures that b is less than 1). It was pointed out that the constant b is specific to the sand subgrade used in the LINTRACK tests that controlled the subgrade deformation. A comparison of the APT subgrade deformation data with the subgrade strain criteria developed by Shell indicated that design criteria established for subgrades based on the Shell method should consider a reliability of 85%.

The formulation of the subgrade rutting model shown in Equation (21) may be derived from the subgrade model shown in Equation (5). This indicates that the β constant in Equation (5) is also a function of the subgrade material. For the APT tests done by Odermatt et al. (1999), the β constant in Equation (9) is 0.27, specific to the silty-sand subgrade used in the HVS tests. The β constant in the model described in Figure 13 is 0.59 for a clayey subgrade.

The subgrade permanent deformation models described thus far have either been related to stresses and strains on top of the subgrade or other response variables such as those determined from FWDs. None of the models account for the material properties of the subgrade materials. Molenaar et al. (1999) noted that this is a shortcoming of performance models determined using APT and that material characterization is useful to improve the applicability of these models. In the case of subgrade materials, there is an understandable reluctance to include material properties in performance models given the location of the materials in the pavement structure. It would be necessary to remove these materials for laboratory testing, which would disturb the in situ state of the materials. Nevertheless, material characterization may be included in the modeling of subgrade deformation. This factor can have an influence on APT, because modeling is sometimes done simplistically. Tseng and Lytton (1989) illustrate this and show that deformation models should be a function of not only stress and strain, but also material properties, as Equation (22) indicates. This lends support to the close interrelationship between APT and material testing. The following reference does not relate directly to APT applications but illustrates the point.

In their model, Tseng and Lytton (1989) propose as follows for subgrade performance. This includes material property parameters that may be determined from triaxial

tests on subgrade materials. The model considers the moisture content of the subgrade material. Note that the model also accounts for the stress-dependent nature of subgrade materials.

$$\varepsilon^p(N) = \left(\frac{\varepsilon_0}{\varepsilon_r} \right) \exp\left(-\frac{p}{N} \right)^\beta \varepsilon_v \cdot h \quad (22)$$

where

- $\varepsilon^p(N)$ = plastic strain accumulated during N load repetitions for the layer;
- ε_r = resilient strain imposed in lab test to obtain material properties ε_0 , ρ , and β ;
- ε_v = average vertical resilient strain in the layer as obtained from the primary response model; and
- h = thickness of the layer.

The ratio $\varepsilon_0/\varepsilon_r$ is estimated according to the type of material, granular or subgrade soil.

For granular soils

$$\begin{aligned} \log\left(\frac{\varepsilon_0}{\varepsilon_r}\right) &= 0.80978 - 0.06626W_c - 0.003077\sigma_\theta \\ &\quad + 0.000003E_r \\ \log\beta &= -0.9190 + 0.03105W_c + 0.001806\sigma_\theta \\ &\quad - 0.0000015E_r \\ \log\rho &= -1.78667 + 1.45062W_c + 0.0003784\sigma_\theta \\ &\quad - 0.002074W_c^2 \sigma_\theta - 0.0000105E_r \end{aligned} \quad (23)$$

For subgrade materials

$$\begin{aligned} \log\left(\frac{\varepsilon_0}{\varepsilon_r}\right) &= -1.69867 - 0.09121W_c - 0.11921\sigma_d \\ &\quad + 0.91219\log E_r \\ \log\beta &= -0.9730 + 0.0000278W_c^2 \sigma_d + 0.017165\sigma_d \\ &\quad + 0.0000338W_c^2 \sigma_\theta \\ \log\rho &= 11.009 + 0.000681W_c^2 \sigma_d - 0.40260\sigma_d \\ &\quad + 0.0000545W_c^2 \sigma_\theta \end{aligned} \quad (24)$$

where

- W_c = water content (percent),
- σ_d = deviator stress (psi),
- σ_θ = bulk stress = sum of principal stresses (psi),
and
- E_r = resilient modulus of the layer (psi).

In the next section, the modeling of APT asphalt rutting performance is discussed.

MODELING OF ACCELERATED PAVEMENT TESTING ASPHALT RUTTING PERFORMANCE

Generalized APT models of asphalt rutting performance are often similar to those for subgrade performance, expressing permanent deformation in terms of strains within the asphalt layer instead of strains on top of the subgrade. The visco-elastic nature of asphaltic materials requires that the influence of temperature and frequency (rate of loading) be considered.

Williams et al. (1999) used the following relationship [similar to Equation (5)] to establish a correlation of rutting observed from APT trials at WesTrack to results of repeated shear at constant height tests:

$$\varepsilon_p = a \cdot N^b \quad (25)$$

where

- ε_p = percent permanent strain,
- N = number of load applications, and
- a, b = modeling constants.

They report that there are two very important criteria that need to be emphasized. The first criterion is the selection of an appropriate test temperature that reflects the in-service temperature at which the pavement will be expected to perform. The second issue is the assumption of laboratory compaction simulating field compaction. Studies are currently being conducted at the FHWA that indicate significant discrepancies between field compaction and several laboratory compaction devices. This compaction issue should be resolved before implementing a performance test in a mixture design process.

Meng et al. (1999) reported on ALF tests of five different stabilized base pavements. They modeled surface rutting of the base in the form of Equation (5) and reported α and β regression constants for the different pavements tested. They found that rutting was confined to the asphalt surfacing layer, but also attributed part of the rutting to the deterioration of the asphalt–base interface. This deterioration was related to the ingress of water through cracks in the asphalt layer.

A difference in temperature and rainfall patterns during testing of the different pavement sections discussed by Meng et al. (1999) complicates the interpretation of the performance data. An example is the case of two test sections constructed having the same asphalt and base thickness but using different base materials that were tested using the same wheel load. The performance of the sections

differed significantly; however, the performance cannot be attributed to differences in base material because of the different temperatures and rainfalls monitored during the tests on these sections.

Epps et al. (1999) assumed that rutting in asphalt was controlled by shear deformation. In simple loading, permanent shear in the asphalt is assumed to accumulate according to the following expression:

$$\gamma^i = a \cdot \exp(b \cdot \tau) \gamma^e N^c \quad (26)$$

where

- γ^i = permanent (inelastic) shear strain at a 50 mm depth,
- τ = shear stress determined at this depth using elastic analysis,
- γ^e = corresponding elastic shear strain,
- N = number of axle load repetitions, and
- a, b, c = regression coefficients.

The equation indicates the relationship between plastic and elastic deformation. Rutting estimates are computed based on elastic shear stress and strain (τ , τ^e) at a depth of 50 mm beneath the edge of the tire. Epps et al. (1999) stated that densification of the asphalt is excluded in the rutting estimates because it has a comparatively small influence on surface rutting.

Time hardening of the asphalt accounted for by evaluating the stiffening of the binder and rutting in the asphalt layer as a result of shear deformation is determined from the following equation:

$$RD = K \cdot \gamma_j^i \quad (27)$$

The VESYS model for predicting permanent deformation also relates plastic and elastic response as shown in the following model, although the modeling constants shown further account for the visco-elastic nature of asphaltic materials:

$$\varepsilon_p = \varepsilon_r \cdot \left(\frac{\mu}{\alpha} \right) \cdot N^\alpha \quad (28)$$

where

- ε_p = percent permanent strain,
- ε_r = percent resilient strain,
- N = number of load applications, and
- μ, α = modeling constants determined from repeated load laboratory testing.

Lijzenga (1999) of Shell reported on APT tests done using the Laboratory Test Track in The Netherlands to evaluate the rutting characteristics of asphalt using modified binders. He noted that such relations were previously determined using static creep experiments, which turned out not to be suitable for modified binders.

In the *Shell Pavement Design Manual* (1978), the effect of the bituminous binder on permanent deformation is incorporated by means of a relationship between the stiffness of the asphaltic mix and its bituminous binder under long loading time (viscous) conditions.

$$\log S_{mix,v} = \log b + q \log S_{bit,v} \quad (29)$$

where

- $S_{mix,v}$ = stiffness of mix under rutting conditions,
- $S_{bit,v}$ = viscous component of the stiffness of its bituminous binder, and
- b, q = parameters specific to a certain asphalt mix.

The parameter $S_{bit,v}$ is obtained from the following equation:

$$S_{bit,v} = \frac{3\eta_0}{W_{eq} \cdot t_w} \quad (30)$$

where

- t_w = wheel loading time as a measure of traffic speed,
- W_{eq} = number of standard wheel passes obtained from traffic spectrum, and
- η_0 = bitumen viscosity at average paving temperature during service life of the road.

This equation accounts for climate and traffic loading. Having determined the stiffness of the mix, the rut depth in the asphalt layer, Δh , is then calculated using

$$\Delta h = k \cdot h \cdot \frac{\sigma_0}{S_{mix,v}} \quad (31)$$

where

- h = thickness of asphalt layer,
- σ_0 = contact stress of the standard wheel, and
- k = a coefficient.

Stiffness is an important material property in asphalt pavement engineering and is required to model pavement structures when using multilayer theory. As part of the comprehensive LINTRACK APT program, Sabha et al. (1995) did a comparison of methods available to predict

the stiffness of a mix from the bitumen stiffness. They recommended that the formula of Francken (1977) [Equation (32)], which allows a prediction of the maximum value for the mix stiffness based on the volumetric properties of the mix, be used.

$$E_{\infty}(V_b, V_a) = 3.56 \cdot 10^4 \frac{(V_b + V_a)}{V_b} e^{(-0.1V_a)} \quad (32)$$

where

$$\begin{aligned} E_{\infty}(V_b, V_a) &= \text{maximum mix modulus at maximum bitumen stiffness (MPa),} \\ V_a &= \text{percent air voids in mix by volume,} \\ &\text{and} \\ V_b &= \text{percent bitumen in mix by volume.} \end{aligned}$$

The dynamic modulus of bituminous materials is a complex modulus in which the real part represents the elastic stiffness and the imaginary part characterizes the internal damping of the materials. It is therefore used for describing the stress-strain relationship of visco-elastic materials. The absolute value of the complex modulus is commonly referred to as the dynamic modulus.

Fonseca and Witzak (1996) developed the following empirical model for estimating the dynamic modulus of asphalt mixes as a function of material properties:

$$\begin{aligned} \log E = & -0.261 + 0.008225 p_{200} - 0.00000101 p_{200}^2 \\ & + 0.00196 p_4 - 0.03157 V_a - 0.415 \frac{V_{beff}}{V_{beff} + V_a} \\ & + \frac{1.87 + 0.002808 p_4 + 0.0000404 p_{3/8} - 0.0001786 p_{3/8}^2 + 0.0164 p_{3/4}}{1 + e^{(-0.716 \log f - 0.7425 \log \eta)}} \end{aligned} \quad (33)$$

where

$$\begin{aligned} E &= \text{asphalt mix dynamic modulus in } 10^5 \text{ psi,} \\ \eta &= \text{bitumen viscosity in } 10^6 \text{ poise,} \\ f &= \text{load frequency in Hz,} \\ V_a &= \text{percent air voids in the mix by volume,} \\ V_{beff} &= \text{effective bitumen content by volume,} \\ p_{3/4} &= \text{percent retained on the } 3/4 \text{ in. sieve by total aggregate weight,} \\ p_{3/8} &= \text{percent retained on the } 3/8 \text{ in. sieve by total aggregate weight,} \\ p_4 &= \text{percent retained on the No. 4 sieve by total aggregate weight, and} \\ p_{200} &= \text{percent retained on the No. 200 sieve by total aggregate weight.} \end{aligned}$$

Material characterization parameters are also included in asphalt permanent deformation modeling of APT data. Epps et al. (1999) reported a regression equation based on WesTrack data that accounts for the binder content and air voids in the asphalt mix as shown here.

$$\begin{aligned} \ln ESALs_{10} = & A_0 + A_1 \cdot P_{asp} + A^2 \cdot V_{air} \\ & + A_3 \cdot P_{asp}^2 + A_4 \cdot V_{air}^2 \\ & + A_5 \cdot P_{asp} \cdot V_{air} \\ & + A_6 \cdot \text{fines} + A_7 \cdot \text{finesplus} \\ & + A_8 \cdot \text{coarse} \end{aligned} \quad (34)$$

where

$$\begin{aligned} ESALs_{10} &= \text{number of ESALs to a rut depth of 10 mm,} \\ P_{asp} &= \text{percent binder content by weight of the mix,} \\ V_{air} &= \text{percent air void content, and} \\ A_i &= \text{regression constants.} \end{aligned}$$

The terms “fines,” “finesplus,” and “coarse” assume values of 1 when sections containing specific mixes are analyzed and 0 otherwise. Thus, for a fine gradation, for example, the equation reduces to

$$\begin{aligned} \ln ESALs_{10} = & 48.19 - 9.43 \cdot P_{asp} \\ & - 0.169 \cdot V_{air} + 0.639 \cdot P_{asp}^2 \end{aligned} \quad (35)$$

Hand et al. (1999) described a methodology developed to predict cumulative rutting over time using incremental rut depth modeling and including material characterization. The benefit of the methodology developed is that it takes into account the combined effects of environmental conditions and time hardening, with particular emphasis on temperature sensitivity in the early life of the pavement. The intent was to capture these effects, using a direct relationship to the Superpave binder specification, on the mixture behavior at WesTrack in regression models. The resulting model could then be applied to environments outside of

TABLE 2
VARIABLES USED TO PREDICT ASPHALT RUTTING (Hand et al. 1999)

Description	Nomenclature	Units
Traffic—ESALs, Delta SALs, or cumulative ESALs	ESAL, DESAL, or CESAL	ESALs
Initial in-place air voids	Avi	Percent
In-place air voids as a function of time or traffic	Avt	Percent
Asphalt content relative to the design optimum	AC	Percent (twm)
Percent of Gmm at initial, design, and maximum gyrations	Gmmi, Gmmd, Gmmm	Percent
Percent voids in mineral aggregate	VMA	Percent
Percent voids filled with asphalt	VFA	Percent
Dust proportion	DP	n/a
Blended aggregate surface area	SA	ft ² /lb
Asphalt film thickness	FT	Microns
Ratio of percent passing the 4.75 mm and 0.3 mm sieves	#4GRAD50	n/a
Percent passing the 0.075 mm sieve	p200	Percent
Binder stiffness	Sbit	kPa
Change in rut depth in previous increment	DRDP	mm
Cumulative rut depth to previous increment	CRDP	mm
Ratio of change in rut depth in previous increment to cumulative rut depth to previous increment	DCP	n/a

ESAL = equivalent single-axle load; DESAL = delta equivalent single-axle load; CESAL = cumulative equivalent single-axle load; Avi = air voids in-place; Avt = air void time; AC = asphalt concrete; twm = total weight of mix; Gmm = maximum theoretical density; Gmmi = percent of Gmm at initial gyrations; Gmmd = percent of Gmm at design gyrations; Gmmm = percent of Gmm at maximum gyrations; VMA = voids-in-mineral aggregate; VFA = voids filled with asphalt; DP = dust proportion; SA = surface area; n/a = not applicable; FT = film thickness; DRDP = change in rut depth in previous increment; DCP = ratio of DRDP to CRDP.

WesTrack, from which data were used in identifying input parameters and verifying the methodology. The rut model developed is comprehensive and includes the potential predictor variables shown in Table 2.

One of the critical elements of this procedure was in determining the stiffness as a function of pavement temperature, Superpave binder properties, and aging. Using multiple linear regression techniques, the model was then developed as a function of stiffness and 10 other variables. Permanent deformation predictions were made based on this model for WesTrack Superpave mixtures and predicted rut depths successfully compared with observed performance. The remaining step will be to calibrate and verify the model using data generated in multiple climatic zones. One of the keys to the model is that it is capable of predicting nonlinear behavior. Even though the model predicts nonlinear behavior, it may not be sensitive enough to the effect of asphalt contents above the optimum level where rutting behavior may be very nonlinear.

Chatti et al. (1999a) reported on a rut model developed and incorporated into the MICHPAVE computer program that is a function of a number of variables associated with the respective layers of the pavement structure and pavement response. The rut model is shown here and considers deformation of the pavement structure as a whole.

$$\begin{aligned}
 Rut = & A_1 + A_2 \cdot AV^A_3 + A_4 \cdot \log AC + A_5 \cdot AKV \\
 & + A_6 \cdot ESAL + \log (A_7 = CS) + SD \\
 & + A_8 \cdot (T - A_9) + A_{10} \cdot \log MRB \\
 & + A_{11} \cdot \log B + A_{12} \cdot \log MRRB \\
 & + A_{13} \cdot \log CSRB + A_{14} \cdot TBTSB
 \end{aligned} \quad (36)$$

where

- A_i = regression constants,
- AV = percent air voids in the asphalt mix,
- AC = thickness of the asphalt concrete
- AKV = kinematic viscosity of the asphalt binder,
- $ESAL$ = number of equivalent single axles at which the rut depth is being calculated,
- CS = compressive strain at the top of the base layer,
- SD = peak surface deflection,
- T = average annual air temperature,
- MRB = resilient modulus of the base layer,
- $MRRB$ = resilient modulus of the roadbed soil,
- B = thickness of the base layer,
- $CSRB$ = compressive strain at the top of the roadbed soil, and
- $TBTSB$ = total equivalent thickness of the aggregate base and granular subbase.

The peak surface deflection SD may either be calculated using a mechanistic model or measured using a FWD. The validity of the rut model was evaluated using APT on two instrumented pavement sections on I-96 in Lansing, Michigan. Chatti et al. (1999a) reported that the MICHPAVE computer program successfully predicted the rutting performance of the test sections over a range of conditions.

Hugo et al. (1999b,c) and Hugo (2000) considered specific factors influencing the relative rutting of the four wheel paths of TxMLS test sections. Ruts in the different wheel paths were compared in terms of a benchmark pavement lane. The wheel path with the least rutting was usually selected as the benchmark rut.

A model was formulated to define the relationship between the other ruts known as “Affected Rut(s)” and the “Benchmark Rut,” in terms of five influence factors:

- Temperature (F_t),
- Structural response (F_s),
- Material compliance after processing (F_m),
- Wheel load (F_l), and
- Tire pressure (F_p).

The quantitative analysis of the rutting performance was based on the assumption that the rut depth is determined by the cumulative effects of five factors that occur concurrently and

$$\text{Total.Affected.Rut(s)} = \alpha(F_t^{\beta_t} \cdot F_s^{\beta_s} \cdot F_m^{\beta_m} \cdot F_l^{\beta_l} \cdot F_p^{\beta_p})BR \quad (37)$$

where BR is defined as the “benchmark” rut, and α and β are regression factors.

For simplicity, the α and β factors were initially set to equal 1. With the results from the increased tire pressure tests it was found that the structural response was overemphasized, and β was changed to 0.5. This value satisfied the equation.

From the data of the three independent MLS tests, the model appears to be sound. It gave reasonable results on the origin of the rutting and, with the increased tire pressure test, it showed the effect on rutting to be directly proportional to the pressure. Modeling the rutting in this manner allowed the proportion of influence on rutting performance to be determined for each of the influence factors.

ACCELERATED PAVEMENT TESTING MODELING OF ASPHALT FATIGUE AND CRACKING PERFORMANCE

Fatigue of APT test sections may be quantified by monitoring the deterioration of pavement stiffness with trafficking. Nondestructive tests such as FWD allow the performance of the pavement structure to be expressed in terms of surface deflection. As the structure weakens, the deflection on the surface increases. Seismic tests such as SASW allow the stiffness of the upper layers of a pavement to be monitored. If cracking is apparent, this may be mapped and related to fatigue performance.

Fatigue of asphalt layers is often related to horizontal tensile strains that may occur at the bottom of layers under loading, leading to the classic bottom-to-top cracking. Fatigue models developed in this way are usually based on fatigue characterization of the asphaltic materials in the laboratory using stress- or strain-controlled, repeated load-

ing tests, with or without rest periods. These models lend themselves to incorporation into mechanistic pavement structural design and analysis systems.

As part of the SHRP study, Tayebali et al. (1994) evaluated the fatigue performance of a thin asphalt pavement section (90 mm of AC over 320 mm of base) at FHWA’s ALF. The full-scale accelerated fatigue test subjected the pavement test section to a unidirectional moving load, with single and dual tires, at a speed of 16.9 km/h. The axle load was 106.8 kN, and the tire pressure was 965 kPa. Beam specimens (63 mm × 51 mm × 381 mm) were sawed from the asphalt test sections for laboratory fatigue testing. All tests were performed under the controlled-strain mode of loading at a frequency of 10 Hz (sinusoidal loading with no rest periods) and at a temperature of 20°C. Fatigue tests were summarized in the form of relationships between fatigue life and initial strain and initial dissipated energy per cycle. The following equations were developed using linear regression analysis:

$$N_f = 425.81 \cdot (w_0)^{-1.846} \quad (38)$$

$$N_f = 8.959 \cdot 10^{-8} \cdot (\epsilon_0)^{-3.574} \quad (39)$$

where

- N = fatigue life;
- ϵ_0 = initial dissipated energy per cycle, psi.
- w_0 = initial peak to peak tensile strain, microstrain; and

Chatti et al. (1999b) used these relationships and the SAPSI-M program to estimate the fatigue lives of the ALF test sections. The SAPSI-M program uses multilayer theory to calculate the stress and strain response of a pavement system under loading. Chatti et al. reported good comparisons of estimated and measured fatigue lives depending on estimates for subgrade stiffness.

Based on a similar approach, Newcomb et al. (1999) reported the following transfer function also developed as part of Mn/ROAD tests for flexible pavements [see also Equation (16)]:

$$N_f = 2.83 \cdot 10^6 \cdot \left(\frac{1}{\epsilon_t} \right)^{3.206} \quad (40)$$

where

- N = number of cycles to the onset of fatigue cracking, and
- ϵ_t = transverse strain at the bottom of the asphalt layer, microstrain.

This equation represents the onset of cracking in a relatively thin asphalt surface over a dense-graded base on a silty-clay subgrade. This low-volume road section failed after the application of approximately 22,000 repetitions of a 356-kN, 5-axle truck. This represented 2 years and 7 months of traffic.

The approaches described have drawbacks in that the models developed, based on laboratory testing, can only estimate the number of cycles until the initiation of cracking. The propagation of the crack through the asphalt must then be taken into account. This is usually done by multiplying the number of cycles to crack initiation by a factor that depends on the thickness of the asphalt layer, mode of loading, rest periods, healing, etc. Furthermore, these models assume that cracking occurs beneath the asphalt layer and cannot account for top-to-bottom cracking.

Odéon et al. (1997) and De la Roche and Rivière (1997) reported on LCPC fatigue tests of different pavement sections with varying asphalt thicknesses. Fatigue was related to surface deflection, and cracking was monitored during trafficking of the sections. A number of different trapezoidal and beam fatigue tests (stress and strain-controlled, with and without rest periods) were done on specimens removed from untrafficked areas of the test sections to characterize the fatigue behavior of the materials tested. The fatigue life of the materials is expressed as a function of a shift factor (k) shown in the following equation that relates the laboratory-determined and field APT fatigue results:

$$N = 10^6 \cdot \left(\frac{\varepsilon_{cal}}{k \cdot \varepsilon_6(\theta)} \right)^{\frac{1}{b}} \quad (41)$$

where

- N = theoretical fatigue life of the pavement structure,
- ε_{cal} = calculated strain beneath the asphalt at the onset of trafficking (determined using linear elastic multilayer theory),
- $\varepsilon_6(\theta)$ = strain causing the failure of the laboratory sample after 1 million load applications at a temperature of $\theta^\circ\text{C}$,
- b = slope of laboratory fatigue curve, and
- k = shift factor relating laboratory and field APT fatigue performance.

Shift factors ranging between 0.8 and 4.1 were calculated. In determining strains within the asphalt using elastic theory, Odéon et al. (1997) reported that the use of rectangular imprints instead of circular imprints to represent tire pressure distributions in the elastic theory analysis reduced the difference between measured and calculated strains,

particularly for the structures having thinner asphalt layers. The introduction of rest periods in laboratory fatigue tests reduced shift factors. They found that the controlled stress fatigue tests better represent fatigue monitored in the APT tests. Ranking of laboratory fatigue and APT fatigue of structures, however, were not always the same.

Molenaar et al. (1999) reported that the trend line that describes the decrease of the asphalt modulus with respect to the number of load repetitions can be described very well in a nondimensional form using

$$\frac{E_n}{E_0} = 1 - 0.5 \cdot \frac{n}{N} \quad (42)$$

where

- n = applied number of load repetitions,
- N = number of load repetitions at which $E = 0.5 E_0$,
- E_0 = modulus of the undamaged asphalt layer, and
- E_n = modulus of the asphalt layer after n load repetitions.

Molenaar et al. (1999) questioned whether a pavement has really failed if the asphalt modulus has decreased to 50% of its original value. Equation (42) does not account for hardening or densification of the layer with initial trafficking as reported by some researchers (Hugo et al. 1999b). Localized strain measurements in the AC layer quickly lose their general meaning for the entire structure as soon as distress develops (not necessarily visible at the pavement surface), because local strains are strongly influenced by this distress. At the start of the performance test, the asphalt stiffness was strongly influenced by temperature. Common laboratory mix stiffness-temperature relationships can then be used to correct measurements to a reference temperature. When distress develops, however, the (declining) back-calculated AC layer stiffness becomes less temperature-dependent, and the usual temperature correction procedures become less adequate. At the end, there is almost no temperature dependency remaining.

Sherwood et al. (1999), based on an analysis of APT data from FHWA ALF tests, did not find a significant relationship between percentage area cracking and crack length. They related fatigue cracking to the binder stiffness property $G^* \sin \delta$. They indicated that an increase in $G^* \sin \delta$ (after RTFOT) relates to lower fatigue life for thinner asphalt pavements (100 mm) based on a 50% cracked area. They were unable to relate fatigue life and $G^* \sin \delta$ for thicker asphalt pavements.

Molenaar et al. (1999) modeled cracking of LIN-TRACK test sections in The Netherlands using the Weibull distribution discussed previously and shown in Equation

Equation (3). They found that the β constant in the equation was related to the thickness of the asphalt layer being tested.

ELASTO-PLASTIC BEHAVIOR OF UNBOUND MATERIALS

A unique application of HVS data is the work done by Wolff (1992). He used the South African HVS data to develop a mechanistic model for use in a design model for granular pavement materials. His aim was to simulate the actual behavior of granular materials under APT. In this analysis, he assumed the material to be in a stress state well below the yield stress condition, which is the situation in a functional pavement.

His method is akin to methods employed by Kenis (1978) and Yandell and Behzadi (1999) in which the permanent strain that takes place during each load cycle is taken into account. The nonlinear elasto-plastic behavior of the unbound granular material is modeled in two phases. In the first phase, he uses the nonlinear elastic finite-element program MICHPAVE (Chatti et al 1999) for backcalculating material parameters from measured deflections. In the second phase, the elasto-plasticity of the material is modeled by a function that relates an invariant of backcalculated stress induced by the HVS wheel loads to the plastic strain measured relative to repetitions of wheel loads.

Using this method in an iterative manner, he was able to accumulate the permanent strain in predefined pavement layers and relate this to the total deformation of the layer. The latter is a value selected in accordance with design guidelines.

The basis of his model is $S-N$ curves (with N being the number of load reversals that will cause structural failure at peak stress S) that were used as transfer functions for rutting. The $S-N$ curves were developed by Wöhler, and they are used in the mechanical engineering field (Wolff 1992). For the development of the transfer function, failure had to be defined as a specific terminal permanent strain value. Wolff developed a series of $S-N$ curves that could be used to determine cumulative permanent strain. This required

the determination of the stress induced in a layer by a wheel load in accordance with the material parameters that he determined from HVS testing. This yielded a point on the $S-N$ curve where the vertical axis represents invariant stresses and the horizontal axis shows the load repetitions. Wolff opted to use theta, the octahedral normal stress for his model. By using HVS data for a variety of materials, he was able to develop a series of $S-N$ curves that could be used to determine cumulative permanent strain. He then used Miner's hypothesis to determine the cumulative strain as a result of different wheel loads trafficking the pavement. A value smaller than unity is then taken to be acceptable, whereas failure is considered to occur as soon as it exceeds unity. In the design process, the sum of the permanent strains in each of the pavement layers must not exceed the appropriate design standard. Naturally, deformation in the bound layers has to be added to the value developed in the unbound materials. The method was very successfully applied to low-volume road pavements, where the unbound material dominates the structure.

CONCRETE MODELING

Because of the limited extent of APT testing done on concrete pavements (see Figure C16), it is understandable that related modeling of APT performance is also limited. Roesler et al. (1999) reported that not all techniques and instrumentation used in HVS testing of asphalt pavements can be used successfully in concrete pavement testing. They do warn against increasing the load incrementally during concrete tests, pointing out that this can lead to errors, because Miner's Law or cumulative damage theory does not work well for sequenced loading conditions in concrete. Therefore, changing the load in the middle of an APT test can make quantifying the fatigue results difficult.

With concrete testing, emphasis is placed on the performance of the joints, dowel bars, load-related cracking, and the bearing capacity of the subgrade beneath the concrete slabs. Roesler et al. (1999) defined failure as when there is a visual crack on the surface of the concrete slab. Test locations have failed with longitudinal, transverse, or corner cracks.

Figure 14 (Roesler 1998) shows the results of the HVS fatigue tests on FSHCC pavements relative to the Portland Cement Association fatigue curve, beam fatigue curve based on 50% probability of fatigue failure, PCC slab fatigue curve taken from laboratory tests, and field fatigue curve by Vesic and Saxena (1970) based on the AASHTO Road Test. This preliminary field fatigue curve for FSHCC pavements was found to be similar to the fatigue resistance of PCC slabs in the laboratory.

To evaluate the fatigue resistance of the FSHCC pavement versus conventional fatigue curves for PCC, bending

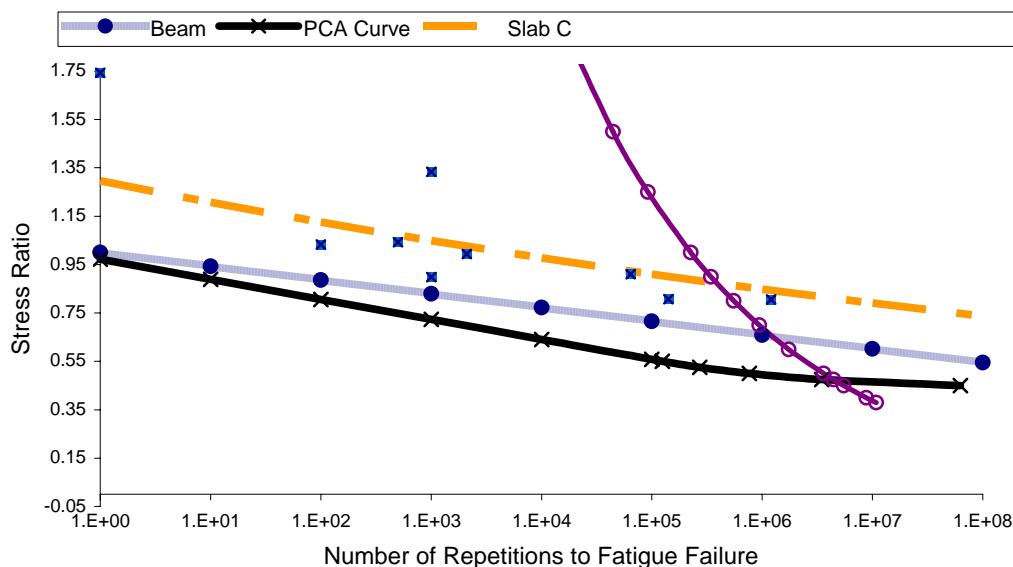


FIGURE 14 Comparison of FSHCC and PCC fatigue performance.

stresses in the slab were back-calculated from measured edge deflections. These back-calculated stresses were then divided by the 90-day flexural strength of the concrete to determine what the applied stress ratio was in the slab during HVS testing. The stress ratios greater than one were ascribed to the results obtained for fatigue life curves developed from beam tests. The calculation of stresses in the slabs were also complicated by the curling of the slabs and differential shrinkage (Roesler 1998). Similar findings were reported by Balay and Goux (1994).

Embacher and Snyder (1999) evaluated the load transferring efficiency of joints in concrete pavements as a subsidiary study to the Mn/ROAD program, using the MinneALF for trafficking in the laboratory. They used the following equation:

$$LTE \text{ (percent)} = (d_{UL}/d_L) \times 100 \quad (43)$$

where

- LTE = percent load transfer efficiency,
- d_{UL} = deflection of unloaded side of crack/joint, and
- d_L = deflection of loaded side of crack/joint.

With this expression, perfect load transfer (where both sides of the crack/joint deflect equally under an applied load) exists when the ratio is 100%. Conversely, no load transfer exists when the ratio is 0% and both sides of the joint or crack move independently. Many agencies consider LTE values of less than 70% to be unsatisfactory and may consider retrofitting load transfer devices in such cases.

SUMMARY

From the review it was apparent that an immediate benefit of APT is that pavement performance may be modeled directly. This is possible because many of the factors influencing performance can be controlled, including

- Wheel loads (magnitude, wandering, rest periods, etc.),
- Tire pressures,
- Pavement structures (compaction, layer thickness, drainage, etc.),
- Pavement materials (gradations, binder contents, etc.),
- Pavement temperatures (only when tests are performed within environmental chambers), and
- Subgrade moisture conditions (only when pavement structures are constructed within test pits or when tests are done within time windows between seasonal variations).

A wide range of models have been developed as part of APT research, including

- Pavement damage,
- Subgrade rutting performance,
- Asphalt rutting performance,
- Asphalt fatigue and cracking performance,
- Elasto-plastic behavior of unbound materials, and
- Concrete performance.

APT performance modeling usually does not include ride quality because the restricted lengths of test areas make the collection of representative and reliable data on

longitudinal unevenness difficult. This is not serious, because riding quality is not necessarily related to the structural condition of the pavement as Croney and Croney (1998) pointed out in their discussion of the AASHTO road test. They argue that it would be more cost-effective to evaluate riding quality in terms of cracking and deformation through observation of in-service highways.

There are limitations to APT modeling of pavement performance. APT cannot directly account for time-related factors that influence distress. These are primarily limited to environmental influences, although traffic-related influences must also be taken into account. Furthermore, it is not always possible to relate APT performance to the performance of in-service pavements under conventional traffic. Real-time trafficked pavements are subject to maintenance before pavement failure. Perhaps the most significant shortcoming of APT modeling, however, is the lack of applicability of models based on one site to other sites. This has motivated the development of models based on probabilistic approaches, including the use of artificial neural networks (Abdallah et al. 1999), to account for variability. It has also necessitated the normalization of data to reference parameters.

Models developed based on APT tests are often expressed in terms of displacements, stresses, and strains within pavements layers. Application of performance models requires that these response parameters be estimated using mathematical models of pavement structures. These

models may be defined using linear elastic theory, FE methods, equivalent thickness, or other multilayer approaches. Pavement response is verified using strain gauges or coils or pressure cells placed in APT test sections. Researchers should recognize that instrumentation of test sections may disturb the materials in which these devices are placed.

Modeling of APT data also requires a definition of failure. This failure is related to performance parameters such as pavement response (displacement, stress, and strain) and material characteristics. The shift to modeling pavement performance in terms of structural performance, instead of functional performance, indicates the trend to express performance in more fundamental terms. This allows a better definition of failure. The cause of failure may be related to specific structural components; for example, fatigue of an asphalt layer or permanent deformation of the subgrade.

Modeling the performance of specific structures alone restricts the applicability of performance models if material characterization of the structural components is neglected. This is particularly important with the development of pavement design systems and performance-related specifications. For this reason, attention has been given to the relationships between observed performance under trafficking and the performance as predicted from pavement analyses using material characteristics determined in laboratory testing. This topic is discussed further in chapter seven.

CHAPTER SIX

DEVELOPMENT AND VALIDATION OF REHABILITATION, CONSTRUCTION, AND MAINTENANCE STRATEGIES

INTRODUCTION

This chapter discusses significant APT findings pertaining to the enhancement of rehabilitation designs of pavements, as well as improvements to practice in the construction and maintenance of pavements.

In rehabilitation design, the stiffness and other characteristics of the existing support structure influence the type and thickness of the rehabilitation overlay(s). A review of the literature on the use of APT for evaluation of structural and rehabilitation designs indicated that the two applications do not differ significantly. However, in rehabilitation design testing, emphasis is placed on evaluating the overlay directly and ensuring that the existing support structure does not contribute significantly to the failure of the overlay.

Construction specifications are normally the way in which lessons learned through APT are implemented. Some construction-related findings on material issues were addressed in chapter four and these should be read together with those presented in this chapter.

The evaluation of different maintenance options is frequently difficult without field applications. In this regard APT applications have been found to be quick and effective.

A number of typical APT studies were selected to present a generic overview of applications pertaining to these topics. Before discussing the applications that were found in the literature, the results from a synthesis of the questionnaire survey will be presented.

QUESTIONNAIRE SURVEY

The responses to Questions 6.1 to 6.4 on construction and rehabilitation are reflected in Figures C42 and C43 in Appendix C. The responses were synthesized and the results are summarized here.

- The study of unconventional materials and the influence of compaction were two aspects that received the most attention (Figure C42).
- The impact of APT on specifications was felt the most in the field of performance-related specifications.
- The development of warranty projects and guidelines towards pay factors (Figure C43) was also considered important.

Views of respondents to the survey on construction and rehabilitation are presented in Tables D6(a) and D6(b) in Appendix D.

REHABILITATION DESIGNS

One of the primary goals of APT is to serve as a tool for gaining insight into the performance of complex, composite rehabilitation structures. The mathematical modeling of such pavement systems and their analysis is not only complex but sometimes impossible. In such cases, the use of APT has been important. Rehabilitation strategies are best illustrated by phenomenological studies and a heuristic approach.

There are many well-documented records of successful applications of APT as integral parts of rehabilitation designs. A detailed discussion on each of these case studies is beyond the scope of this report. However, it was concluded that some of this information should be included in the appendixes for reference purposes (see Appendixes F through H). A selection of case studies is discussed here.

Asphalt over Asphalt (Including Recycling)

CAL/APT (Harvey et al. 2000) reports on APT studies of rehabilitation strategies on pavement structures tested to failure with the HVS. Sections of these pavements were overlaid with dense-graded asphalt concrete (DGAC) or gap-graded asphalt rubber hot mix (ARHM-GG) to evaluate the current Caltrans method of overlay design for these materials. The thickness of overlay required on fatigue cracked pavements when using ARHM-GG was one-half of that required by DGAC and this was confirmed by HVS testing (37 mm vs. 75 mm). CAL/APT emphasizes that it is important in APT testing of rehabilitation strategies that rutting from deformations in the untreated pavement components deep in the structure do not control the performance of the overlay.

TxMLS tests evaluated the effectiveness of two rehabilitation processes used for overlays (Hugo 1999; Hugo et al. 1999a). It was important to identify where pavement failures occurred in the underlying 40-year-old pavement that was tested, because failure of an overlay is sometimes caused by a subsurface layer and not by the overlay itself. For this reason, forensic testing included FWD testing of

the pavement structure as a whole and an investigation into the drainage of the structure. Apparently there was a difference in the structural capacity of the underlying structure of one rehabilitation strategy that affected its rutting performance. However, after discounting this effect, it was still possible to distinguish which of the two strategies was better. Even then, wet trafficking showed that both strategies were susceptible to stripping owing to the nature of the composite structure that had LWAC as an interlayer at a depth of 75 mm. Here APT was able to evaluate performance better than relying on analytical procedures alone.

APT testing at WesTrack (Epps et al. 1999) required maintenance and rehabilitation of test sections that failed prematurely. They recommended two rehabilitation procedures that proved successful and may be useful for in-service highways. For pavement rutting, milling to a depth of 50 to 75 mm and replacing with new HMA was an effective technique for extending pavement structural capacity. To repair extensive fatigue cracking, the deep T-patch shown in Figure 15 was very effective.

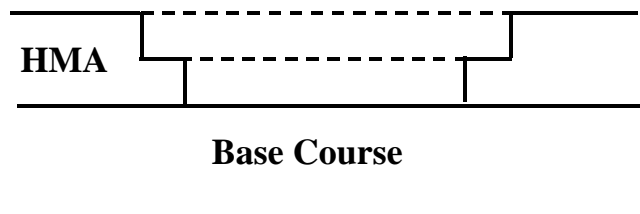


FIGURE 15 Schematic representation of a deep T-patch for remediation of fatigue cracking.

ARRB–ALF testing in Australia has been used to evaluate rehabilitation options included in the *Austrroads Pavement Design Guide*, which is primarily based on empirical relationships derived from overseas data (e.g., Shell), and to validate design inputs for asphalt materials being used in Australia (Sharp et al. 1999a). APT testing was instrumental in evaluating under field conditions the performance and benefits of different material types, including materials with modified binders. APT trials focused on evaluating the relative fatigue characteristics of various types of asphalt rehabilitation applied to a distressed pavement. A deficiency in the Austrroads design method was identified where only a single rut criterion, based on limiting subgrade strain, is used. The method has subsequently been revised to account for the temperature-related plastic deformation of the asphalt layers. APT trials of pavements with materials having modified binders demonstrated a significant performance improvement with use of modified binders in the overlay, with more than double the life achieved compared with conventional binders. This far outweighed the additional cost of the material. APT research also indicated that Austrroads Benkelman Beam deflection-temperature adjustment curves used for the design

of overlays were not applicable to FWD deflections. The results showed that correction factors were required for polymer-modified asphalts.

ARRB–ALF APT testing has been used to evaluate rehabilitation strategies involving deep-lift in situ recycling, which incorporates a cementitious binding agent to strengthen pavements (Sharp et al. 1999a). Research has been done to establish the performance of deep-lift recycled pavements using a slag/lime binder over subgrades of relatively low and relatively high strengths and to gain a better understanding of the distress mechanisms of these pavements. Studies have been done to determine if performance depends on stabilization depth (depths of 250, 300, and 360 mm) and to compare the performance with that of a 400-mm thick unbound granular pavement. The findings suggested that this type of pavement recycling was suitable for moderate, rural, arterial traffic. Furthermore, if field compaction techniques could be further improved to increase the level of compaction of material below 300 mm, then substantial gains in performance would be anticipated.

Blackman et al. (1996) reported on full-scale accelerated load testing of recycled Heavy Duty Macadam (HDM) road-base materials using the Pavement Test Facility (PTF) at the TRL in the United Kingdom. Tests were also done on a conventionally produced HDM to compare its performance with the performance of the recycled material. The recycled HDM road base incorporated 50% reclaimed material in the mix. The HDM materials were constructed in two layers, each 75 mm thick, on top of a 150-mm-thick crushed-limestone subbase. A 40-mm surfacing layer was used. Blackman et al. (1996) stated that no measurable difference was observed in the performance of the recycled and conventional HDM in the accelerated tests.

Van der Merwe et al. (1992) report HVS testing to evaluate rehabilitation design of a bitumen-treated base (BTB) pavement in South Africa. The original pavement consisted of a 160-mm BTB that was constructed in two layers on top of a natural gravel subbase and a selected layer, each 200-mm thick. An 80-mm thick, semi-gap-graded asphalt overlay was placed over this structure. The influence of aging on the performance of the overlay was investigated. Artificial aging was applied by heating the road surface to 100°C and then maintaining this temperature for 7 and 28 days for different test sections. Aging stiffened the asphalt mix on the surface. A comparison of the HVS performance of the pavements with unaged and aged asphalt indicated improved rutting but poorer fatigue performance for the aged asphalt test sections. Van der Merwe et al. (1992) concluded that the shift factor used to calculate the fatigue life of the asphalt overlay (propagation of cracking) decreased from 5 to 1 with aging of the asphalt.

Asphalt over Concrete

Strauss et al. (1988) reported on HVS testing of various rehabilitation strategies for a jointed unreinforced concrete pavement without dowels. The concrete pavement had failed because of microscopic cracking from alkali-aggregate reactors. This cracking not only reduced the stiffness of the slab but also reduced the strength of the subbase (ingress of water and higher load-associated stresses). The result was structural failure of the pavement. The following experimental overlay sections were constructed for HVS testing:

- Gap-graded asphalt (60 mm) with rolled-in precoated chips on four different interlayers;
- Jointed unreinforced concrete pavement (JCP), 125- and 150-mm thick, with joints spaced at 4 m;
- Continuously reinforced concrete pavement (CRCP), 100- and 125-mm thick, with 0.67% longitudinal reinforcement;
- Continuously graded crushed-stone overlay, 150- and 200-mm thick, with a 40-mm-thick, semi-gap-graded asphalt wearing course, with 19 mm of rolled-in precoated aggregate chips;
- Semi-gap-graded HMA, 70-mm thick, with rolled-in chips over interlayers of a single seal coat with soft conventional binder (150/200 pen), bitumen rubber binder, and a woven and nonwoven geofabric; and
- Gap-graded asphalt overlay ranging in thickness from 30 to 90 mm, with a 30-mm open-graded bitumen rubber surfacing.

An effort was made to eliminate the bond between the failed concrete pavement and the overlay options. Bonded sections were considered; however, these resulted in cracking and punch-outs. To ensure an unbonded PCC overlay, a 25-mm-thick flexible AC layer was placed on top of the old pavement. This layer served as a bond breaker and reduced the risk of voids beneath the PCC overlays in the event of warping. From the HVS trafficking, it was concluded that the rehabilitation options could sustain trafficking of 2.7 to 4.5 million ESALs for the bitumen rubber asphalt and up to 40 million ESALs for the thin CRCP.

This APT experiment served as proving ground for the use of the crack activity meter (CAM) (Viljoen et al. 1987). The CAM was of particular value in monitoring load transfer at the joints, as well as the effect of such joint movement on the performance of the experimental overlays. The CAM successfully measured total crack movement (CM), which was a 2-D composite of vertical and horizontal joint movement as described by Viljoen et al. (1987). By monitoring the CM as trafficking progressed it was possible to evaluate the condition of the pavement relative to the number of load applications. The findings

from the rehabilitation study led to understanding of the mechanisms that were affecting the performance of the rehabilitation options. The following observations were made during trafficking:

- Opening and closing of joints as a wheel passes over the crack was detected by the CM.
- Change in the pavement support structure during APT affects CM. As an example, voids below joints in the pavement structure affected the response in terms of CM as trafficking progressed.
- Joint repairs caused CMs to be reduced from 600 μm to 50 μm .
- During trafficking, the CM response initially increased to reach a peak; later it reduced progressively as the underlying structure disintegrated into smaller blocks.

It was concluded that

- CM was dependent on pavement structure, surface deflection, and block size between joints.
- Tolerance limits relating CM to allowable traffic were found to be dependent on asphalt mixture type, environmental conditions, and structural changes during trafficking.
- Conventional asphalt can accommodate a traffic-load-associated CM of up to 200 μm .
- Bitumen rubber HMA was able to accommodate a traffic-load-associated CM of up to 400 μm .
- With the 90 mm CRCP the CM at shrinkage cracks was negligible, and HVS trafficking was equivalent to 40 million ESALs.

All of the rehabilitation options tested under SA-HVS trafficking performed well under APT. The researchers found that the position of joints in concrete overlays, relative to joints and cracks in the overlaid pavement, is an important consideration influencing the deflection of the pavement and the vertical stress on the subgrade. They recommended that it is better to provide joints in the concrete overlay as far away as possible from the joints in the distressed pavement. The expected overlay life to first reflection cracking, as found with the HVS tests and some preconstruction analysis, is summarized in Table 3 (NDOT-SA 1997).

The researchers concluded that JCP overlays (sections 1 and 2) were viable options for rehabilitation of distressed concrete pavements. The thin layer of AC with bitumen rubber (section 5) performed exceptionally well. The thicker overlays performed better, as expected, although the semi-gap-graded asphalt overlay (section 4) cracked at the old joints. On the basis of the APT study, the South African National Roads Authority decided to use the thin layer of AC with bitumen rubber and an interlayer. The

TABLE 3
EXPECTED OVERLAY LIFE TO FIRST REFLECTION CRACKING, FROM HVS TESTING AND
PRECONSTRUCTION ANALYSIS (NDOT-SA 1997)

Option	Overlay	Expected Life in ESALs (millions)
1a	150 mm JCP new joint 300 mm away	3.5
b	150 mm JCP new joint far away	4.7
2a	125 CRCP crack at old joint	3.4
b	125 CRCP crack 300 mm away	6.5
3	200 mm crushed stone	2.3
4a	80 mm semi-gap asphalt (without interlayer)	0.1
b	80 mm gap-graded asphalt (with geofabric interlayer)	0.4
5	40 mm bitumen rubber asphalt (without interlayer)	1.2
6	80 mm semi-gap asphalt (with interlayer)	2.5

Notes: ESALs = equivalent single-axle loads; JCP = jointed unreinforced concrete pavement; CRCP = continuously reinforced concrete pavement.

interlayer was added because it had enhanced performance, although this option was probably a short-term solution. More is said about the subsequent performance of the pavement in the next chapter.

The study also demonstrated the effectiveness of geofabrics in retarding reflection cracking. The successful use of geofabrics was further validation of an application of APT in 1973. At the time, a geofabric was used to overcome reflection cracking from a cement-treated base course. APT was used in the very early stage of the SA-HVS program to explore the long-term performance of the methodology. A diagnostic study of the performance of that pavement under in-service trafficking 10 years later reported the application as very successful (Hugo et al. 1982).

By 2001, a total of 4.5 million ESALs had trafficked the highway, including the trial test sections, without serious distress (J.C. Van der Walt, personal communication, December 3, 2001). The traffic volume on the 40-mm-thick open-graded bitumen rubber asphalt overlay had already reached a level well beyond the original level that was achieved with the HVS trafficking. It was concluded that this was because of the harsh conditions during HVS trafficking that led to an unduly conservative estimate of performance. Furthermore, an interlayer had been added to protect the HMA, and the deteriorated joints in the underlying pavement had been properly repaired.

Whitetopping

Kuo et al. (1999) reported on APT tests done to evaluate the performance of an ultra-thin fiber-reinforced concrete (UTFRC) overlay on asphalt and concrete pavements to determine the optimum thickness and content of polyolefin and polypropylene fibers. APT testing has also been done to investigate the performance of concrete pavements containing recycled concrete aggregate and to evaluate patching materials for rigid pavements.

The researchers found that adequate bond between the UTFRC and the asphalt base was essential for the long-term performance of the UTFRC overlay. UTFRC pavements showed less cracking than plain concrete pavements. Based on that study, they recommended that joint spacings for 75- and 100-mm-thick UTFRC should be 1.22 to 1.83 m. For a 50-mm-thick UTFRC, the joint spacing should not be greater than 1.22 m. The most advantageous properties of fiber-reinforced concrete overlays are the ability to retard the initial formation of cracks and the ability to restrict the propagation of already formed cracks.

Debonding of patching materials from the concrete was another problem identified. Results indicated that elastomeric patching materials have a greater tendency to debond from the concrete than do the cementitious patching materials. It was shown that a conventional square-cut procedure before patching may not be necessary with high-strength and fast-set patching materials.

Vandenbossche and Rettner (1999) reported on Mn/ROAD research to evaluate ultra-thin whitetopping (UTW) with fiber-reinforced concrete. This involves placing a thin concrete overlay directly on top of an existing distressed asphalt pavement. Typical applications include low-volume pavements where rutting, washboarding, or shoving is present.

The researchers found that achieving satisfactory long-term performance required a bond between the overlay and the underlying asphalt. The Mn/ROAD researchers pointed out that, as the overlay begins to debond, tensile stresses will develop at the bottom of the overlay. These stresses will increase as the strength of the bond decreases, and the life of the overlay will then decrease. They recommend a short joint spacing to help reduce curling and warping stresses. Research into the performance of the UTW is ongoing.

Results of an FHWA-PTF UTW study have been published (Rasmussen et al. 2001; Qi et al. 2002, 2004). In 1998, the FHWA and the American Concrete Pavement As-

sociation jointly constructed eight full-scale lanes of UTW over existing HMA pavements, which included a range of asphalt binders. ALF loading of the lanes showed that the stiffness of the underlying HMA had significantly more effect on the development of cracking distresses in the UTW than did the variables designed into the overlays themselves (UTW thickness, joint spacing, and fiber reinforcement). Results from the ALF tests are being used to improve mechanistic models and design procedures for UTW overlays.

CONSTRUCTION AND MAINTENANCE ISSUES

Epps et al. (1999) reported that the primary objective of the WesTrack research in Nevada was the development of performance-related specifications. An integral part of these specifications is the establishment of penalties and bonuses (pay factors) that are related to the quality of construction. They outline an approach that assumes substandard construction will result in early rehabilitation, which costs the agency. Better quality construction, on the other hand, will defer rehabilitation. They propose that the difference in present worth of rehabilitation costs, that is, for as-constructed versus as-specified, provides a rational basis for setting the level of pay factors relating to construction quality. The effect of the following construction variables was addressed:

- Asphalt content,
- Air-void content,
- AC thickness, and
- Aggregate gradation.

Monte Carlo simulation was used to evaluate the influence of the construction variables on both fatigue and rutting performance models based on results from APT. From these simulations it was then possible to estimate the effects of off-target construction and calculate pay factors. The full report of the WesTrack project has just been completed (Epps et al. 2002). It reflects the extensive range of findings from this comprehensive APT experiment.

Theyse (1999) reported on extensive HVS testing in South Africa to evaluate different base materials placed using labor-intensive road construction. The purpose of the HVS testing was to assess the quality and performance of pavement base layers constructed in this way, but also to gain a better understanding of material performance when it is primarily processed by hand. Emulsion-treated gravel, waterbound macadam, composite macadam, and a selected clinker ash material known as Premamix, were used in the base layers of test sections. A machine-constructed crushed-stone base layer was also included for comparison with the labor-intensive constructed base layers. It was concluded that the emulsion-treated gravel performed well.

The 100-mm emulsion-treated clinker ash also performed well, but did not have the same bearing capacity in terms of rut rate (millimeters/million road repetitions) as the other emulsion-treated material. The respective rut rates were 2.6 for the clinker ash versus 0.6 for the gravel. The waterbound macadam had a slightly lower bearing capacity than the emulsion-treated gravel (0.7 versus 0.6). This was related to the compaction effort applied using light pedestrian pavement rollers. As a result, the field density of the waterbound macadam was very low and this would have affected the performance of this material. None of the materials tested performed as well as the crushed stone.

Theyse (1999) also reported benefit-cost ratios for the tests. These were determined by comparing the number of axle load applications to reach a permanent deformation of 10% of the initial thickness relative to the initial cost of the layer per square meter. The 100-mm crushed-stone base yielded a benefit-cost ratio approximately twice that of the emulsion-treated gravel base. Compared to the untreated clinker ash, the benefit-cost ratio of the crushed-stone base was 2.7 times higher, although it was approximately 8 times higher than the emulsion-treated clinker ash and the waterbound macadam.

Harvey et al. (2000) provided examples of how APT testing in California has demonstrated the benefits of lower air-void contents in asphalt mixes for extending the fatigue life of flexible pavements. Pavements with thick AC layers designed for heavy traffic were found to obtain greater relative improvements from increases in compaction than pavements with thinner AC layers. Based on these results, changes were recommended to Caltrans to reduce the allowable air-void content as much as possible, while still maintaining an achievable specification. Because of this change, Caltrans construction specifications for AC have typically resulted in constructed air-void contents of 9% on average with end-result specifications, compared with 12% on average with the method specifications previously used.

Construction of APT test sections that are instrumented with strain gauges, pressure plates, and cells, requires special consideration. Numerous studies in the literature report problems, owing to misalignment and damage to instrumentation resulting from the construction process or to premature failure of test sections because of inadequate compaction of instrumented test sections. Burnham (1999) reported on problems experienced in Minnesota with the Mn/ROAD with the installation of strain sensors in concrete slabs during construction; these ultimately required removal and retrofitting of the sensors. Hugo et al. (1997) reported on pavement failure in Texas related to inadequate compaction of a base layer beneath and over a pressure plate placed for the Mobile Load Simulator response monitoring. This led to premature failure of the asphalt layer.

Hugo et al. (1997) also discussed three construction-related problems that affected the performance of pavements tested with the TxMLS. They found that deep-seated variability in the pavement foundation resulted in differential pavement performance at the surface. Lenses of poor materials within constructed layers had the same effect. Poor compaction of the asphalt layer resulted in high-void content and early fatigue failure of the HMA.

The influence of variability of pavement materials in the DIVINE project in New Zealand was also investigated by Kenis and Wang (1999). They concluded, on the basis of reliability analysis, that reduced pavement structural variability will increase the reliability of pavement service life. Such variability may be caused by the variability of pavement materials or the nonuniformity of pavement construction.

HVS trials at Hornsnek, South Africa, also indicated that inadequate control and construction of cemented materials resulted in layers of unstabilized materials and layers with poor interfacial contact (Opperman 1984). These case studies lend further support to Nunn (1997), who reported considerations for long-life pavements. He emphasized that it is necessary for the road to be well-constructed and maintained, with good quality asphalt and a good foundation, so that deterioration does not result from construction or material deficiencies.

The performance of marginal sandstone material stabilized in situ has also been evaluated (Yeo et al. 1999). Testing was conducted in Dandenong, about 30 km southeast of Melbourne, Australia, on a marginal sandstone when it was unbound and when it was stabilized in situ with bitumen/cement and slag/lime blends. The researchers pointed out the importance of compacting stabilized material, both in the field and in the laboratory, as soon as possible after mixing. They also found that overcompaction of these materials during construction could result in a breakdown of marginal sandstones. They recommended that a maximum compaction standard of 95% of modified maximum dry density be adopted for in situ stabilization works of this type when the parent material to be stabilized is a marginal sandstone material liable to break down under a load. They concluded that stabilized pavements require 7 days of moist curing or immediate sealing with an approved curing compound. Alternatively, the next layer of the pavement should be constructed to prevent excessive drying of the stabilized surface that may lead to cracking.

Vuong et al. (1996) stated that ARRB-ALF research has resulted in major changes to construction practice in Australia, where multilayer cement stabilized bases are constructed. They reported that the ALF trials conducted at Beerburum in Queensland contributed to the state of the art of the design and construction of both stabilized and unstabilized granular pavements. The importance of adequate

compaction is emphasized. They noted that for high-quality, crushed-rock pavements, compaction is critical, because these materials appear to be more sensitive to moisture damage at lower levels of compaction. The optimum compaction and saturation of these materials must therefore be addressed. For granular pavements, design and maintenance strategies must consider the possible effects of severe short-term environmental and loading conditions on pavement performance.

In an earlier study, Vuong et al. (1994) found that the life of a crushed-rock base was very dependent on the compaction level and the percentage of moisture in the base in terms of degree of saturation. Comparison of pavement life indicated that at an optimum moisture content (OMC) of 70%, the base at optimum relative compaction of 104% maximum dry density had the longest life. A 1% increase or 2% decrease from this level could cause up to an 800% reduction in pavement life. The effects of moisture content or degree of saturation were also significant. A 5% change in relative moisture content from the moisture content limit of 70% OMC could cause up to a 400% change in pavement life. They found that the optimum situation was to specify a maximum limit for moisture at sealing in terms of degree of saturation (85% saturation). They also recommended that specifications be changed to reduce risk that could arise owing to high compaction levels and high degrees of saturation. It should be noted that TDR gauges were used to monitor the moisture changes in the pavement structure and that this was very successful.

Stage Construction

Stage construction is an economical method of pavement design, although there is a risk associated with this approach with regard to the availability of long-term funds. Freeme (1984) reported on the use of the SA-HVS to provide information for a decision on the timing of the second phase of planned stage construction at a site in Swinburne, South Africa. The first phase of the planned stage construction consisted of two stabilized 150-mm subbase layers and a thin asphalt surfacing. The APT results showed the necessity of implementing the second phase of the stage construction before serious degradation of the upper subbase had occurred.

Autret and Gramsammer (1990, 1995) indicated that the LCPC in France has shown that applying a maintenance overlay of 80 mm to a damaged pavement is equivalent to following a deferred maintenance strategy consisting of applying a 40-mm layer and then a second layer with the same thickness when the first becomes damaged. Kleyn et al. (1985) reported on a related issue from a HVS study on an in-service highway in Transvaal in South Africa. They found that considerable savings would accrue if timely

maintenance interventions were implemented rather than rehabilitating the highway when it reached the terminal level of serviceability.

Constructability

Constructability is an issue that has also been addressed in APT programs. This is probably because factors that affect performance also affect constructability. Examples of such factors for HMA are composition in terms of particle shape and size, binder content, and compaction. This issue is discussed in this section.

One of the objectives of the Caltrans APT research is the application of CAL/APT results to long-life flexible and concrete pavement reconstruction. Harvey et al. (1999) reported that CAL/APT is geared towards reconstructing flexible pavements by incorporating design features that minimize the thickness of the pavement and improve constructability. Elements of this strategy were addressed previously and include

- Compaction of the AC layer to 5% air voids,
- A rich bottom layer, 50 to 75 mm thick at the bottom of the AC,
- Exclusion of the rich bottom layer or any rut-susceptible mixes from the critical zone for rutting within 100 to 150 mm of the surface,
- Design for rutting of the unbound pavement layers, and
- Use of thicker AC layers instead of an ATPB just beneath the AC.

Harvey et al. (2000) determined that constructability is controlled by the tolerances imposed by the existing infrastructure (issues such as bridge heights, underground drainage and utilities, guard rails, and signage) and the extent to which traffic delays are caused by closing lanes to permit the reconstruction or rehabilitation work. They emphasize that high construction productivity is vital to minimizing traffic delay.

In the case of reconstruction of rigid pavements, the California researchers suggested that construction productivity may be improved by

- Using pavement thicknesses that are less than the thickness of existing rigid pavement to eliminate opening and subsequent recompaction of the subgrade and to avoid interference with subsurface drainage systems, conduits, and other subsurface infrastructure; and
- Keeping the reconstructed road surface elevation at or only slightly above that of the existing rigid pavement to eliminate the need to raise bridges, drainage features, guard rails, ramps, etc.

Galal and White (1999) also discussed constructability. They found that composition of the HMA affects the density of the HMA that can be achieved, which in turn affects the rutting performance. Because compaction affects the constructability, they deduced that performance is affected by constructability. As a corollary, enhancement of constructability enhances performance. This explains the emphasis that is being placed on constructability as a factor that has to be taken into account in the design and construction of pavements.

In the last decade a number of innovative materials have been introduced in South Africa, and HVS testing has been instrumental in the further development, design, and evaluation of these materials. Findings and results from accelerated testing have been implemented toward improving the constructability of these materials and establishing design criteria and standards. These materials include granular emulsion mixes (GEMs) and large aggregate mixes for bases (LAMBs).

De Beer and Grobler (1993) reported on HVS testing toward improved structural design criteria for GEMs. The HVS testing focused on the determination of the structural capacity of GEMs in terms of fatigue cracking and fracturing. A marginal weathered dolerite, a fine-grained gabbro rock, was used as the parent material and was mixed with 2.5% lime to reduce the plasticity index before emulsion treatment. For the HVS tests, five sections were constructed using GEMs with emulsion contents ranging from 1% to 5%. For each of the sections, a 150-mm GEMs layer was constructed on a cemented subbase. De Beer and Grobler stated that lime-treated GEMs increase in strength and stiffness with curing. The highest rate of strength increase was observed between 3 and 4 months after construction. Indirect tensile strengths increased from approximately 300 kPa to 900 kPa. The resilient modulus of sections having 3% emulsion increased from initial values of approximately 800 MPa after construction to 3,000 MPa after 10 months curing before HVS testing was applied to the sections. HVS testing of the GEMs sections indicated that an emulsion content of 2% was required to ensure design traffic levels of at least 10 million ESALs. An optimum emulsion content was finally recommended based on ancillary laboratory tests. Design charts were provided for GEMs constructed on poor and strong subgrades and these were used to provide a catalogue of GEMs pavements for different traffic classes and road categories.

Emery (1995) reported that to evaluate the performance of pavements containing LAMBs, three trial sections were constructed in the Province of KwaZulu-Natal, South Africa, and evaluated by means of accelerated testing by the HVS. Based on the results obtained from HVS testing on continuously graded LAMBs, indications are that these mixes should be able to carry traffic well in excess of 50 million standard 80-kN axles without failure in terms of

deformation within the base. Lessons learned in the design and construction of these large stone mixes led to extensive use of these materials in Kwazulu-Natal. Experiences with LAMBs were collected and published in a Sabita manual (SABITA 1993).

Rust and MacCarron (1989) reported on a material, which is a cold-mixed asphalt that had been designed for pothole filling and trench reinstatement. It is easy to apply or use and needs minimum compaction. The report gives details of the APT conducted by the former Division of Road Transport Technology in South Africa on four variations of the formula for the production of the material.

SUMMARY

This chapter covered a number of issues related to the rehabilitation design of pavements, as well as construction and maintenance issues.

Structural designs are typically tested at fixed sites, whereas rehabilitation designs are usually evaluated in the field. In a few cases, structural designs have been tested to failure at fixed sites and subsequently been overlaid and retested. A review of the literature of APT research applied to evaluate both structural and rehabilitation designs indicated that the methods applied do not differ significantly.

In rehabilitation design testing, however, emphasis is placed on evaluating the overlay directly and ensuring that the support structure does not contribute significantly to the failure thereof.

Overlay options investigated by means of APT include asphalt over asphalt, asphalt over concrete, concrete over concrete (PCC and whitetopping), concrete over asphalt, in situ recycling, and stabilization of base structures.

APT has been instrumental in validating and refining agency structural and rehabilitation design guidelines.

The literature review indicated that APT has contributed to the establishment of construction specifications relating to field compaction (density and uniformity), layer thickness, material uniformity, patch repair, binder and moisture contents, and drainage requirements. However, topics such as construction tolerances and proof testing have not received much attention worldwide. Likewise, the effect of quality control and assurance has also not been explored specifically. These applications of APT could enhance the development of performance-related specifications for construction and maintenance. The short turnover possible through the use of APT makes this an attractive application. It should provide a basis for the determination and quantification of pay factors for construction and the confident application of warranty contracts.

CHAPTER SEVEN

PAVEMENT ENGINEERING APPLICATIONS AND ISSUES**INTRODUCTION**

Thus far, the relationship between APT and constituent elements of the pavement engineering system has been reviewed. In this chapter, a number of APT-related issues are covered. However, before considering the various issues, it is appropriate to discuss the wide range of APT applications that have been recorded.

In *NCHRP Synthesis of Highway Practice 235* (Metcalf 1996), the applications of APT to practice were discussed in some detail. The fields of application in this report were expanded in the current study to cover some additional aspects of pavement engineering. The applications cited by Metcalf (1996) were then categorized according to the defined fields. The list was expanded to include applications that had been reported at the recent International APT Conference in Reno, Nevada, together with related publications issued since then. The results of this analysis are contained in Appendix G indicating the respective fields and the related objectives of the tests. This summary is indicative of the potential of APT as a core element of pavement engineering. The same applies to the annotated bibliography that was assembled from the responses to the questionnaires. The aforementioned information should be of value when exploring documented case studies that have been reported by APT users.

In the remainder of the chapter, the discussion is focused on several important and related pavement engineering issues and two special APT applications.

- The relationship between APT and in-service pavements,
- Failure criteria
 - Rutting and
 - Fatigue and cracking,
- The relationship between APT and LTPP studies,
- APT applications to block pavers, and
- APT applications to airport pavements.

RELATIONSHIP OF ACCELERATED PAVEMENT TESTING TO IN-SERVICE PAVEMENTS WITH CONVENTIONAL TRAFFICKING

The first question that needs to be asked is: Why is there a difference between APT and conventional trafficking? Ac-

ording to Metcalf (1996) there are essentially two reasons.

- Environmental effects, especially long-term aging, are difficult to capture in APT. (The combined effect of environment and time difference is not simulated.)
- A full spectrum of in-service wheel loads are not applied in APT.

In reality, all APT tests have to consider these two factors when developing methodologies for using APT results optimally. Therefore, conventional in-service highways and/or formal LTPP studies feature both in such development. This is an important aspect of APT that warrants detailed discussion. Very little has been reported on this issue. However, the approach of some well-advanced APT programs provided valuable input. In this section, the relationship between APT and in-service highways in general is discussed. Later in the chapter, the focus will be on formal LTPP studies.

LCPC Approach

The LCPC has an effective method of addressing the problem (Gramsammer et al. 1999). The procedure is as follows:

- Laboratory fatigue tests are conducted on materials that are to be used in a pavement structure. Strains within the pavement structure are then determined theoretically by analytical or numerical modeling according to their rational pavement design method.
- The calculated strains are then used to evaluate performance life in terms of the laboratory findings.
- These findings are then compared to the performance life of the pavement under trafficking by the carousel (LCPC-APT device). The two results are used to establish a “coefficient of correspondence.”
- By relating the theoretical laboratory performance life to conventional field traffic performance, a “coefficient of adjustment” is determined.
- The interrelationship between laboratory, APT, and field traffic is then established by comparing the coefficient of correspondence to the coefficient of adjustment. The extensive knowledge that they have on long-term performance of in-service pavements serves as benchmarks for establishing the relationships.

On the basis of the established relationships, the LCPC researchers are able to evaluate the performance of new materials using APT. This methodology has been used extensively by LCPC and their industrial partners to establish the performance of new materials (many of which are proprietary) and/or structural design systems.

The coefficient of correspondence, K_c , for the Circular Test Track is given by

$$K_c = \varepsilon_{cal} / \varepsilon_6(\theta, f) \cdot \langle NE/10^6 \rangle^b \cdot 10^{-ub\delta} K_s$$

where

- NE = number of axle load passages leading to the rupture of the structure,
- ε_{cal} = strain calculated in the modeled equivalent structure,
- $\varepsilon_6(\theta, f)$ = strain leading the rupture during the laboratory fatigue test for 1 million cycles at the temperature θ and the frequency f ,
- b = slope of the material fatigue curve,
- δ = standard deviation depending on actual thicknesses and fatigue test results,
- u = random variable related to the risk considered of the normal law, and
- K_s = correction coefficient of soil homogeneity.

Corté et al. (1997) stressed that to compare performance of different materials to a reference mix it is necessary that

- The rut depths are sufficiently large after 100,000 loadings to generate significant differences in performance, and
- Speeds of load application are the same.

In this way, LCPC is able to interrelate the carousel and an in-service pavement that has a proven record of performance. This also allows them to use their LTPP results in conjunction with APT results.

ARRB Approach

In 2001, K.G. Sharp provided a summary on the procedures that are followed by the ARRB in their transformation of ALF trafficking into conventional traffic on in-service highways. Because of the generic nature of the outline, it is quoted below with minor editorial amendments:

The method of handling loading obviously depends on the type of experiment/test. In many experiments we are only concerned with the relative performance of one type of “experimental” pavement with another type of “control” pavement. The idea is that we have a good knowledge of how the

“control” performs in service (because it is a standard pavement widely used in practice), so, if we can demonstrate that the performance of the experimental pavement is similar to the control pavement, then there is increased confidence in its likely performance in service. These “experimental” pavements might incorporate non-standard materials, recycling techniques, etc. In those cases, the Equivalent Single Axle [load] (ESAL) concept is as good as any, i.e., cycles of load of X kN converted to the Standard Axle load assuming the 4th power law.

Similarly, we might be comparing a range of maintenance options. In those cases, we will traffic the trial pavements with the same number of cycles of the same load and compare performance. This, of course, is also the classic way of conducting an “axle load equivalency” trial—either test all pavements as above or, alternatively, compare the number of cycles of differing loads required to generate the same performance (say a 20-mm rut).

Such an approach was also appropriate during the series of asphalt deformation trials we conducted. The aim was to compare the performance of the various mixes/binders, so we placed the test mixes onto a very strong cemented base to ensure that all deformation would be induced in the mixes. We also used the pavement heating system to ensure that all testing was conducted at the same temperature (50°C). We then tested all mixes with the heaviest load (80 kN) and compared the deformation—leading to a “ranking” of the mixes in terms of deformation resistance. Meanwhile, we conducted laboratory testing on the same mixes (both cores taken from the pavement and laboratory manufactured samples) and also “ranked” them according to the results. We then compared the field and laboratory results. We have also done this type of testing of unbound materials using ALF and Repeated Load Testing (RLT) testing.

It is when we are looking at specifically structural design issues, that it gets a bit more complicated. I am referring here mainly to fatigue tests of bound materials where you are trying to either develop, or confirm, fatigue life prediction models. At the moment in Australia the damage exponent for cemented materials is 12 (based on “experience” and limited testing), while for asphalt it is 5 (Shell). Using these relationships we can predict the “allowable life” for a given test pavement by modeling the pavement using CIRCLY (Wardle 1977), calculating the horizontal strain at the base of the bound layer, and hence fatigue life using these performance relationships. These are in the *Austrroads Pavement Design Guide* (Austrroads 1992), which is currently being updated for release in 2002.

We then turn ALF on and monitor the number of loading cycles to “failure” (whatever that is) and compare it with the predicted life. We also do some laboratory testing and compare the three predictions. Defining “failure” is tricky enough: we know that surface cracking may not be the failure point. The layer may have cracked at the bottom and the crack worked its way up and we also know that the layer, even though cracked, still has a strength (cemented layers can survive for years after cracking—you simply apply a surface seal every 5 years or so when the cracks reflect through to the surface!).

Another way of defining “failure” of bound materials is in terms of back-calculated modulus. We conduct FWD tests at the start of trafficking and use EFROMD2 (Vuong 1991) to predict the modulus of the bound layer. We continue to conduct FWD testing during trafficking and note the decrease, if any, of the modulus of the bound material (the theory being that the moduli of the other layers (e.g., subgrade) will stay the same because test conditions are controlled). We have found that the modulus of asphalt can decrease to about half its initial value before surface cracking is observed whilst, for cemented materials, the value can reduce to as much as 1/10 of the initial value before cracking is observed.

Fatigue testing of bound (particularly cemented) materials is tricky at the best of times because of the variations in parent

material, binder type, binder content, etc. We never have had a good agreement with laboratory beam testing. This is not a problem unique to us! (K.G. Sharp, ARRB, personal communication, December 3, 2001).

LINTRACK Approach

Bhairo et al. (1998a,b) debated this issue in some detail. Their LINTRACK program is strongly focused on modeling. Coupled with that is the question of whether or not a pavement has failed. The problem lies in that stiffness loss invariably occurs well before cracking manifests. The Dutch researchers assumed that a section has failed when the stiffness has dropped to a level of 50% of the virgin asphalt. The procedure takes account of factors such as lateral wander and healing because of rest periods of nonoperational time. Allowance is also made for crack propagation, which depends on the layer thickness. However, when all of these factors are accounted for, there is still a 2- to 4-fold difference between LINTRACK life and the laboratory-determined value. The authors do not discuss the issue of extending the performance relationship to include a regular highway.

South African Approach

The South African approach does not have conversion factors between APT structural pavement behavior and real-life structural pavement performance. However, this is not believed to be crucial to the success of the process (De

Beer et al., personal communication, November 26, 2001). They consider the number of variables that affect the real-life performance and life expectancy of a road to be so high that they state:

It is extremely difficult to directly relate real-life to APT unless you have a huge APT database where you have varied (and tested) all these impacting factors. The approach on the implementation side is therefore rather an “adaptive management process” than a “predictive control process.” Real-life dictates and we have to manage our activities (maintenance and rehab) to ensure we get the performance that we want from the road.

The South African process is shown in Figure 16. In essence, there is no attempt to convert HVS-initiated pavement structural behavior to real field pavement performance. The approach is to study pavement response and performance in great detail by means of APT and then develop practical pavement designs by applying the knowledge gained. The South African mechanistic–empirical pavement designs are calibrated from time to time in collaboration with pavement engineering consultants and the road authorities.

This approach is underpinned by the work that was done during the early phases of the SA–HVS program. In 1984, Freeme summed up the approach as follows:

- Primary indicators of performance such as rutting and cracking were monitored. In the same vein, secondary indicators, which are responses in terms of

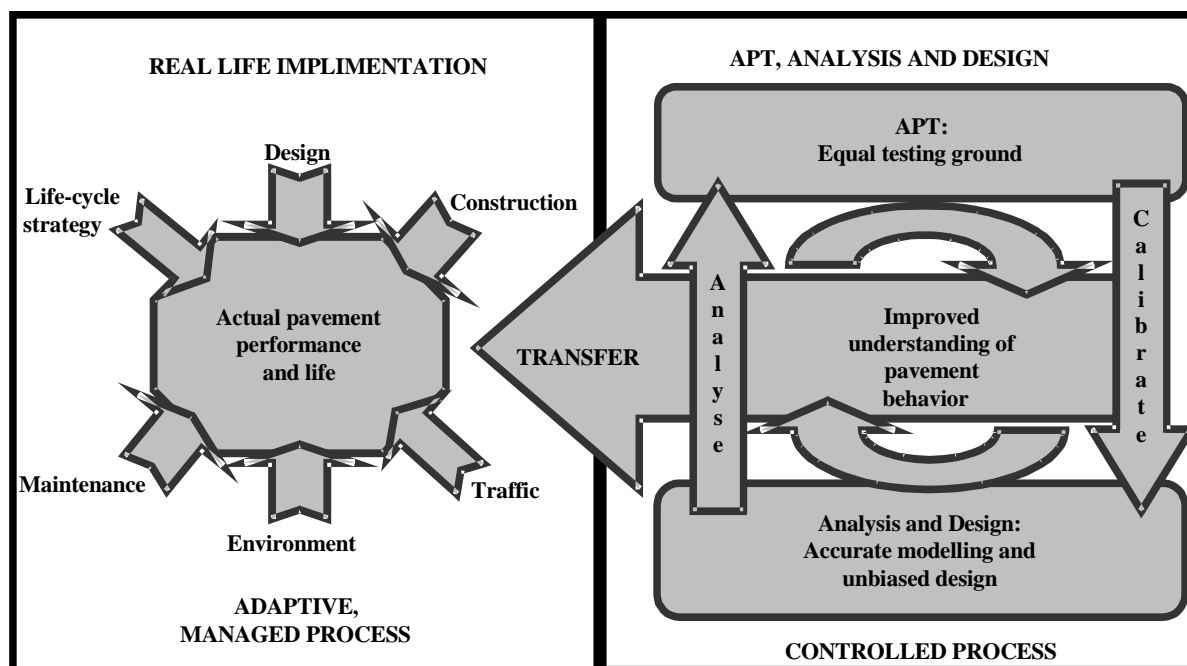


FIGURE 16 Schematic outline depicting the interaction between SA–HVS APT results and real-life implementation and pavement performance (De Beer et al. 2001, personal communication).

deflection with depth, and in situ strength and strain, were monitored. With this process, changes in secondary indicators were linked to primary indicators and used to calibrate mechanistic models of pavement structures. Confidence was built when measured deflection profiles matched calculated deflections.

- There has been reasonable correlation between HVS performance and actual in-service pavement performance. This has enabled general performance of pavement structures to be clearly illustrated and understood. In turn, this has improved understanding of factors that influence performance of pavement structures. This knowledge has enabled performance of rehabilitation strategies to be predicted.

From the foregoing discussion, it is apparent that APT findings are transformed in various ways to enable the results to be used by the different APT users for their specific purposes. This process is not without constraints. Some of the problems that have arisen will be illustrated by means of selected case studies indicating how the ultimate performance of APT sections compare with the original APT findings and the related performance prediction.

CONSIDERING SOME CONSTRAINTS IN THE PROCESS OF TRANSFORMATION OF TEST FINDINGS BETWEEN TRAFFICKING SYSTEMS

It is necessary to review some of the constraints that need to be considered in transforming test findings between trafficking systems. Typically, the constraints relate to issues that have been discussed elsewhere in the report, such as vehicle–pavement–environment interaction over time (see chapter three) and construction and maintenance (see chapter six). The matter is further exacerbated by differences in distress criteria that apply to APT and in-service highways. These constraints are particularly relevant in the case of performance prediction of conventionally trafficked in-service highways, as will be seen from the following case studies. Three cases, each extending over almost two decades, were selected to illustrate the complexity of the problem.

Case Study One: A composite pavement with thin HMA and a crushed-stone base on cement-treated subbase—Route P157-1 South Africa. Jooste et al. (1997) presented a comparison of HVS-predicted performance with the actual performance of a road in South Africa. The road (Route P157-1) had been tested 16 years earlier with the HVS. Characteristics such as deflection, Dynamic Cone Penetrometer shear strength, moisture, and density were found to correlate reasonably well with the initial measurements. Environmental effects did not appear to significantly influence the performance of the pavement. However, the researchers point out that a 13-mm surface seal coat had

been placed some time earlier and this had probably prevented the ingress of surface water. The average rutting was similar to that measured during APT at the equivalent number of standard axles. However, in both cases, the ruts were very small while the variance differed. This was the first comparison of its kind that they had undertaken and, although good agreement was found in the study, they identified a number of important issues that needed to be considered in such comparisons. In particular, accurate traffic statistics in terms of axle loads are necessary. They also suggest that statistics on ride quality would be useful. A greater number of similar tests would also be necessary to improve the level of confidence.

Case Study Two: HMA surfacing and base—Natal, South Africa. Wolff et al. (1997) investigated the performance of a pavement with a HMA surfacing and base structure that had been tested with the HVS in 1984. Their goal was to compare the actual performance of the pavement with that predicted after the HVS testing. The original test was to evaluate the performance of a structure consisting of bituminous surfacing and base on a stabilized granite subbase in a wet environment.

In the original study, the pavement was subjected to the equivalent of 20.3 million ESALs with the HVS in a dry condition. At that time, the pavement showed a 10-mm rut that was primarily the result of deformation in the HMA. When the section was then artificially wetted, it failed after application of a further 300,000 ESALs with a rut of 20 mm (10 mm in the asphalt and 10 mm in the stabilized subbase). The failure mechanism was reported as being

- A longitudinal crack in the wheel path owing to fatigue in the asphalt layer initiated by a stabilization crack in the subbase layer or a crack resulting from the settlement of the fill,
- Pumping the result of trafficking following ingress of water into the pavement system,
- Erosion of the stabilized subbase layers and subsequent pumping into layers above because of trafficking, and
- Permanent deformation of the carbonated stabilized subbase.

The artificial wetting was accomplished through surface wetting during trafficking and filtering water into the layer system from the side under a head of 1 to 2 m of water. The moisture content in the subbase layer, after artificial wetting, was still slightly less than the actual pavement at the time of failure; that is, after 25 years of service life.

The actual pavement that was investigated in close proximity to the original test section exhibited distress in the form of pumping after 1.4 million ESALs of conventional trafficking under the natural environment.

From an examination of the long-term performance of the highway pavement, the researchers concluded that the failure mechanism was similar to that which had been found with HVS testing. However, failure had occurred after a significantly different number of ESALs. In the case of the HVS tests, the failure had occurred after approximately 300,000 E 80s of wet trafficking, whereas it took a total of 1.4 million ESALs under the natural, but wet climatic conditions to reach similar failure on the highway before rehabilitation was undertaken. This difference was attributed to differences in the ingress of water into the system. Apparently there had been intermittent phases of wetting and drying of the layers in the long-term pavement test. The researchers suggested that it would be better to wet the pavement intermittently throughout the HVS test rather than only at the end of the dry test phase or, alternatively, better to wet at an early stage rather than only at the end of the dry test phase. A further interesting point from the study is that a second rehabilitation was initiated in 1996 when the PMS signaled the development of the same type of distress as before. At that time approximately 1.5 million ESALs had been added after the rehabilitation. This was almost the same as the traffic carried during the first phase (1.4 million). It is also worth noting the high HVS traffic volume that the section had carried in the dry state (20.3 million). This case study demonstrates the importance of integration of APT and studies of the performance of in-service pavements and the need to take into account the environmental impact in a manner that simulates the actual field conditions during trafficking.

Case Study Three: Overlay on an alkali–aggregate reaction distressed concrete pavement. In chapter six, the rehabilitation of a jointed concrete pavement in South Africa was discussed (Strauss et al. 1988). The pavement had suffered severe distress because of the reaction between the high alkali cement and the concrete aggregate. The rehabilitation was undertaken after completion of HVS testing of alternative options that were constructed on the in-service pavement (Viljoen et al. 1987; Strauss and Van der Walt 1990). The HVS trials showed little rutting with the alternative options. Cracking was the predominant mode of failure. The following options were investigated:

- 150 mm crushed stone with 50 mm asphalt wearing coarse,
- 30 mm open-graded asphalt with a bitumen–rubber binder wearing coarse,
- 80 mm asphalt with bitumen binder,
- 80 mm asphalt with low-modulus nonwoven geofabric interlayer,
- 80 mm asphalt with bitumen–rubber stress-relieving interlayer, and
- 80 mm asphalt with high-modulus woven geofabric interlayer.

Testing took place primarily during the wet winter season. Water was also sprayed onto the surface when there was no rain. Conditions were therefore particularly harsh during APT. Cracks initiated where the underlying old concrete pavement exhibited movement. Several rehabilitation options were considered feasible, but the most economical one for a short term (7-year life cycle) was found to be bitumen–rubber asphalt. The HVS study predicted 3 years of life for the bitumen–rubber asphalt.

The rehabilitated pavement has been in service for almost 19 years with only limited maintenance. The maintenance was in the form of a seal coat and joint repair through removal of failed material and reinstatement of concrete where the material had deteriorated owing to the ingress of water and air (J.C. Van der Walt, personal communication, December 3, 2001). The performance of the road has been intermittently monitored since the original construction. A report was compiled in 1997 (NDOT–SA 1997).

It was apparent that the performance was far better than found with HVS testing. The theoretical analysis by Strauss et al. (1988) concluded that the actual performance could be as much as four times longer than the HVS performance, if the mean condition of the underlying concrete pavement is considered instead of the most severely distressed sections. In addition, the harsh conditions during APT trafficking would have led to a conservative estimate of performance life. The information gathered from the diagnostic performance monitoring has provided noteworthy insight on the relationship between APT and in-service performance. Some lessons learned were

- The actual long-term performance of the original test sections was as found with the HVS testing in 1984.
- The concrete overlays (jointed and CRCP) have performed well, with little or no visible distress.
- The bitumen–rubber asphalt section that had been constructed with extender oil added has performed well.
- The stress-absorbing interlayers have played an important role in the long-term performance. This relates to the reduction of the ingress of water into the pavement structure and reduction of shear and tensile stresses in the asphalt.

The three case studies demonstrate how vehicle–pavement–environment interactions affect LTPP. Clearly, the transfer of APT results to in-service pavements has to be done with caution and specific consideration of all factors that can affect the results, particularly the environmental factors. Also to be considered are the frequency of maintenance and possible alternative failure mechanisms, especially when the pavement structure is altered.

FAILURE CRITERIA

This issue relates to the previous topic. It is the basis for defining benchmarks to ensure comparable APT performance relative to real pavement performance under conventional traffic. Several factors have to be taken into account, such as the limited size of test sections, the difference in the nature of trafficking, the difference in time scale including the effect of aging, the limited number of experiments, and the limited ability to determine the integrity of the pavement nondestructively. Two forms of load-related distress are generally considered, rutting and fatigue cracking.

Rutting

This form of distress is the easier one to monitor and evaluate. The rut profile measurement is taken to be representative of the performance of a section of in-service pavement that it simulates. In general, the average maximum rut at a specific cross section is reported. A number of impact factors are then taken into account to enable performance of a pavement under different trafficking systems or conditions to be compared. In the case of APT testing of an in-service highway, it is taken to be on a one-to-one basis; that is, the rutting performance should be the same after accounting for climatic effects, load amplitude, and frequency of load applications. Epps et al. (2001) followed a systematic procedure for doing this in relating the performance of the MMLS3 to the full-scale truck trafficking at WesTrack. This allowed for differences in aging, load frequency, temperature, and lateral wander. Epps et al. (2001) also took into account the difference in the extent of the stress profiles owing to the difference in load amplitude. Once these factors had been accounted for, they found that the rutting performance was comparable on a one-to-one basis with a small margin of error.

It is of interest to note that the method of recording rutting used in the Spanish APT program (Romero et al. 1992) is able to capture changes in the transverse rut profile that are the result of shoving of the asphalt owing to lateral wander. In their transverse profile measurements they differentiate between the maximum rut depth and the rut depth on the center line of the wheel path.

Maccarrone et al. (1997) reported that permanent deformation results obtained with ALF testing in the field (in Australia) and wheel tracking in the laboratory gave a good correlation. A similar magnitude of deformation level and deformation rate was obtained with ALF field testing and laboratory wheel tracking when the latter was done at 60°C.

The problem becomes more difficult where the deformation occurs throughout the pavement structure including the nonbound, stress-dependent materials. Theyse (1997)

presented a conceptual model for the permanent deformation of pavement layers. In the process, he developed permanent deformation design transfer functions for a number of unbound material quality groups, following the principles of a basic model. The main source of data for developing the design models was HVS test data collected over a long period of time in South Africa. This covered dense-graded crushed stone and natural gravel with due regard to variations in quality, as well as a range of pavement foundation material quality groups. These were subsequently incorporated into the design recommendations for highways (*Structural Design of Interurban . . .* 1996). The ARRB followed a similar procedure (Sharp et al. 1999a).

Fatigue and Cracking

Fatigue is a more complicated form of distress because it relates to cracking and stiffness loss. In general, it is accepted that failure has occurred once the in situ stiffness has dropped to a level of 50% of the original untrafficked pavement (Bhairo 1998a). Various methods of monitoring the stiffness loss have been reported (Lee et al. 1997; Bhairo 1998a; Harvey et al. 2000). With full-scale APT it is necessary to monitor the cracking as it develops and several procedures have been developed to do this. Scheffy et al. (1999) explored a number of digital and manual crack detection and mapping methods and developed a reliable and consistent method of crack detection and measurement for fatigue cracks. The method employs off-the-shelf software and hardware, making it inexpensive and easy to implement. Hugo et al. (1997) used transparent mylar sheets to log cracking of a 12-m test section as trafficking progressed. Prints were then made of the sheets and their size reduced to enable photocopies to be made. The electronic images were vectorized with the aid of a commercial software package. The cracks could then be analyzed to categorize them according to orientation. Groenendijk et al. (1997) also present details for capturing and recording cracks in the pavement using Mylar sheets. The methodology they used for categorizing the crack orientation is the one that was followed by Hugo et al. (1997). Other APT programs each have their own methodology for monitoring and recording cracks.

RELATIONSHIP BETWEEN ACCELERATED PAVEMENT TESTING AND LONG-TERM PAVEMENT PERFORMANCE STUDIES

There have been, and still are, a wide range of formal experiments that are designed to monitor the performance of designated or specially constructed in-service pavement sections, over time. Such formally structured experiments are generally known as LTPP studies. The relationship between APT and formal LTPP studies is discussed in this section.

As discussed earlier, a number of APT programs have monitored and kept detailed records on the performance of pavements tested in an accelerated mode, either directly or indirectly. Other programs, such as several in South Africa, have only recently included such procedures in their test plan (Jooste et al. 1997). This ongoing process provides an important comparative base for relating actual performance of formal LTPP sections under conventional trafficking to performance under accelerated trafficking. The benefits of such an approach are highlighted in an overview on the topic submitted by Sharp and Clayton (personal communication, November 30, 2001) in which they give details of the relationship between APT and long-term performance trials of the ARRB. This is of a generic nature and considered to be of value to the APT community at-large. Therefore, it has been included as Appendix H. Aspects of their approach are briefly discussed later. It appears as if this interaction between APT and LTPP was also contemplated in the original formulation of the SHRP–LTPP experiment according to the following extract from the TRB SHRP Research Plan report (1986):

The LTPP program embraces the total range of pavement information needs. It draws on technical knowledge of pavements presently available and seeks to develop models that will better explain how pavements perform. It also seeks to gain knowledge of the specific effects on pavement performance of various design features, traffic and environment, use of various materials, construction quality, and maintenance practices.

In the years to come, as sufficient data become available, “analysis” is expected to be conducted by numerous interested agencies. The formal LTPP products are expected to include better predictive models for use in design and pavement management, better understanding of the effect of many variables on pavement performance, and new techniques for design and construction. These improved “tools” are then expected to result in improved pavement management.

The LTPP study program has three potential types of studies. These include General Pavement Studies (GPS), Specific Pavement Studies (SPS), and APT. The GPS involves a very large experiment that embraces an array of site selection factors expected to produce a broad range of products and results. The SPS will have their own set of more limited goals, construction needs, and experimental approaches; and are generally aimed at more intensive studies of a few independent variables for each of a number of study topics. The other category of studies, which is to be considered for future adoption, is the Accelerated Pavement Testing Program.

It is apparent that APT and formal LTPP programs share many goals. This is significant given the growth in the APT programs in the United States. Furthermore, both systems are attempting to build pavement knowledge in areas such as

- Validation of laboratory performance-related materials tests;
- The linkage between laboratory, APT, LTPP, and normal in-service highways in terms of distress and performance;
- Construction-related pavement defects;

- Quantification of risks in warranty projects;
- The efficacy of maintenance procedures;
- Vehicle–pavement–environment interaction; and
- Development of durable, low-maintenance pavements with improved performance prediction.

Because of the commonality, APT records contain information compatible with, and in many respects similar to, that already being collected as part of formal LTPP studies or programs, such as the SHRP–LTPP experiment. This provides a basis for efficiently and effectively comparing APT performance with that of related or comparable LTPP sections. It is therefore understandable why research entities are in general keen and willing to interface their APT programs with formal LTPP programs. The Australian ARRB approach to this matter is presented in Appendix H as outlined by Sharp and Clayton (2001). The following are salient features of their approach.

An Austroads-funded project was established to address APT and LTPP issues and to take advantage of the opportunity to be directly involved in the SHRP program. This had as its primary aim the monitoring of the performance of a range of Australian test sections as a complimentary project to the U.S. SHRP–LTPP experiment. The goal was to improve performance prediction models for the benefit of LTPP.

The overall objectives of the Austroads LTPP study are to

- Enhance asset management strategies through the use of improved pavement performance models based on an improved understanding of the behavior of pavement structures (the SHRP–LTPP program), and
- Compare the results of accelerated pavement test studies with actual road pavement performance (the ALF–LTPP program).

Nineteen Australian test sections have been monitored continuously for 5 years. Some of these were specifically established in tandem with ALF trials. The preliminary analyses conducted to date have already produced significant findings, many of which are discussed elsewhere in this report.

With the expansion of the APT programs in the United States, the benefits to be gained from closer linkage between the performance of in-service highways, formal LTPP programs, and APT studies are apparent. As was evident from earlier discussions in this report, there is already an extensive array of significant findings that can serve as a basis for such a collaborative effort.

The foregoing discussions demonstrated that the interactive use of results from the performance of in-service pavements, together with formal LTPP monitoring and

APT programs, has improved understanding of the performance of pavements and its prediction. In turn, this has led to cost savings and it has enhanced construction and rehabilitation practices. As a result it has reduced risk in performance prediction. These findings are being used in warranty projects and are proving of value in the improvement of pavement management.

In the next sections the discussion will focus on APT studies conducted on nonconventional pavements such as concrete block pavers and airport pavements.

APPLICATION OF ACCELERATED PAVEMENT TESTING TO BLOCK PAVERS

Concrete block pavements have been tested using APT in a number of facilities worldwide. Shackel (1990) provided an overview of developments going back as far as 1967 in Rotterdam. At the time, the test facility comprised a 20-m-diameter circular test track. Subsequently, tests were carried out in Australia, New Zealand, South Africa, and Japan. Studies have focused on

- Strengths,
- Shape of pavements,
- Thickness of pavements, and
- Layout pattern.

In studies using the HVS, Shackel (1980, 1982) explored the failure mechanisms and the factors that affect performance.

Performance has been found to be somewhat similar to flexible pavements, with some specific differences such as

- Ability to tolerate higher resilient deflection, and
- Stiffening of the pavement structure after the initial 500 load cycles were needed to develop full interlock.

It was also found that the pavements have a prominent structural capacity as reflected by a sharp reduction in vertical stress at the level below the bedding sand layer.

This brief overview shows how the state of knowledge on pavers has been enhanced through APT and it serves as an excellent example of how applications followed initial research studies to enhance the use of the product.

In 2001, Sharp provided an interesting case study, pertaining to the Sydney Opera House, on concrete pavers that dates back 18 years. In 1998 and 1999, the Sydney Opera House Trust commissioned an ALF study to investigate failure of granite sets (pavers) on a heavily trafficked access road to the Opera House. The sets were paved on a mortar bed and the waterproof membrane on top of a rein-

forced concrete slab. The sets had failed through displacement by passing traffic, after being loosened during trafficking. The ingress of water followed with subsequent secondary effects on the underlying structure. The study focused on determining the optimum laying pattern as well as bedding and jointing methods. Five panels were tested, with alternative set patterns and bedding methods applied to the respective layouts (K.G. Sharp, personal communication, December 3, 2001).

In this instance, the goal was to rank the relative performance in terms of the extent of cracking and deformation. Another goal for the test was to determine the effectiveness of the waterproof membrane. Dual-wheel load tests (40 kN) were conducted, and it was apparent that differential failure had occurred among the alternative test plans (Figure 17). A second experiment was conducted with 40-, 60-, and 80-kN ALF loads and trafficking was taken to almost 1 million equivalent standard axles. In an attempt to promote premature failure, areas of mortar jointing were saw cut to duplicate cracking and allow ingress of water into the pavement. Both wet trafficking and heated trafficking were undertaken. The latter was to investigate the effects of heat on the rubber membrane. Some minor cracking was observed in both panels that were tested after 36,000 cycles. No further distress developed. The saw cuts did not appear to affect the structural performance. Only minor cracking was observed in both panels after 36,000 cycles; no other distress was observed at that time. There appeared to be no evidence of the application of heat affecting the performance of the water membrane underlay, and the underlay did not appear to affect the performance of the granite set pavement.



FIGURE 17 Failure of block pavers after 9,000 cycles of 40-kN loading. Note the amount of sand that has been pumped from under the granite blocks (Sharp 2001).

APPLICATION OF ACCELERATED PAVEMENT TESTING TO AIRPORT PAVEMENTS

APT already has an impressive record of applications to airports, so much so that special equipment has been developed for this purpose (Hayhoe et al. 2001). Some of the cases will be used to demonstrate the applications.

Guo and Marsey (2001) investigated the effect of temperature variation on the performance of concrete slabs in the FAA's NAPTF. Load transfer between adjacent slabs was found to be poor during winter (low temperature). They also investigated joint behavior and concluded that load transfer may be sensitive to traffic direction. An interesting finding was that the sum of the deflection in two opposite directions across a joint varied very little. This may serve as a guide to the sensitivity of slabs to curvature.

Hayhoe et al. (2001) investigated the impact of multiple-wheel and multiple-truck landing gear configurations and their spacings on six flexible pavements. A total of 522 tests were performed. Various items were also involved in 108 tests on three rigid pavements. The test vehicle completed these slow-rolling tests at 0.15 m/s. The purpose was to study wheel load-pavement interaction in terms of response under the moving wheel loads. Multi-Depth Deflectometers were used in conjunction with the static load tests on the flexible pavements under varying wheel loads.

Garg and Hayhoe (2001) reported on tests that were done with various slow-moving wheel loads. The loads were varied and so was the temperature. As expected, the strains varied strongly with temperature and speed; at the upper range, the values were as much as three times higher than those predicted by layered elastic computer programs. They also found significant permanent deformation at high temperature.

The primary objective of the HVS-A research program is to validate the 3-D pavement design and evaluation program being developed by the ERDC. The airfield pavement design system was a direct result of a long history of APT/full-scale testing.

The test plan provides for trafficking with the HVS-A to determine response and performance using multiple-wheel loadings. The first two flexible pavement systems were designed, constructed, and instrumented using the USACE Layered Elastic Design program. The structure included a clay subgrade with a CBR of 6, a crushed limestone base with a CBR of 100, and an asphalt surface. Trafficking simulated a 727 aircraft with a modified overall load of 223 kN per tire on the main gear. The pavement configuration allowed for different base course thicknesses.

Local materials were used. The quality of HMA as constructed did not meet specifications, but the test was completed to explore the effect of noncompliance. Tests were continued until trafficking was no longer possible. The test sections were fully instrumented and included three five-level, multiple-depth deflectometers. The test program is continuing.

The HVS-SA program successfully completed APT studies on airport pavements in South Africa in the early 1980s (Clifford et al. 1982; Clifford and Opperman 1983). The first was at the Cape Town International Airport and the second at the Johannesburg International Airport.

In the Cape Town International Airport case study, HVS testing was conducted to evaluate the status of the taxiways. Three sites were selected and trafficking done with 40- and 80-kN wheel loads (using regular truck wheels). This was followed by trafficking with a 200-kN wheel load, using a single wheel of a Boeing 747 at full load. In the latter case, bleeding occurred and cracks developed. Trafficking was terminated when the rut depth reached 40 mm. From the analysis of the results, it was concluded that deep-seated distress was occurring because of insufficient coverage over the submerged sandy subgrade. It was proposed that full-depth asphalt rehabilitation be done. This was undertaken 2 years later and as of 2001 the pavements were being rehabilitated again with milling and the replacement of the asphalt layers. The historical traffic over the taxiway amounted to 78,000 aircraft wheel-load applications before the recent rehabilitation (F.J. Pretorius, personal communication, December 2001). In the HVS testing in 1982, trafficking was terminated at 31,000 load applications, implying that the HVS tests were conservative in application. A somewhat similar result was found with a second test run close by, which was terminated after 14,000 load applications with the rut depth at only 14 mm.

It should be remembered that trafficking done was bi-directional, which is believed to be more severe than unidirectional (Brown and Brodrick 1999). This could have affected the performance.

At the Johannesburg International Airport, HVS-SA tests were conducted on fresh asphalt on a new taxiway adjacent to the newly constructed parallel runway. The total asphalt thickness was to be 100 mm, semi-gap graded with 19 mm aggregate. The pavement was very stiff with high-quality crushed-stone base course on cement-treated sub-base layers. With the HVS testing it was found that the deformation increased sharply when the test temperature was raised from 30°C to 40°C. The laboratory Marshall designs had indicated rutting susceptibility. This was confirmed with the HVS testing when 40 mm rutting was reached after 27,500 repetitions of a 200 kN Boeing 747 wheel. As a result it was recommended that the asphalt layer thickness be reduced because the substructure was sufficiently stiff. As of December 2002 the pavements are still in service.

SUMMARY

In essence, APT results have been applied toward

- Validation and modification of design procedures,
- Pavement configuration comparison in terms of performance,
- Evaluation of material performance,
- Performance prediction of pavements,
- Evaluation and improvement of construction practices, and
- Evaluation of maintenance and rehabilitation practices.

In this chapter, the applications and issues emanating from APT applications were considered. It was evident that the applications that have been reported worldwide offer a vast reservoir of knowledge that should be tapped by all APT programs prior to embarking on new endeavors. The fields that were covered represent not only a wide range of applications but also some very valuable information that provides strong economic incentives for conducting APT. It is apparent that the pavement engineering knowledge base has been enhanced through APT and much of the knowledge is being applied. However, it remains a challenge to integrate the information into the entire pavement engineering design and construction system.

A comprehensive statement on key findings is provided in chapter nine. It was clear that all APT programs had already contributed valuable information toward the building of a sound understanding of pavement performance under APT. However, gaps were identified with respect to vehi-

cle–pavement–environment interaction and substantial effort will be needed in this regard to create a sound basis for future development.

Another matter that was evident was the advantage in establishing a close relationship between LTPP studies and APT. The benefit of progressive review of pavement performance under conventional traffic and the possibility of emulating this through intermittent APT trials offers scope for further study, and this should be pursued. Thus far the economic aspects of applications have not been specifically considered and these form the topic of the next chapter.

It is clear that work remains in various fields of pavement engineering and in this regard the following should be noted:

- The need to formalize the approach for extrapolating APT to full-scale trafficking on regular, conventional pavements;
- The need to attempt improvement on the quantification of the impact of the environment on APT results. This is not only necessary to improve the understanding of pavement performance, but also to validate the credibility of APT; and
- The need to establish repeatability of test findings and related confidence limits. Collaborative APT programs have already demonstrated the benefits in this regard.

CHAPTER EIGHT

IMPROVEMENT OF PAVEMENT ECONOMICS AND MANAGEMENT THROUGH ACCELERATED PAVEMENT TESTING APPLICATIONS

INTRODUCTION

This chapter in effect represents the core of what APT programs are about. Unfortunately it is also an area where sufficient information is often not available. Nevertheless, reports have been published with enough information to provide insight into the economics of APTs. Success stories have been accumulating and these should serve as a base for management of APT systems, as well as provide information for improving management decisions, thereby reducing the effect of risk. It should help APT users to capitalize on the funds that they are spending or programs that they may be contemplating. With respect to the latter, some unique features of recently launched programs will be featured.

Before discussing some of the wide variety of applications that were found in the literature, the results from a synthesis of the questionnaire survey will be presented.

QUESTIONNAIRE SURVEY

The response to Questions 1.6 to 1.14 on management is reflected in Figures C6 to C14 in Appendix C. The response was synthesized and the results are contained in the following list.

- The typical duration of APT tests is related to the types of devices as well as the programs of the various entities. Some of the test programs run over extended periods of time. It is noteworthy that most of the programs appear to be running between 4 and 6 months per test; however, there are tests that run for more than 24 months (Figure C6).
- The capital expenditure involved in APT programs is high, as was expected. The extent of this is shown in some detail in Figure C7, where it can be seen that a number of programs have capital expenditures exceeding \$5 million.
- The operational budgets vary widely, which is clearly dependent on the nature of the test programs as well as the related devices (Figure C8).
- The breakdown of disbursement through the annual budget indicates that operational expenditure is generally above 30% of the budget and maintenance appears to vary from less than 10% to 20%. Not surprisingly staff expenditure consumes more than 30%

of the annual budget of most of the programs (Figure C9).

- Average operational cost is reportedly less than \$500,000 per test for the majority of test programs (Figure C10).
- Staffing needs generally appear to be less than five individuals in each of the professional, technical, and administrative categories (Figure C11).
- Overall estimated savings or benefits for individual APT programs appear to be high, greater than \$2 million, and therefore it is not surprising to see benefit-cost ratios reported to be 20 to 1 or greater (Figures C12 and C13).
- Figure C14 relates to the benefits of APT in terms of pavement engineering as a whole. This provided valuable insight into the ways in which the information is being applied or knowledge is being gained. Improved structural design and performance modeling appear to be cited most often; however, not surprisingly, the information gained in terms of improved material design and the use of new and innovative materials follows closely behind. Topics related to this are, as would be expected, the development of performance-related specifications and a better understanding of variability.

Views of respondents to the survey on management are presented in Table D1 in Appendix D.

The synthesis of the APT programs clearly indicated a number of categories in which the application of APT had contributed significantly toward more economic pavements, with improved performance. In the previous chapters technical aspects of the programs were considered. In this chapter the improvement of pavement economics and management through APT applications is considered.

With the growth in APT facilities it has become easier and more feasible to demonstrate and quantify the benefits of APT for pavement engineering and management. This was particularly evident from the viewpoints expressed by the respondents to the questionnaire survey.

The comments varied from very specific method statements for quantifying the benefits to statements of nontangible, less-measurable items. A listing is given in Table 4. A wide range of specific views or applications was also found in the literature and many are included in Table 4.

TABLE 4
APT BENEFITS RELATIVE TO FIELDS OF ACTIVITY IN PAVEMENT ENGINEERING

APT Program	Description
<i>(a) Benefits of APT: Improved structural design procedures</i>	
APLF	Structural responses measured with strain gauges and LVDTs are used to improve design procedures and modeling techniques.
ARRB–Au	Input into revisions of <i>Austrroads Pavement Design Guide</i> —damage relationships, particularly for cemented materials; confirmation of Shell relationships for asphaltic fatigue; subgrade deformation, etc.
CAPTIF–NZ	Use of unbound and cemented subbase under plain unreinforced concrete bases. Procedures for the design of pavements incorporating bitumen/cement and slag/lime blends.
FAA–NAPTF	Allows for the verification of new structures and/or philosophies against existing processes in a controlled environment.
HVS–SA	New design data for six-wheel aircraft landing gears.
NCAT Auburn	Reduction of pavement costs by reducing unnecessary pavement thickness or by improving the structural balance of the design.
PFR–La	Avoidance of failure caused by the use of unproven designs or by abnormally heavy traffic.
UK–UUIst	Rapid evaluation and comparison of rehabilitation measures for flexible, semi-flexible (stabilized), and rigid pavements.
ERCD–GSL	Recommend different layer coefficients for SMA mixes that use the same materials as comparable Superpave sections.
	Correlate pavement design estimates versus actual life, verifying pavement layer coefficients.
	Allowed comparison of traditional designs with thinner, stiffer layers.
	APT helped with strain criteria for subgrade and asphalt. APT helped with stress ratio criteria for concrete.
<i>(b) Benefits of APT: Improved performance modeling</i>	
APLF	Structural responses measured with strain gauges and LVDTs are used to improve design procedures and modeling techniques.
ARRB–Au	Development of performance relationships for the fatigue life of materials stabilized with bitumen/cement and slag/lime blends, etc. Improved maintenance intervention strategies for unbound pavements with thin bituminous surfacings.
CAPTIF–NZ	Allows the verification of new structures and/or philosophies against existing processes in a controlled environment.
NCAT Auburn	Validating laboratory performance testing by comparing to actual field performance.
PRF–La	Matching actual performance vs predicted. Trafficking loads are exactly known.
<i>(c) Benefits of APT: Improved material design procedures</i>	
APLF	Lateral profiles measured with a laser profilometer are used to monitor the stability of AC mixes.
ARRB–Au	Extensive input into the laboratory characterization of the deformation and fatigue properties of asphalt associated with the Materials Testing Apparatus (dynamic creep test, etc.).
HVS–SA	Development of testing protocols for the characterization of unbound materials using repeated load triaxial testing.
NCAT Auburn	Greater knowledge and understanding of pavement and materials behavior.
PRF–La	Compare two or more sections and advise sponsors on best way to use local materials (e.g., better performance by blending on the coarse side of the maximum density line).
UK–UUIst	Conventional soil–cement base courses were examined against thicker, but weaker cement-treated layers. Inverted pavements were also proven.
ERDC–GSL	Enabled assessment of minimizing layer thicknesses.
	Base course physical property requirements; ERDC–GSL AC mixture design.
<i>(d) Benefits of APT: Use of new innovative materials</i>	
ARRB–Au	Evaluation of marginal materials, lateritic gravel, fine-grained materials, stabilized flyash; ground granulated blast furnace slag; stabilization using slag/lime and bitumen/cement blends; modified binders in asphalt.
HVS–SA	Rapid evaluation of materials that are not standard road-building materials.
PRF–La	Fibers (polypropylene) and geogrid materials were tested.
UK–UUIst	Allowed comparison of traditional and new materials before large scale trials.
ERDC–GSL	Resin-modified pavement, sand grid, hex-mat, fiber stabilization of sand, geosynthetics, foam blocks, fiberglass-reinforced panels.
<i>(e) Benefits of APT: Development of performance-related specifications</i>	
ARRB–Au	Revision of USACE specifications for lateritic gravels.
	Development of testing protocols for the deformation properties of asphalt.
	Use of geotextile-reinforced seals on expansive clay subgrades. Revision of Queensland Main Roads specification for fine-grained marginal material.
CAL–APT	Fully described elsewhere in the report.
FAA–NAPTF	Enabled impact of six-wheel gears to be assessed.
WesTrack	A comprehensive report with wide-ranging results on the findings of the trafficking experiment with proposals for implementation is available.
NCAT Auburn	Suggest pay factor adjustments for variations in asphalt content that occur during construction.

TABLE 4 (Continued)

APT Program	Description
<i>(f) Benefits of APT: Material databases</i>	
ARRB–Au	Extensive database available for researchers and practitioners.
FAA–NAPTF	Enabled impact of six-wheel gears on materials to be assessed.
FHWA–PTF	The program has been operational since 1986 and an extensive database of findings is available for researchers and practitioners.
TxDOT	Provided opportunities to link nondestructive testing (NDT) data to performance results. Improvements in NDT data collection, in situ instrumentation techniques, analysis techniques, and performance modeling. Understanding advantages and limitations of APT. Rutting and cracking data from all TxMLS test pads provided invaluable opportunities to establish and/or calibrate performance models.
WesTrack	A comprehensive report with wide-ranging results on the findings of the trafficking experiment is available for researchers and practitioners.
<i>(g) Benefits of APT: Improved pavement management</i>	
HVS–SA	Improved pavement design methods allow better (optimal) use of funds and natural resources.
NCAT Auburn	Asphalt contents intentionally elevated on comparison sections to quantify effect of construction variability on actual performance.
PRF–La	Extra measures were implemented to ensure reliability even for 60 m lane to accommodate parallel test sections.
<i>(h) Benefits of APT: Better understanding of variability</i>	
CAPTIF–NZ	Detailed measurements related to fixed reference points allows measurements to be repeated at a later date; also, the initial variability can be related to actual behavior.
<i>(i) Benefits of APT: Warranty contracts</i>	
NCAT Auburn	Validate laboratory performance predictions so designers and builders can have confidence in future performance of roadway.
INDOT	Validate laboratory performance predictions so designers and builders can have confidence in future performance of roadway.
<i>(j) Benefits of APT: Weather databases</i>	
ARRB–Au	Weather databases: air temperature and rainfall for all trials; pavement temperature and moisture movement as appropriate.
NCAT Auburn	Automated weather station monitors environment while data acquisition systems record multidepth temperatures within each of 46 test sections.
<i>(k) Benefits of APT: Evaluation/validation of Superpave</i>	
PRF–La	Planned for 2002.

Notes: LVDT = linear variable differential transformer; SMA = stone matrix asphalt; AC = asphalt concrete.

(Source: Significant findings from full-scale APT testing Question 1.14.)

Anecdotal statements on specific measures with savings owing to innovative use and/or application of APT also provide a means to gauge benefits. A selection of such anecdotes is presented.

Apart from the anecdotal presentations, the chapter also contains discussions on topics that are directly related to the main theme of economy and management. An overview of some current and planned future APT applications is also presented with a brief comment on some international trends.

EXAMPLES OF PAVEMENT ECONOMIC GAINS THROUGH ACCELERATED PAVEMENT TESTING

NCHRP Synthesis of Highway Practice 235 (Metcalf 1996) presented a summary of a number of reports on the effectiveness and cost-benefit ratios pertaining to published APT programs. This section contains a further selection of recently reported findings as a supplement (in anecdotal format).

Steyn et al. (1997) reported on a multiyear APT study of the performance of rehabilitated LCP structures. The aim was to quantify the structural benefits and to optimize the life-cycle cost for the South African National Road Agency. They found that the rehabilitated LCPs only failed in two ways; by permanent deformation the result of pumping of fines in the wet condition and by bleeding of the double seal where it was used. The pavements consisted of high-quality crushed-stone base course (G1) and thin (<50 mm) asphalt surfacing. The economic analysis of these rehabilitated LCP structures indicated that the double-seal rehabilitation option was the most economical option for traffic classes with equivalent traffic demands less than or equal to 10 million equivalent standard axles. The G1 crushed-stone rehabilitation option was the most economical option for 10 to 30 million equivalent standard axles.

The WesTrack facility in Nevada has provided valuable information on functional performance of pavements. This was achieved through careful analysis of data pertaining to

vehicle–pavement interaction. During the course of trafficking, pavement sections had to be rehabilitated as a remedial measure to remove roughness and reinstate failed sections. The necessity arose because of surface roughness and structural distress. The vehicle operational records provided the data to determine the impact of the deterioration on the truck operational unit. The average fuel usage before and after rehabilitation showed a 4.5% improvement in fuel economy as a direct result of the smooth surface. It was also concluded that the savings would have been slightly more if the environmental conditions had been similar; significantly, they were harsher. The potential economical effect of this can be substantial. Not surprisingly the roughness also affected truck maintenance cost, including frame fracture, spring failures, and loosening of components. This was vividly demonstrated by a dramatic reduction in spring failures after implementation of the rehabilitation (Sime and Ashmore 2000).

Brown and Powell (2001) reported similar findings from the NCAT experiment. From preliminary data it was found that the rate of fuel consumption appears to be directly related to changes in the average roughness of the pavement surfaces. During the first five million ESALs, the average IRI increased from a value of approximately 1.08 to approximately 1.18. It was of interest to note that the IRI actually decreased to 1.02 during the first 5 months before increasing to 1.18. In the same time frame, fuel consumption increased by slightly more than 2%. After completion of the test, it is anticipated that it will be possible to evaluate seasonal effect on engine efficiency.

Harvey et al. (2000) reported comprehensively on the assessment of economic benefits that would accrue from the implementation of the following three changes in flexible pavement technology resulting from findings from the CAL/APT program:

1. Increase compaction requirements for HMA,
2. Require the use of tack coats to improve bonding between HMA lifts in all construction projects, and
3. Include a rich bottom layer in thick AC structures.

A full-cost model was developed and used to calculate the direct cost savings to Caltrans with the use of the new pavement technologies. The basis for the analysis was the increase in the life of the pavement and the time between necessary maintenance and rehabilitation actions. An increase of 15% in the period between overlays results in a savings of \$6,933 per two-lane-km equivalent. Applying this savings to the roadway system yields a potential statewide savings of more than \$56 million. If the period between overlays is extended by 5 years, statewide savings is more than \$244 million, a net value of more than \$163 million.

In addition to direct construction savings, user cost savings and safety cost savings will be realized. Because maintenance and rehabilitation actions will be required less frequently, fewer shutdowns, closures, and roadway capacity reductions will be required. Hence, user costs and safety costs will be reduced.

These savings were calculated for a representative project on I-5 near Sacramento. For example, their study showed that the time cost savings would be \$1,335,600, or 54% of the total benefits. Safety improvements would yield \$658,627, or 20% of the total benefits. Direct cost savings to Caltrans on the project amounted to \$468,480, or 19% of the total cost. The increase in pavement life and reduction in frequency of required rehabilitation yielded a benefit of approximately \$2.5 million for the representative project.

The researchers argue that this benefit is realized at relatively little cost. The new pavement technology is primarily focused on method or technique and not the application of new, additional, or more costly materials. The new pavement technologies are expected to have little or no impact on person-hours of labor required on a given contract.

Overall, the potential for cost savings using these new pavement technologies appears to be quite large. If such a saving is applied statewide, using the factor of proportionality of 19%, the researchers estimated that the total savings potential could be in the neighborhood of \$587 million (1998 dollars). They concluded that more research was needed to explore aspects such as pavement age and project location.

Harvey et al. (2000) also reported on an issue that has a bearing on the quality and the economy of the constructed product; namely, quality control/quality assurance (QC/QA). They showed that CAL/APT data can provide the basis for a rational procedure for the development of pay factors. For this they used the calibrated mix analysis and design system. Pay factors based on fatigue analysis have already been developed. The factors include the effects of degree of mix compaction (represented by relative compaction), binder content, and asphalt thickness. The proposed factors have been combined with those developed from rutting analyses for the WesTrack test road. This is yet another example of the synergism that collaborative APT efforts yield. The system stresses the importance of proper compaction to ensure improved fatigue and rutting performance. In the same vein, the importance of thickness control for asphalt layers is stressed in the reported study. The authors (Harvey et al. 2000) concluded that a significantly improved HMA performance bonus/penalty system as a part of a QC/QA program has the potential to significantly improve asphalt pavement performance if implemented.

The DIVINE project (OECD 1998), discussed in chapter three, provided conclusive evidence of the effect of interaction between suspension, quality of initial construction, and pavement materials on surface deterioration. This has an important bearing on strategies for vehicle-related options and pavement design, construction, and maintenance. The final report commented on this as follows:

Vehicle-related options could be supported by new strategies for pavement design, reconstruction, and maintenance; these might be required to produce pavements that induce less dynamic loading and are less sensitive to its effects, and could result in stronger, more even pavements on designated freight routes. Pavement design and construction techniques should emphasize uniformity in materials, construction, and surface smoothness to ensure that heavy vehicle dynamic loads do not substantially reduce pavement life and increase maintenance costs. Structural and surface (evenness) uniformity should be emphasized in pavement design and construction cost/performance “trade-offs.” The DIVINE project provides further support for the characterization and measurement of highway conditions, to enhance the pavement management systems on which all OECD member countries are increasingly reliant.

The unique ability of APT to capture this information in a quantitative manner is featured as a significant finding; whereas the economic impact of the finding is self-evident even though it has not been quantified.

Autret and Gramsammer (1990) cited a variety of cases where there were distinct pavement economic gains through the application of APT. They reported that the understanding of pavement mechanics has been substantially improved. This has led to a refinement of their (French) catalogue of new pavement structures. It has also enabled them to revise the classification of untreated granular materials. Of particular importance was the new information that had been obtained about the laws of equivalence for damage by different axles, especially since these contradict the rules derived from the AASHO tests (AASHO 1961). They also indicated that these updated values are comparable to those of certain performance models such as the HDM3 model. The same authors reported on tests with the inverted structure. This was discussed earlier in this report, but it was important to note that the findings were immediately implemented on a motorway in France and this had resulted in substantial savings. In a study by the LCPC, they found that it was possible to rate the performance of different asphalt mixes under traffic. The use of bitumen-coated materials as drainage layers was evaluated under traffic. This was important, particularly since a number of commercially available load-bearing materials were being placed on the market. At the end of 2 million loading cycles in sequential summer months, the performance of two thin-rolled asphalt materials was found to be satisfactory.

Corté et al. (1997) discussed the importance of mix composition and noted that APT has enabled the stability

of asphalt mixes to be evaluated by trafficking at temperatures above 45°C. At this temperature, they have demonstrated that, both in the laboratory and in the field, the nature of the binder has an important effect toward counteracting rutting. Significant economic benefits have accrued through the prudent selection of asphalt mixes.

The Beerburum II ALF trials, consisting of 34 experiments in Australia, led to guidelines for the design and construction of stabilized and unstabilized granular pavements. This resulted in reduced pavement depths being adopted for Winton sandstone. As a consequence, the Queensland Department of Main Roads saved approximately 15% on the total cost, with no reduced performance characteristics (Vuong et al. 1996).

SOME LESSONS FROM IN-SERVICE HIGHWAY FIELD ACCELERATED PAVEMENT TESTING TRIALS

In South Africa and Australia, field trials on in-service highways are the norm. However, very little experience with such trials exists in the United States. It is therefore appropriate to consider the few examples that have been executed in the United States. In 1992, the first field tests were conducted with the FHWA ALF in Montana and Wyoming. Apart from serving to confirm the capability of on-site testing, the trials were productive and successful on both in-service highways (WASHTO 1990; Bonaquist 1992a). Insight was gained on mobility and reliability of the device. Its all-weather capability was also proven. Tests seemed to validate recommendations that had been made by the respective DOTs toward the proposals for addressing their problems with rutting. However, there was no temperature control during the experiments, which limited the ability for interpretation, because the results were subject to the environmental conditions prevalent during testing.

Bonaquist (1992a) pointed out that, although the antirutting mixture that had been developed by which the state had delayed the development of rutting, there was evidence of plastic flow. This indicated that the rutting resistance needed to be further investigated through APT. The intent was to determine the relationship between asphalt binder with modifier and required layer thickness. The cost of the two trials amounted to \$297,000, or \$148,500 per test. This compares favorably to the values reported in the APT survey (see Figure C10 in Appendix C).

The testing of US-281 in Texas from 1997 to 1999, with the TxMLS, was the second application of APT on an in-service highway after the ALF trials in Montana and Wyoming (Hugo et al. 1999a,b). Despite the extended duration of the testing owing to unforeseen circumstances, interfacing with traffic was without serious incidents. The

nature of the pavement structure was such that it would not have been possible to conduct an experiment of this kind in any other way. An extensive source of knowledge was built up. The tests also provided further validation of the application of seismic testing to monitor changes in the stiffness of the asphalt mixes, creating the basis for comparing the effect of wet and dry trafficking on performance (Walubita et al. 2000).

In May 1998, shortly after the start of the TxDOT test program in Jacksboro, field testing started on SR-14 in Palmdale, California, with the HVS2 (Harvey et al. 2000). These field trials have already resulted in some significant findings, which have been discussed in chapter four.

ENHANCEMENT OF PAVEMENT MANAGEMENT SYSTEM PROCEDURES

Pavement performance is a primary element of PMS. It is therefore logical that improved understanding of factors that affect pavement performance would lead to improvements in PMS. Unfortunately, this is not necessarily a straightforward course of events, as will be seen from the following case studies.

Rust et al. (1997) presented a typical example of an enhancement to the South African PMS derived from the HVS program. It relates to the adoption of visual cracking as a trigger for resealing. The HVS showed that cracking in thin surfacing used in South Africa would lead to rapid pavement deterioration with ingress of water before any significant change in deflection. This contrasts with practice elsewhere in which changes in deflection are used for triggering such action for the widely used thicker asphalt bases. On this issue, Autret and Gramsammer (1990) found that the date of rehabilitation of surfacing does not have as much effect on the life of surfacing. The application of a maintenance asphalt layer of 80 mm was reported to have the same pavement life as two layers of 40 mm applied sequentially with a time delay in between. This demonstrates the importance of considering all aspects of the situation when formulating strategies towards the maintenance and rehabilitation of pavements.

It was pointed out in chapter three that water had a profound effect on pavement performance. The strong emphasis by the Australians on improved understanding of the impact of factors such as compaction and moisture on the performance of pavement has proven to be a sound approach with tangible economic benefits. Vuong et al. (1996) found that high-quality crushed rock pavements benefit significantly from increased compaction because of the reduced influence of moisture. It was found that the degree of saturation is of paramount importance. In the case of granular materials with low plasticity, the degree of

saturation is considered to be a better indicator than optimum moisture content. Under short-term ALF loading conditions, in situ stabilization using 2% bitumen and 2% cement was found to be more effective than other treatments that had been explored as replacement for the sandstone and high-quality crushed rock. It was found that the reduced pavement depths that could be used with the Winton sandstone translated into total project cost savings of 15%.

DEVELOPMENT IN ACCELERATED PAVEMENT TESTING-RELATED TECHNOLOGIES

The SA-HVS program has spawned a number of ancillary artifacts that are being widely used to enhance the APT programs (De Beer et al. 1997; Rust et al. 1997). Examples are Stress-in-Motion, the VRSPTA, and CAM. The multi-depth deflectometer used for measuring dynamic deflection and permanent deformation is another example of an ancillary APT device. Multidepth deflectometers or equivalent are now being manufactured in Texas, France, and Australia. The application of the Dynamic Cone Penetrometer in conjunction with APT programs has led to its widespread acceptance as a diagnostic tool for measuring pavement strength. Other APT programs have had much the same experience (Gramsammer et al. 1999; Sharp et al. 1999a). In the case of WesTrack, the effective and successful use of driverless vehicles is noteworthy (Epps et al. 1999). Earlier, Japan also used the same approach in an APT program (Metcalf 1996).

The digital and manual crack detection and mapping methods developed by Scheffy et al. (1999) were reported as being reliable and consistent for detection and mapping of fatigue cracks. Their method, which employs off-the-shelf software, was reported as being inexpensive and easy to implement.

DEVELOPMENT IN ACCELERATED PAVEMENT TESTING-RELATED DATABASES AND TECHNOLOGY TRANSFER

APT programs are generating data worldwide. Specific activities have been set in motion to ensure that the APT community-at-large captures this information in various ways for use. In particular, the format of data collection has been formalized under the auspices of APT committee A2B09 of the TRB. The information is available in a TRB circular at <http://www.nas.edu/trb/publications> (report on APT data survey recorded by APT programs, Number E-C004) (Hugo et al. 1999d). To provide for maximum sharing and use of APT data, NCHRP is preparing *NCHRP Report 512: Accelerated Pavement Testing: Data Guidelines* (Saeed and Hall 2004). This project will develop definitions of the data elements associated with APT and rec-

ommend guidelines for their collection, storage, and retrieval.

As mentioned earlier in the synthesis, a close link has been established with the COST 347 program, which provides access to the European APT activities (website: <http://www.cordis.lu/cost-transport/src/cost-347.htm>). It should be noted that the European community has opted to use ALT as the acronym for their accelerated load testing programs. The objectives of the program can be found on the website. Deliverables include a database containing an inventory of existing and planned new APT (ALT) facilities and a report on previous and current research.

In line with the trend toward electronic communications, all active APT programs in the United States have websites. Some already contain extensive information pertaining to the APT specific program as well as a database with information on completed tests. The FAA's NAPTF program is a good example of such an operational website with access to the data that are being generated.

The CAL/APT program has already built up a wealth of findings since its inception in 1994. The immediate results of the research after reaching a research goal are captured through the production of reports and other research products. Data produced from later research goals are frequently combined with earlier results to produce new insights or improve earlier interpretations. This provides a basis for synthesis and further development beyond the original goal(s) of the research. As part of the CAL/APT program, a database was established and it is being populated. The intent is for partners in the CAL/APT research to be supported in their use of the database. In general, it was found that the databases of APT programs that were established in the last decade are in various stages of development.

In view of the close relationship between the SA-HVS program and a number of APT programs in the United States, data from international HVS applications are also being included in a continuous process in the SA-HVS database. The latter program has been operational for almost 30 years and therefore has an extensive volume of information. The same is true of other mature APT programs such as ARRB-ALF and the LCPC.

A list of the websites of all APT programs that are featured in this synthesis can be found in Appendix B. The extent of this development in communication and the volume of data that are already available is a tangible measure of the economic benefits being generated by the APT programs.

SOME CURRENT AND PLANNED FUTURE ACCELERATED PAVEMENT TESTING APPLICATIONS

Most of the APT programs in the United States are in the early stages of development. Nevertheless, a wide range of significant findings has already been reported as is apparent from the synthesis. Almost all of these programs are ongoing, and this section is intended to provide a link between completed studies, reported findings, and relevant follow-on studies. The respective respondents to the questionnaire survey provided the information.

CAL/APT

On the basis of the submission by the respondents, this program is probably the most comprehensive APT program in the United States. It is an excellent example of partnering using two HVS machines. The one unit is operating in a controlled laboratory environment and the other on an in-service pavement near Palmdale. The latter is an extensive program on concrete pavements using HCC and PCC. The program is interfaced with the Caltrans PMS database. Currently (2003) a deep in situ recycling study is underway and there is a strong focus on rehabilitation pavement design.

CEDEX

The CEDEX facility now has two trafficking bogies and these have doubled the trafficking output in terms of the number of applied axles (A. Mateos, Centro de Estudios de Carretera, personal communication, December 2001). Currently, tests are focused on the performance of subgrades and mechanical stabilization. The first phase has been completed and the second phase was scheduled to start in December 2001. The same asphalt pavement is being used throughout. Sections have been instrumented to measure structural response and subgrade quality in terms of plastic deformation and cracking. Field conditions (temperatures and water table elevation) are also monitored. The curves of the test track are also used for testing the performance of surface courses under high horizontal surface forces.

ERDC-GSL

The main purpose of the test device is to provide the required field data to verify and validate the 3-D pavement design and evaluation program by the ERDC in Mississippi. A multifaceted 4-year test plan has been established involving construction, instrumentation, and trafficking of two or more test sections within a 1-year time frame. Provision was made to monitor moisture in the subgrade to determine when changes take place. Trafficking was initiated on the first section in March 1999. In the future, issues such as freeze-thaw and weathering or aging are to be included in the investigations. Thus far, one airfield study

has been completed and one roadway study is under way. Aircraft load carts and military trucks are being used in conjunction with the HVS-A (Bigfoot) in the APT program.

FAA

During 2001, nine pavements were tested with the NAPTF in New Jersey. Three subgrade classifications were used—low, medium, and high. The initial results are very promising, and tests are continuing on the three rigid and six flexible test sections. Data were acquired, processed, stored, and disseminated from more than 1,000 sensors, using 3 data collection systems. The information on response and pavement performance under simulated B-747 and B-777 loading is being used for development of mechanistic design procedures for airport pavements. Four- and six-wheel aircraft gear loads were applied at speeds of 4 and 8 khp, with lateral wander over a distance of 2 m.

FHWA-PTF

Although the current Superpave system is very effective for selecting the right unmodified asphalt binder for given environmental and traffic conditions, it is far less effective for characterizing modified binders. The FHWA recently (summer 2002) placed 12 lanes of HMA containing modified and unmodified binders in its PTF. Results of ALF loading of these pavements over a 3-year period will be combined with data from an extensive laboratory testing program to support development of an asphalt binder specification that correctly predicts the relative performance of modified binders. The 12 lanes include one unmodified, 6 polymer-modified, and 2 crumb-rubber-modified asphalt binders in an experiment designed to improve the Superpave binder specification. It is also designed to evaluate how well performance models being proposed for the 2002 *Pavement Design Guide* work for polymerase-modified asphalt mixtures. Primary funding for the project comes from national pooled-fund project TPF-5(119). The project is expected to continue at least through March 2005. The data from the study will also be used to evaluate models in the pavement design guide being developed in NCHRP Project 1-37A and to evaluate Superpave Simple Performance Test predictions for fatigue cracking and rutting.

Florida DOT

The primary objective of Florida's APT and research program is the improvement of the state's pavements. The goal is to acquire and implement the knowledge and technology to extend the useful service life of pavements and prevent premature distresses in a cost-effective manner (FDOT test plan 2001). The intent is to conduct research

through partnering with industry, the FHWA, academic institutions, and other interested constituencies. Implementation is designed to take place as soon as practical with technology transfer to all stakeholders. The first experiment is in partnership with the University of Florida and the asphalt industry. The experiment is focused on evaluating the effect of polymer modifiers on the performance of Superpave mixtures. The intent is to evaluate two binders: one a PG67-22, the other a PG67-22 modified with a SBS polymer, resulting in a binder equivalent to a PG76-22.

HVS-CRREL

This facility is focused on testing the impact of subgrade type, moisture content, and temperature on the performance of pavements. In particular, stress-strain response in thawing soils is being investigated, as well as subgrade failure criteria. The study is funded by the FHWA, and tests are being conducted at optimum and wetted optimum conditions. Other studies include reinstatement of utility cuts, rapid repair work during the winter, geosynthetic reinforcement of base course layers, and sensor evaluation.

HVS-NORDIC

The HVS-Nordic was moved to Sweden in 2000, where eight typical Swedish road structures were tested. Two test sections have thin surfacings (50 mm) and two other test sections have rehabilitated structures. These four structures have well-known performance records and their characteristics are well documented. Tests 5 and 6 were constructed from imported Icelandic materials and tested under Icelandic supervision. The test program also allowed for trafficking of steel-reinforced pavements in collaboration with industry. The test plan was to return the device to Finland after the completion of the tests; there, further tests would be done on reinforced and unreinforced pavement structures. The intent was also to include a light-weight pavement using expanded polystyrene. The latter pavements are for low-volume roads. The last tests in the current series were intended to study the importance of the road cross section. In Sweden, two research programs are attempting to develop relationships between strains in various design structures that are the result of loading, rutting, and cracking. As in other programs, the intent is to coordinate the testing with the monitoring of LTPP sections in Finland and Sweden.

Kansas DOT

The performance of foamed asphalt stabilized base in a full-depth reclaimed asphalt pavement is being investigated. The purpose of the current testing is to evaluate the structural performance of RAP material that has been con-

taminated in the reclamation process after treatment with foam asphalt. The contamination relates to the presence of granular base material and possibly subgrade soil inadvertently mixed in during the reclamation process. Rutting is expected to be the mode of failure. Four pavement sections will be tested. Each will have the same 75-mm-thick surface AC layer, while the base will be 150, 225, and 300 mm of foamed asphalt stabilized RAP. All will be constructed on 225 mm of conventional crushed-stone base course. The sections will be loaded in pairs and a load of 104.5 kN at room temperature will be used.

Louisiana ALF Facility

This facility has been in existence for 6 years. ALF tests on Superpave mixes will follow the completion of current tests (third experiment), which entail the evaluation of base course layers built with RAP. Concurrently, the implementation of results from the second experiment on the evaluation of rubberized asphalt pavements produced according to the Wet-Rouse process is being considered. Findings from the first experiments on structural systems are also being implemented by the Louisiana Department of Transportation and Development. This entails two design concepts, namely the use of thicker, but weaker cement-treated base courses, and the use of the inverted pavement structure that has proven so successful in other APT programs, after being reported for the first time by the SA-HVS program.

National Center for Asphalt Technology

For the 2003 research cycle, the NCAT track was prepared for the following:

- A new experiment consisting of milling and inlaying 14 sections with new rutting study mixes,
- Deep removal of 8 sections to facilitate a small (instrumented) AASHO-like structural experiment, and
- Continuing traffic on the remaining sections. The latter will extend the original 2000 experiment over a second application of design traffic of a further 10 million ESALs.

The reconstruction project is again being funded through a multistate research cooperative, with pooled fund management and construction contract administration provided by the Alabama DOT. All construction activities were completed by the end of September 2003, and trucking was started in late October.

A comprehensive report on field performance of the 2000 Track is currently being prepared. It will contain comparisons on field performance and correlations between laboratory and

field performance based on data collected during phase I of the program.

Texas

The Texas program is expected to undergo changes with the establishment of the Texas Accelerated Pavement Test Center in Austin. This will enable both fixed-site and field applications to be pursued. A 5-year plan is being drafted. The original and primary objectives (Hugo 1996) have not changed, but a planning session identified the following three important issues that will be investigated:

Load-zoned roadways,
Selected calibration of the 2002 design guide under development by the NCHRP, and
New truck tire load enforcement legislation.

The TxMLS is currently being refurbished and it is anticipated that it will be placed back into service during 2003.

University of Illinois

The initial test program for the loading system (ATLaS) under the auspices of the University of Illinois is focused on CRCPs.

The objective with this 150 m section is to determine

- Optimum thickness of CRCP sections,
- Optimum steel percentage, and
- Crack spacing for Illinois.

Future projects include a study of AC overlays on CRCP and validation of a new unbonded overlay design procedure. The construction of two 150-m extended-life CRCP sections was scheduled for completion in 2001. Full operation of ATLaS was expected to begin early in 2002.

SOME INTERNATIONAL TRENDS

A recent, very enlightening report on emerging issues in the Australian Transport Industry provides some noteworthy views on the likely future commercial vehicle types and masses and, more importantly, expected trends in terms of tire types and pressures, suspension types, and axle configuration (Pearson and Foley 2000). The impact of this on pavement engineering was recognized and a call was made for follow-up work on

- Air suspensions,
- Wide single tires,

- Quad-axle groups with an allowable loaded mass 3 tons greater than the allowable mass of a tri-axle, and
- An increase in tire pressure to 850 kPa.

Clearly, these developments are most likely to be explored through APT in Australia, but also elsewhere in the world as trends cross international borders.

CLOSING REMARKS

From a review of the benefits cited in Table 4 and elsewhere in the report by the various APT programs, it was concluded that the following tools are being used to identify and implement findings from the various programs:

- Econometrics of pavements in terms of
 - Enhancement of knowledge,

- Design and construction of layers,
- Extended service life, and
- Increased benefit-cost ratio;
- Specifications in terms of
 - Selection of materials for layers,
 - Quantification and setting of realistic tolerances, and
 - Configuration and construction of layers;
- QC/QA systems;
- Pay factors reflecting measures of
 - Nonconformance,
 - Limits/risks, and
 - Variability;
- Forensic studies for reviewing mechanisms that affect response and performance; and
- Improved methods of performance prediction.

The information that has been assembled through this study should enable DOTs to make greater use of APT in their quest to serve the transportation community.

CHAPTER NINE

CONCLUSIONS

Based on the survey and the extensive literature resources that were available it is clear that a high level of knowledge and information has been built up in the field of accelerated pavement testing (APT). The scope of APT studies is indeed very large, which was evident from the analysis of the questionnaire responses (Appendixes B–D) and case studies that were derived from the subject bibliography. These were included as integral parts of the various chapters and related Appendixes G and H.

The nature of this synthesis is such that the details of the various aspects of APT that were reviewed are presented in a number of locations for subsequent retrieval by researchers and practitioners who are active in APT or in using the results of APT. An index is provided that should prove useful in this regard.

Overall, it was concluded that APT had served as a means of improving performance and economics of pavements. It has improved the understanding of the factors that affect pavement performance through the ability to

- Explore a wide variety of structural compositions and configurations;
- Simulate mechanisms, conditions, and processes through loading and environment;
- Test and characterize materials; and
- Analyze and understand response and performance.

The acquired knowledge is being widely applied and it has enhanced innovation in pavement engineering.

The following general conclusions were drawn relative to the generic core of significant findings in terms of applications.

On the topic of design, construction, maintenance, and rehabilitation the survey and literature showed that

- Unique, unconventional pavement structures could be tested and evaluated through APT.
- Failure mechanisms could be meticulously evaluated so that it became possible to cost-effectively counteract distress mechanisms.
- A wide range of structural design packages have been evaluated or developed and this has greatly enhanced their implementation.
- Systematic investigation of the vehicle–pavement–environment interaction has been made possible and

feasible through APT, although much still remains to be done on this subject.

- A large number of APT tests were related to pavement materials. This is indicative of the potential of APT to provide sound answers about pavement materials. More particularly, it has been shown to be useful for answering questions relating to the use of new materials, composite materials, and materials with complex physical characteristics.
- APT is a tool for confirmation and validation of laboratory test procedures.
- APT has become a useful tool for systematically developing and evaluating performance models.
- APT is a means of answering questions related to rehabilitation, construction, and maintenance in the field. Answering those questions would be more difficult and take far longer without APT experiments.

This synthesis provides evidence of the economic and management benefits that have been generated by APT. More particularly

- The economic gains as a result of APT are measurable. Details were given as to what has been achieved in terms of benefit-cost ratios, savings on capital expenditure, and the use of recycled and new materials and new pavement structures. Benefit-cost ratios appear to vary from 1:1 to more than 20:1.
- APT has provided a quantitative basis for communicating with decision makers about pavement performance. However, it will be necessary to upgrade APT systems to be able to account for environmental effects on a quantifiable basis.
- APT has attributes that supplement many aspects of pavement management systems (PMS) and in-service pavement evaluation. If the identified gaps in the system are addressed, it may lead to rapid advances in pavement engineering and ultimately to long-life pavements with reduced maintenance costs.
- Many ancillary artifacts have been developed in APT-related technologies in support of programs throughout the world. These have had considerable impact on the ability to understand pavement response and performance. A variety of examples were discussed. A good example is the improved understanding of tire–pavement interaction and its effect on performance.

The growth of APT in the United States may stimulate advances in the field. This might gain even further momentum as OECD COST 347 achieves its goals in Europe.

It was apparent that APT programs in general, and in the United States in particular, have a number of common objectives. This became clear from the synthesis of the results of the survey questionnaire. By prudent use of the available information and collaborative research efforts, APT programs could advance pavement knowledge more rapidly. This could include some planned replication to improve on the reliability of findings and to establish confidence limits.

A number of issues that require collective input or collaborative efforts were evident from the synthesis.

- There was an apparent lack of feedback on the extent to which APT performance predictions had been validated. This applies to components of the system as well as complete and comprehensive design systems. Consideration should therefore be given to tracking the performance of in-service pavements that have been tested in APT programs, as a matter of course, where and when possible. This will enable comparative performance studies to be conducted.
- In line with international trends, APT programs should, where possible, have closer association with in-service pavement evaluation and formal long-term pavement performance and related PMS programs.
- There is an urgent need to improve on the quantification of environmental impact on APT performance. Progress in this regard could improve the credibility of APT among other professional decision makers in the field of pavement infrastructure. This would require a well-structured, strategic plan to address all aspects of the vehicle–pavement–environment interaction.
- The advancement in the understanding of vehicle–pavement interaction during the last decade provides a basis for further studies that could enhance pavement performance prediction.

The stimulus that is being provided by the strong growth of APT in the United States is likely to lead to major advances in the field. This may gain even further momentum as OECD COST 347 achieves its goals in Europe.

The wide range of pavement types and configurations that have been tested through APT provide a heritage of knowledge on pavement engineering. This synthesis is the link to this knowledge. It has served to create an awareness of the benefits that are to be gained from prudent use of the information through collaborative efforts. One of the reasons for the collaborative approach lies in the vast number of possible test parameters that can be tested for different structural configurations. This trend is growing; for example, the COST 347 project and the pooled fund studies in the United States. It is recognized that a new generation of researchers have entered the APT field. This synthesis, together with *NCHRP Synthesis of Highway Practice 235*, should assist these researchers in their quest to become acquainted with all aspects of APT.

Internationally, the situation is somewhat different where facilities have reached maturity and services are being rendered in an environment of privatization. Clients are now often road agencies, and industry and projects are being completed on the basis of Design, Build, and Operate. This is leading to partnering and the use of APT in support of warranty contracts and improved management of pavement infrastructure.

With globalization it would seem prudent to anticipate similar wide-ranging changes in the United States. It is therefore particularly fortunate that the APT programs in the United States have entered a phase of development that should provide the tools, technology, and APT practices that will enable them to be well prepared for the challenge.

This development also has a negative aspect that needs to be considered. With the trend toward privatization and partnering, the results of APT studies are no longer naturally in the public domain. This does not necessarily restrict access to the information; however, it often slows down the technology transfer through conferences and publications, although the Internet may change all of that dramatically. APT activities throughout the world have become linked and this is greatly enhancing exchange of data and information.

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- Structural Composition
- Loading Environment
- Materials and Tests
- Modeling
- Construction and Rehabilitation
- Accelerated Pavement Testing in General
- Management

The response was extensive. The results reflect the way in which the respective respondents categorize their APT applications and related findings. In this bibliography, each topic is associated with the specific chapter to which it relates in the synthesis. Each of the topics should therefore be considered in the same context as this synthesis. Some of the references can relate to more than one topic, but no attempt was made to rearrange the submissions.

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MANAGEMENT

Publications in this category are related to chapter eight, *Improvement of Pavement Economics and Management Through Accelerated Pavement Testing Applications*.

GLOSSARY

The following are the words and definitions of some common terms used in the field of pavement engineering that may be unknown to some of the readers of this synthesis.

Asphalt—A mixture of inert mineral matter, such as aggregate, mineral filler (if required), and bituminous binder in predetermined portions. Commonly known in the United States as asphalt concrete (AC) or hot-mix asphalt (HMA).

Asphalt, continuously graded—A mechanically mixed asphalt in which the aggregate and filler are distributed in size fractions from coarse to fine within a specified smooth grading envelope.

Asphalt, gap-graded—An asphalt mixture composed of mineral particles, with certain intermediate sizes missing from the size range, and filler.

Asphalt, LAMBs—Large aggregate mixes for bases containing graded large aggregates and meeting prescribed engineering properties for use as base course material in South Africa.

Asphalt, open-graded—A mechanically mixed asphalt constituted to give a high air void content and rough surface texture in the compacted state.

Asphalt, semi-gap-graded—An asphalt mixture composed of mineral particles, with certain intermediate sizes missing from the size range, and filler. The coarse aggregate fraction is more graded than that of gap-graded asphalt.

Asphalt-treated permeable base (ATPB)—Known as a drained pavement in California.

Bitumen—A noncrystalline solid or viscous mixture of complex hydrocarbons that possesses characteristic agglomerating properties. Bitumen, which is obtained from crude petroleum by refining processes, softens gradually when heated and is substantially soluble in trichloroethylene. Commonly known in the United States as asphalt.

Bitumen rubber—A blend of bitumen and approximately 20% by weight of crumb rubber, containing where necessary extender oil and/or diluent.

Bituminous-treated base—A layer consisting of granular material mixed with a bituminous binder.

Bogie—A mechanical structure designed to enable a wheel carriage to transfer loading to the surface on which it runs, such as a pavement or a rail.

Cape seal—A single application of binder and stone followed by one or two applications of slurry.

Cementation—Stabilization with the objective of increasing the compressive or tensile strength to a predetermined level. The term “cemented material” is also used.

ESAL—Equivalent single-axle load. In the United States, this equates to a load of 80 kN. It is sometimes abbreviated as E80.

FORCE Project—An accelerated full-scale pavement test at the Laboratoire Central des Ponts et Chaussées (LCPC, Central Laboratory for Roads and Bridges) circular test track in Nantes, France. The joint test program is known internationally as the FORCE Project (1988–1991).

GEMs—Bitumen–emulsion treatment of soils and crushed stone. Commonly known as granular emulsion mixes in South Africa.

Macadam—Contains a high-quality aggregate with large, single-sized particles stabilized by filling the voids with a suitable material. Typically the macadam is defined more specifically in relation to the material used for filling the voids; e.g., waterbound macadam (WM) has a filler of natural material with a low plasticity, whereas slurry-bound macadam (SM) has a filling of slurry.

Macadam, dense bitumen (DBM)—A very coarse and densely continuously graded asphalt used in the United Kingdom.

Macadam, heavy-duty—A variation of macadam.

Milled granulated blast furnace slag (MGBS)—Granulated slag, a by-product of the processing of iron ore, milled to a fine powder.

Modified material—A material the physical properties of which have been improved by the addition of a stabilizing agent, but in which cementation has not occurred.

Pavement behavior—The function of the condition of the pavement with time.

Pay adjustment schedule (for quality)—Also called “price adjustment schedule” or “adjusted pay schedule.” A preestablished schedule, in either tabular or equation form, for assigning pay factors associated with estimated quality levels of a given quality characteristic. The pay factors are usually expressed as percentages of the original contract bid price.

Pay adjustment system (for quality)—Also called “price adjustment system” or “adjusted pay system.” All pay adjustment schedules along with the equation or algorithm that is used to determine the overall pay factor for a submitted lot of material or construction. (A pay adjustment system, and each pay adjustment schedule, should yield sufficiently large pay increases/decreases to provide the contractor some incentive/disincentive for high/low quality.)

Polymer-modified bitumen—A bitumen with improved physical properties obtained by the addition of a polymer.

Precoating—The precoating of the seal stone with a binder to improve the initial adhesion between the stone and the seal binder (precoating of chips).

Seal—A term frequently used instead of “reseal” or “surface treatment.” Also used in the context of “double seal” and “sand seal” where sand is used instead of stone.

Surface treatment—Applications of bituminous materials to a pavement surface with a cover of mineral aggregate.

Surface treatment, double—An application of bituminous binder and stone, followed by a second application of binder and stone or sand. A fog spray is sometimes applied on the second layer of aggregate.

Surface treatment, single—An application of bituminous binder, followed by a layer of stone or clean sand. The stone is sometimes covered with a fog spray.

Standard aggregate base—Known as an undrained pavement in California.

Test lane—The track (normally linear) along which a bogie travels, applying axle loads to the surface on which it runs.

Truck—Set of wheels or a frame mounted on wheels to support a structure. [Synonym for “bogie” and “undercarriage.”]

Wheel assembly—May be fixed to an APT device (e.g., a test truck traveling along a test pavement). It may also be a loose assembly that is guided to travel along a pre-planned wheel path. [Synonym for “bogie,” “truck,” and “undercarriage.”]

Wheel tracking—Application of wheel load repetitions to a surface.

Undercarriage—Supporting framework of a vehicle with a wheel system (United States). [Synonym for “landing gear” (of an aircraft), “truck,” and “bogie.”]

UNPG—The aggregate producers union in France.

ABBREVIATIONS AND ACRONYMS

AC	asphalt concrete
ALF	Accelerated Loading Facility
APT	accelerated pavement testing
ARRB	Australian Road Research Board
ASR	alkali–silica reaction
ATLaS	Accelerated Transportation Loading System
ATPB	asphalt-treated permeable base
CAL/APT	California Department of Transportation Accelerated Pavement Testing
CAM	crack activity meter
CAPTIF	Canterbury Accelerated Pavement Testing Indoor Facility
CBR	California Bearing Ratio
CEDEX	Spanish Centro De Estudios De Carreteras test facility
CM	crack movement
COST	Cooperative Science and Technology
CRCP	continuously reinforced concrete pavement
CRREL	(USACE–ERDC) Cold Regions Research Engineering Laboratory
CSIRO	Council for Scientific and Industrial Research Organization
CTCR	cement-treated crushed rock
CTSB	cement-treated subbase
DBM	dense bitumen macadam
DIVINE	Dynamic Interaction between Vehicles and Infrastructure Experiment
DOT	department of transportation
EDE	environmental damage exponent
ERDC	U.S. Army Corps of Engineers Research and Development Center
ESAL	equivalent single-axle load
EVA	ethylene vinyl acetate
FE	finite element
FWD	Falling Weight Deflectometer
GEMs	granular emulsion mixes
GSL	(USACE–ERDC) Geotechnical and Structures Laboratory
HCC	hydraulic cement concrete
HDM	heavy-duty macadam
HMA	hot-mix asphalt
HVS	Heavy Vehicle Simulator
HVS–Nordic	mobile linear full-scale accelerated pavement testing machine
IRI	International Roughness Index
JCP	jointed unreinforced concrete pavement
LAMBs	large aggregate mixes for bases
LCPC	Laboratoire Central des Ponts et Chaussées
LINTRACK	(Dutch) LINear TRACKing Apparatus
LTPP	long-term pavement performance
LWAC	lightweight aggregate asphalt concrete
MMLS3	one-third scale mobile load simulator
Mn/ROAD	Minnesota Road Research Project
NAPTF	National Airport Pavement Test Facility
NCAT	National Center for Asphalt Technology
PCC	portland cement concrete
PMS	pavement management system
PTF	Pavement Test Facility
OECD	Organization for Economic Cooperation and Development
RAP	recycled asphalt pavement
SASW	spectral analysis of surface waves
SBS	styrene butadiene styrene

SHRP	Strategic Highway Research Program
SMA	stone matrix asphalt
SMDM	South African Mechanistic Design Method
TRL	Transport Research Laboratory (United Kingdom)
TxMLS	Texas Mobile Load Simulator
USACE	U.S. Army Corps of Engineers
UTFRC	ultra-thin fiber-reinforced concrete
UTW	ultra-thin whitetopping
VRSPATA	Vehicle–Road Surface Pressure Transducer Array
VTI	VAG-OCH TRANSPORTFORSKNINGSINSTITUT (Swedish National Road and Transport Research Institute)

APPENDIX A

Survey Questionnaire

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Project 20-5, Synthesis Topic 32-04

SIGNIFICANT FINDINGS FROM FULL-SCALE/ACCELERATED PAVEMENT TESTING

QUESTIONNAIRE

Purpose of this Survey

This is a survey to collect information on issues pertaining to full-scale/accelerated pavement testing (APT). In this regard, APT is defined as the application of a wheel loading, close to or above the legal load limit(s) to a prototype or actual, layered, structural pavement system. The objective of the survey is to collect significant findings from various experimental activities to assess the application of APT in research and practice and to address actual and potential benefits to the U.S. pavement community. A questionnaire is set out for completion online. This is preferable. To do so return to the Internet site and access the electronic version. Alternatively, you can complete and mail this downloaded version to one of the addresses provided below. The information you supply will provide valuable input to the development of a summary report on this important topic.

Please provide the name of the person completing this questionnaire or someone else who may be contacted to obtain any needed follow-up information, below:

Name: _____

Title: _____

Agency: _____

Street Address: _____

City/State/Zip: _____

Country: _____

Telephone: _____

Fax: _____

E-mail: _____

Please complete and return this questionnaire and any supporting documents you can provide, such as copies of papers, proceedings or reports by June 30, 2001 to

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In lieu of sending hard copies of supporting documents by mail, it would be appreciated if you could provide access to electronic files. Should you have any questions, please contact:

Dr. Epps at +1 (979) 862 1750 (t), (979) 845 0278 (f) or
Dr. Hugo at +27 (21) 808 4364 (t), +27 (21) 808 4361 (f), or
e-mail them at: a-epps@tamu.edu or fhugo@sunvax.sun.ac.za

Preface to Questionnaire

During the international APT conference in Reno, Nevada, in October 1999, it was apparent that a primary goal of APT world wide was ultimately to improve the performance and economics of pavements. This was being done by focusing on APT programs on all aspects of pavement engineering; from design to maintenance and management of constructed pavements, as well as rehabilitation of distressed pavements.

To achieve this goal, various tools for monitoring pavement response and various APT trafficking devices have been used. While these aspects are important, the purpose of this questionnaire is to gather information on ATP findings. Given the extent of APT research and application around the world, the focus of the survey will therefore be on a number of categories of information that were identified in preliminary surveys as being major factors that impact on the stated goal namely

- Structural Composition
- Loading and Environment
- Materials and Tests
- Modeling
- Construction
- Rehabilitation
- Maintenance

Figure A1 gives an outline of the apparent interrelationship between these elements. This was used as a framework for exploring the vast volume of knowledge from APT programs.

A survey of this nature cannot and does not attempt to address each of the above listed items in detail. However, in order to optimize the procedure, the questionnaire has been structured to solicit responses at three levels. The first level (green) should not require too much time to complete, and the answers should be readily available. The second level (blue) will require more time and effort, while the third level (red) is probably best suited for those APT users that have intensive programs with detailed information readily available. Respondents are kindly requested to provide as much information as they are able to.

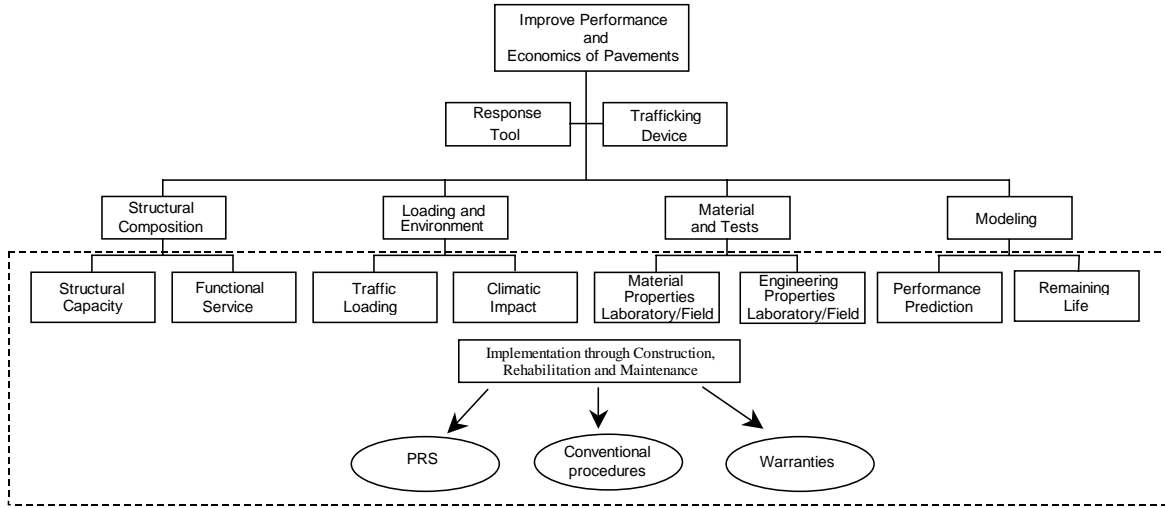


FIGURE A1 Framework for exploring knowledge generated by APT programs.

1. MANAGEMENT

1.1 Nature of your APT program (check as many as apply).

- | | | | |
|---------------------------|--------------------------|---|--------------------------|
| National research program | <input type="checkbox"/> | Academic research program | <input type="checkbox"/> |
| State research program | <input type="checkbox"/> | Partnership with others in private sector | <input type="checkbox"/> |

If other, please specify.

1.2 Implementation of your APT is geared towards (check as many as apply):

- | | |
|--|--------------------------|
| Evaluation/validation of pavement structural composition | <input type="checkbox"/> |
| Evaluation/validation of loading environment (traffic/climate) | <input type="checkbox"/> |
| Evaluation/validation of materials and tests | <input type="checkbox"/> |
| Evaluation/validation of performance models | <input type="checkbox"/> |
| Evaluation/validation of construction techniques | <input type="checkbox"/> |
| Evaluation/validation of rehabilitation strategies | <input type="checkbox"/> |

1.3 Type of APT application (check as many as apply).

- | | | | |
|------------|--------------------------|-----------------------|--------------------------|
| Field | <input type="checkbox"/> | Laboratory | <input type="checkbox"/> |
| Fixed-site | <input type="checkbox"/> | In-service pavements | <input type="checkbox"/> |
| Test roads | <input type="checkbox"/> | Specially constructed | <input type="checkbox"/> |

1.4 Type of APT device/system.

- | | <u>Number of Axles</u> | |
|----------------|--------------------------|--------------------------|
| | Single | Multiple |
| Linear | | |
| Unidirectional | <input type="checkbox"/> | <input type="checkbox"/> |
| Bidirectional | <input type="checkbox"/> | <input type="checkbox"/> |

- Circular
- Elliptical
- Trucks
- Other

If other, please specify.

- 1.5 Number of pavement sections tested: 1–5 6–10 11–20 21–50 >50
- 1.6 Typical duration of APT tests in months: 1–3 4–6 7–11 12–24 >24
- 1.7 Estimated capital cost of APT facility and equipment: <\$1 M \$1–2 M \$2–5 M >\$5 M
- 1.8 Yearly APT budget:
 <\$0.1 M \$0.1–0.2 M \$0.2–0.4 M \$0.4–0.8 M \$0.8–1.6 M >\$1.6 M
- 1.9 Breakdown of budget:
 - Operational <10% 10–20% 20–30% >30%
 - Maintenance <10% 10–20%
 - Staff <10% 10–20% 20–30% >30%
- 1.10 Average (typical) operational cost/test: <\$0.5 M \$0.5–1 M \$1–1.5 M >\$1.5 M
- 1.11 Number of direct APT personnel:
 - Professional <5 >5
 - Technical <5 5–10 >10
 - Administrative <5 >5
- 1.12 Overall estimated savings/benefits in monetary terms:
 <\$100 k \$100–200 k \$200–500 k \$0.5–1 M \$1–2 M >\$2 M
- 1.13 Benefit/cost (B/C) ratio of APT programs:

<1:1	<input type="checkbox"/>	10:1	<input type="checkbox"/>
1:1	<input type="checkbox"/>	15:1	<input type="checkbox"/>
2:1	<input type="checkbox"/>	20:1	<input type="checkbox"/>
5:1	<input type="checkbox"/>	>20:1	<input type="checkbox"/>

Please briefly outline the process used to determine B/C ratio.

1.14 Benefits of APT (check as many as apply).

- | | | | |
|---|--------------------------|-------------------------------------|--------------------------|
| None | <input type="checkbox"/> | Improved performance modeling | <input type="checkbox"/> |
| Improved structural design procedures | <input type="checkbox"/> | Improved pavement management | <input type="checkbox"/> |
| Improved material design procedures | <input type="checkbox"/> | Better understanding of variability | <input type="checkbox"/> |
| Use of new or innovative materials | <input type="checkbox"/> | Warranty contracts | <input type="checkbox"/> |
| Development of performance-related specifications | <input type="checkbox"/> | Weather databases | <input type="checkbox"/> |
| Material databases | <input type="checkbox"/> | Evaluation/validation of Superpave | <input type="checkbox"/> |
| Other | <input type="checkbox"/> | | |

If other, please specify.

Motivate answer in less than 50 words per item.

2. STRUCTURAL COMPOSITION

2.1 What was the purpose of the structural compositions used in your APT program?

Structural performance Functional performance

2.2 Indicate which pavement layers were evaluated/validated in the structural performance tests.

Layer/ Material	Seal	Sand	Clay	Granular	Cement Stabilized	Asphalt	Concrete	Composite/ Recycled	Ultrathin White-topping
Surface	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Base		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
Subbase		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>				
Subgrade		<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>					

2.3 Distress criterion evaluated for seals.

Ravelling (abrasion) Bleeding
 Other Aggregate loss (loss of bond)
 Not applicable

If other, please specify.

2.4 Distress criterion evaluated for pavements with clay/sand material.

Collapsing Freeze/thaw
 Swelling Permanent deformation
 Other Not applicable

If other, please specify.

2.5 Distress criterion evaluated for pavements with granular materials.

Permanent deformation Shear failure
 Frost/thaw damage Other
 Not applicable

If other, please specify.

2.6 Distress criterion evaluated for pavements with stabilized or cemented materials.

- | | | | |
|----------------|--------------------------|-------------|--------------------------|
| Cracking | <input type="checkbox"/> | Carbonation | <input type="checkbox"/> |
| Crushing | <input type="checkbox"/> | Other | <input type="checkbox"/> |
| Not applicable | <input type="checkbox"/> | | |

If other, please specify.

2.7 Distress criterion evaluated for pavements with asphaltic materials.

- | | | | |
|--------------------------|--------------------------|---------------------------|--------------------------|
| Rutting | <input type="checkbox"/> | Moisture damage/stripping | <input type="checkbox"/> |
| Fatigue | <input type="checkbox"/> | Aging | <input type="checkbox"/> |
| Low temperature cracking | <input type="checkbox"/> | Other | <input type="checkbox"/> |
| Not applicable | <input type="checkbox"/> | | |

If other, please specify.

2.8 Distress criterion evaluated for pavements with concrete.

- | | | | |
|--------------------|--------------------------|-----------------------|--------------------------|
| Cracking | <input type="checkbox"/> | Fatigue | <input type="checkbox"/> |
| Stress ratio | <input type="checkbox"/> | Curling and warping | <input type="checkbox"/> |
| Joint failure | <input type="checkbox"/> | Load transfer failure | <input type="checkbox"/> |
| Faulting | <input type="checkbox"/> | Spalling | <input type="checkbox"/> |
| Punchouts | <input type="checkbox"/> | Steel rupture | <input type="checkbox"/> |
| Erosion of subbase | <input type="checkbox"/> | Other | <input type="checkbox"/> |
| Not applicable | <input type="checkbox"/> | | |

If other, please specify.

2.9 Distress criterion evaluated for pavements with composite materials.

- | | | | |
|----------------|--------------------------|-----------|--------------------------|
| Rutting | <input type="checkbox"/> | Fatigue | <input type="checkbox"/> |
| Cracking | <input type="checkbox"/> | Debonding | <input type="checkbox"/> |
| Slippage | <input type="checkbox"/> | Other | <input type="checkbox"/> |
| Not applicable | <input type="checkbox"/> | | |

If other, please specify.

2.10 Which aspects of functional performance were addressed?

- | | | | |
|----------------|--------------------------|------------|--------------------------|
| Safety | <input type="checkbox"/> | User costs | <input type="checkbox"/> |
| Environment | <input type="checkbox"/> | Roughness | <input type="checkbox"/> |
| Not applicable | <input type="checkbox"/> | Other | <input type="checkbox"/> |

If other, please specify.

2.11 Which safety aspects were addressed in your APT program?

- | | | | |
|-----------------|--------------------------|----------------|--------------------------|
| Rutting | <input type="checkbox"/> | Punchouts | <input type="checkbox"/> |
| Skid resistance | <input type="checkbox"/> | Delamination | <input type="checkbox"/> |
| Roughness | <input type="checkbox"/> | Spalling | <input type="checkbox"/> |
| Other | <input type="checkbox"/> | Not applicable | <input type="checkbox"/> |

If other, please specify.

2.12 Which environmental aspects were addressed in your APT program?

- | | | | |
|-------|--------------------------|----------------|--------------------------|
| Noise | <input type="checkbox"/> | Dust pollution | <input type="checkbox"/> |
| Other | <input type="checkbox"/> | Not applicable | <input type="checkbox"/> |

If other, please specify.

2.13 List significant APT findings related to pavement structural composition.

3. LOADING AND ENVIRONMENT

3.1 To which of the following load characteristics has APT performance been related (check all that apply)?

- | | | | |
|---------------------------|--------------------------|-----------------------|--------------------------|
| Applied wheel load | <input type="checkbox"/> | Channelized/wandering | <input type="checkbox"/> |
| Tire pressure | <input type="checkbox"/> | Speed | <input type="checkbox"/> |
| Tire type | <input type="checkbox"/> | Rest periods | <input type="checkbox"/> |
| Contact stress | <input type="checkbox"/> | Overloading | <input type="checkbox"/> |
| Load configuration | <input type="checkbox"/> | Roughness/PSI | <input type="checkbox"/> |
| Suspension system | <input type="checkbox"/> | Other | <input type="checkbox"/> |
| Vehicle/pavement dynamics | <input type="checkbox"/> | | |

If other, please specify.

3.2 To which of the following environment/weather data has APT performance been related (check all that apply)?

- | | | | |
|----------------------|--------------------------|------------------|--------------------------|
| Air temperature | <input type="checkbox"/> | Water table | <input type="checkbox"/> |
| Pavement temperature | <input type="checkbox"/> | Drainage | <input type="checkbox"/> |
| Rainfall | <input type="checkbox"/> | Depth to bedrock | <input type="checkbox"/> |
| Relative humidity | <input type="checkbox"/> | Other | <input type="checkbox"/> |
| Aging | <input type="checkbox"/> | | |

If other, please specify.

3.3 Which of the following environment/weather conditions are directly controlled (check all that apply)?

Air temperature	<input type="checkbox"/>	Subgrade moisture	<input type="checkbox"/>
Pavement temperature	<input type="checkbox"/>	Aging	<input type="checkbox"/>
Relative humidity	<input type="checkbox"/>	Other	<input type="checkbox"/>

If other, please specify.

3.4 APT Test temperature used (check all that apply).

Hot (>40°C) (>104°F)	<input type="checkbox"/>	Cold (<10°C) (<50°F)	<input type="checkbox"/>
Moderate (>10°C < 40°C) (>50°F < 104°F)	<input type="checkbox"/>	Freezing (<5°C) (<41°F)	<input type="checkbox"/>

3.5 List significant APT findings related to loading environment.

4. MATERIALS AND TESTS

4.1 APT has led to an improved characterization of (check all that apply).

Granular materials	<input type="checkbox"/>	Whitetopping	<input type="checkbox"/>
Stabilized/cemented materials	<input type="checkbox"/>	Geofabrics	<input type="checkbox"/>
Asphalt (hot mix)	<input type="checkbox"/>	Reinforcement	<input type="checkbox"/>
Asphalt (cold mix)	<input type="checkbox"/>	Concrete	<input type="checkbox"/>
Concrete	<input type="checkbox"/>	Other	<input type="checkbox"/>

If other, please specify.

4.2 Which of the following asphaltic materials have been tested?

	Surface	Base
Continuously graded	<input type="checkbox"/>	<input type="checkbox"/>
Open graded	<input type="checkbox"/>	<input type="checkbox"/>
Semi-gap graded	<input type="checkbox"/>	<input type="checkbox"/>
Gap graded	<input type="checkbox"/>	<input type="checkbox"/>
Large stone mixes	<input type="checkbox"/>	<input type="checkbox"/>
SMA	<input type="checkbox"/>	<input type="checkbox"/>
Porous asphalt	<input type="checkbox"/>	<input type="checkbox"/>
RAP	<input type="checkbox"/>	<input type="checkbox"/>
Gussasphalt	<input type="checkbox"/>	<input type="checkbox"/>
Sand asphalt	<input type="checkbox"/>	<input type="checkbox"/>

4.3 Which of the following material properties have been related to APT performance?

Stiffness	<input type="checkbox"/>	Binder content	<input type="checkbox"/>
Poisson's ratio	<input type="checkbox"/>	Film thickness	<input type="checkbox"/>
Density	<input type="checkbox"/>	Moisture content	<input type="checkbox"/>
Gradation	<input type="checkbox"/>	Visco-elastic properties	<input type="checkbox"/>
Atterberg limits	<input type="checkbox"/>	Aging index	<input type="checkbox"/>
Volumetric properties	<input type="checkbox"/>	Other	<input type="checkbox"/>

If other, please specify.

4.4 Laboratory tests used in conjunction with APT.

Wheel trafficking tests:		Other performance related tests:	
PTF	<input type="checkbox"/>	Direct tensile tests (strength or fatigue)	<input type="checkbox"/>
MMLS3	<input type="checkbox"/>	Indirect tensile tests (strength or fatigue)	<input type="checkbox"/>
French Rut Tester	<input type="checkbox"/>	Bending beam fatigue	<input type="checkbox"/>
Hamburg Tester	<input type="checkbox"/>	Cantilever fatigue tests	<input type="checkbox"/>
Asphalt Pavement Analyzer	<input type="checkbox"/>	Semi-circular bending test	<input type="checkbox"/>
Other wheel tracking	<input type="checkbox"/>	Triaxial testing	<input type="checkbox"/>
		Dynamic creep	<input type="checkbox"/>
		Static creep	<input type="checkbox"/>
		Other performance related tests	<input type="checkbox"/>

Laboratory tests used in conjunction with APT (cont.)

SST:		Laboratory compaction:	
Volumetric shear test	<input type="checkbox"/>	Marshall	<input type="checkbox"/>
Repeated shear test at constant height	<input type="checkbox"/>	Modified Marshall (Hugo)	<input type="checkbox"/>
Simple shear test at constant height	<input type="checkbox"/>	Gyratory	<input type="checkbox"/>
Repeated shear test at constant stress	<input type="checkbox"/>	Roller	<input type="checkbox"/>
Uniaxial strain test	<input type="checkbox"/>	Other compaction tests:	
Shear frequency sweep test at constant height	<input type="checkbox"/>	Short- or long-term aging	<input type="checkbox"/>
Asphalt binder tests:		Permeability	<input type="checkbox"/>
Penetration, softening point, ductility	<input type="checkbox"/>	Basic aggregate tests:	
Dynamic shear rheometer	<input type="checkbox"/>	Unconfined compressive strength	<input type="checkbox"/>
Bending beam rheometer	<input type="checkbox"/>	California bearing ratio	<input type="checkbox"/>
Rotational viscometer	<input type="checkbox"/>	Seismic measurements	<input type="checkbox"/>
Sliding plate rheometer	<input type="checkbox"/>		
Other asphalt binder tests	<input type="checkbox"/>		
Other	<input type="checkbox"/>		

If other, please specify.

4.5 Which of the following concrete materials/structures were tested with APT?

	JCP	CRCP	Pre-stressed	Block Pavers	Other
<input type="checkbox"/> None (continue with Question 4.8)					
Ordinary portland cement concrete	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
High alumina cement concrete	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Blast furnace cement concrete	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Polymer-modified concrete	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Fiber-reinforced concrete	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

If other, please specify.

4.6 Which of the following properties have been related to APT performance of concrete pavements?

- | | | | |
|----------------------|--------------------------|-------------------|--------------------------|
| Tensile strength | <input type="checkbox"/> | Flexural strength | <input type="checkbox"/> |
| Compressive strength | <input type="checkbox"/> | Stiffness modulus | <input type="checkbox"/> |
| Other | <input type="checkbox"/> | | |

If other, please specify.

4.7 Which laboratory tests were used in conjunction with APT of concrete pavements?

- | | | | |
|-------------------------------|--------------------------|------------------------------|--------------------------|
| Direct tensile strength tests | <input type="checkbox"/> | Direct tensile fatigue tests | <input type="checkbox"/> |
| Cylinder compression tests | <input type="checkbox"/> | Field core strength tests | <input type="checkbox"/> |
| Split tensile strength tests | <input type="checkbox"/> | Split tensile fatigue tests | <input type="checkbox"/> |
| Cube compression tests | <input type="checkbox"/> | Other | <input type="checkbox"/> |

If other, please specify.

4.8 Which field tests were used in conjunction with APT?

- | | | | |
|----------------------------------|--------------------------|----------------------------------|--------------------------|
| Scaled wheel trafficking (MMLS3) | <input type="checkbox"/> | Seismic measurements | <input type="checkbox"/> |
| Penetration tests (DCP) | <input type="checkbox"/> | Ground penetrating radar | <input type="checkbox"/> |
| Density/moisture measurements | <input type="checkbox"/> | FWD | <input type="checkbox"/> |
| Benkelman Beam | <input type="checkbox"/> | Permeability | <input type="checkbox"/> |
| Rolling Dynamic Deflectometer | <input type="checkbox"/> | In situ concrete strength | <input type="checkbox"/> |
| Plate load tests | <input type="checkbox"/> | Relative concrete joint movement | <input type="checkbox"/> |
| Other | <input type="checkbox"/> | | |

If other, please specify.

4.9 List significant APT findings related to materials and tests.

5. MODELING

5.1 Which aspect of modeling have you studied using APT (check all that apply)?

- | | | | |
|------------------------|--------------------------|-----------------------------|--------------------------|
| Stress/strain modeling | <input type="checkbox"/> | Back-calculation of modulus | <input type="checkbox"/> |
| Deflection modeling | <input type="checkbox"/> | Load equivalency | <input type="checkbox"/> |
| Deformation modeling | <input type="checkbox"/> | Pavement serviceability | <input type="checkbox"/> |
| Fatigue modeling | <input type="checkbox"/> | Other | <input type="checkbox"/> |

If other, please specify.

5.2 Which instrumentation have you used to gather modeling data?

- | | | | |
|----------------|--------------------------|---------------------------|--------------------------|
| Strain gauges | <input type="checkbox"/> | Displacement gauges | <input type="checkbox"/> |
| Pressure cells | <input type="checkbox"/> | Subgrade moisture sensors | <input type="checkbox"/> |
| Load cells | <input type="checkbox"/> | Other | <input type="checkbox"/> |

If other, please specify.

5.3 Which models have you been using with your APT studies?

- | | | | |
|------------------------|--------------------------|-------------------------|--------------------------|
| None | <input type="checkbox"/> | Elasto-plastic analysis | <input type="checkbox"/> |
| Elastic layer analysis | <input type="checkbox"/> | Finite-element analysis | <input type="checkbox"/> |
| Visco-elastic analysis | <input type="checkbox"/> | Other | <input type="checkbox"/> |

If other, please specify.

Please provide specifics of models developed from APT tests.

5.4 List significant APT findings related to modeling.

6. CONSTRUCTION/REHABILITATION

6.1 Which aspects of pavement engineering have you studied to enhance construction and rehabilitation through APT (check all that apply)?

- | | | | |
|--------------------------|--------------------------|-----------------------|--------------------------|
| Unconventional materials | <input type="checkbox"/> | Gradients | <input type="checkbox"/> |
| Joints | <input type="checkbox"/> | Slippage | <input type="checkbox"/> |
| Buried pipes | <input type="checkbox"/> | Road marking | <input type="checkbox"/> |
| Durability | <input type="checkbox"/> | Traffic accommodation | <input type="checkbox"/> |
| Compaction | <input type="checkbox"/> | Patching | <input type="checkbox"/> |
| Reinforcement | <input type="checkbox"/> | Risk management | <input type="checkbox"/> |
| Preventative maintenance | <input type="checkbox"/> | QA/QC | <input type="checkbox"/> |
| Surface texture | <input type="checkbox"/> | Surface tolerance | <input type="checkbox"/> |
| Surface drainage | <input type="checkbox"/> | Subsurface drainage | <input type="checkbox"/> |
| Other | <input type="checkbox"/> | | |

If other, please specify.

6.2 APT has aided in the development of construction specifications and contracts with regards to

- | | | | |
|------------------------------------|--------------------------|-----------------|--------------------------|
| Performance-related specifications | <input type="checkbox"/> | Pay factors | <input type="checkbox"/> |
| Warranties | <input type="checkbox"/> | Risk management | <input type="checkbox"/> |
| Other | <input type="checkbox"/> | Not applicable | <input type="checkbox"/> |

If other, please specify.

6.3 List significant APT findings related to construction.

6.4 List significant APT findings related to rehabilitation.

7. REFERENCES

It is assumed that active APT programs have extensive databases and bibliographies related to their research. It is with this in mind that respondents are requested to provide references pertaining to each of the listed items below that have been published in recognized journals or proceedings. Information on reports will also be useful. This feedback will enable specific information to be accessed beyond the scope that was possible to extract through the general questionnaire.

7.1 Please include a list of your published references that pertain to APT. Link your references to each of the listed related fields. Alternatively, you may insert your references as a single list in the box provided at the end of this section. You can of course expand the size of the boxes to suit your requirements.

Management

Ref. Number	Author(s)	Date	Title	Journal/Proceeding/Report	Publisher

Structural composition

Ref. Number	Author(s)	Date	Title	Journal/Proceeding/Report	Publisher

Loading environment

Ref. Number	Author(s)	Date	Title	Journal/Proceeding/Report	Publisher

Materials and tests

Ref. Number	Author(s)	Date	Title	Journal/Proceeding/Report	Publisher

Modeling

Ref. Number	Author(s)	Date	Title	Journal/Proceeding/Report	Publisher

Construction

Ref. Number	Author(s)	Date	Title	Journal/Proceeding/Report	Publisher

Rehabilitation

Ref. Number	Author(s)	Date	Title	Journal/Proceeding/Report	Publisher

List of references pertaining to APT in general

Ref. Number	Author(s)	Date	Title	Journal/Proceeding/Report	Publisher

THANK YOU FOR THE EFFORT YOU PUT IN TO COMPLETE THE QUESTIONNAIRE. WE APPRECIATE IT!

Please send your response to one of the two optional addresses on the front page of the questionnaire if you are not submitting the electronic version via the Internet. In the same vein, all other material that you have prepared and are able to send should also go to one of the same addresses on the front page.

If you have any questions, please call either Dr. Fred Hugo or Dr. Amy Epps or send an e-mail or fax.

APPENDIX B

Summary of Questionnaire Responses

United States Programs		Respondent	
Ref.	Entity	Name	E-mail
1.	University of California	Harvey	jharvey@meow.berkeley.edu
2.	Federal Aviation Administration	Hayhoe	gorton.hayhoe@faa.gov
3.	Florida DOT	Choubane	bouzid.choubane@dot.state.fl.us
4.	Federal Highway Administration	Mitchell	terry.mitchell@fhwa.dot.gov
5.	Indiana DOT	Galal	KGAL.AL@indot.state.in.us
6.	University of Illinois	Roesler	jroesler@uiuc.edu
7.	Kansas State University	Romanoshi	sromanosh@ksu.edu
8.	MN/DOT—Office of Materials and Road Research	Worel	ben.worel@dot.state.mn.us
9.	National Center of Asphalt Technology	Fowell	brigg@eng.auburn.edu
10.	Ohio University	Edwards	BEdwards@midohio.net
11.	Louisiana Transportation Research Agency	Rasoulian	mrasouli@dotd.state.la.us
12.	Texas DOT	Chen	DCHE@dot.state.tx.us
13.	US Army Engineer Research and Development Center	Freeman	reed.b.freeman@erdc.usace.army.mil
14.	US Army Corps of Engineers Cold Regions	Janoo	vjanoo@crrel.usace.army.mil
15.	Federal Highway Administration	Mitchell 2	terry_mitchell@fhwa.dot.gov
*State DOTs: Alabama, Florida, Georgia, Indiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, and FHWA.			
**State DOTs: Iowa, Kansas, Missouri, Nebraska, and HIWA.			
International Programs		Respondent	
Ref.	Entity	Name	E-mail
16.	ARRB Transport Research	Sharp	kierans@arb.com.au
17.	University of Canterbury	Steven	b.steven@ctvhl.caterbury.ac.nz
18.	Center for Study and Research on Public Works	Matos	arnateos@codex.us
19.	Technical University of Denmark	Ullidt	pu@ctt.dtu.dk
20.	Swiss Federal Institute of Technology	Caprez	caprez@igt.baug.ethz.ch
21.	VTT, Finland, and VTI	Wiman	leif.g.wiman@vtt.se
22.	Gautrans, SA/CSIR Transportek	De Beer et al.	flong@str.co.za / duplessis@str.co.za
23.	Laboratoire Central des Ponts et Chaussées	Gourdon	Jean-Louis.Gourdon@lepc.fr
24.	Delft University of Technology, Road	Houben	j.j.m.houben@citg.tudelft.nl
25.	GH Assefci Technical University of LASI	Vlad/Zarojary	vvlad@mail.dntis.ro / zarojary@hotmail.com
26.	TRL Limited	Blackman	dblackman@trl.co.uk
27.	Research Institute of Highway, The Ministry of Communications	Meng	st.meng@rioh.ac.cn
28.	University of Ulster	Woodward	wdh.woodward@ulst.ac.uk

United States Departments of Transportation with submissions stating no APT facilities						
Ref.	Entity	Location	Year	Respondent		Status 2001
				Name	E-mail	
1.	Arkansas DOT	Arkansas	NA	Meadors	Alan.Meadors@ahtd.stat.ar.us	No APT
2.	Colorado DOT	Colorado	NA	Griffin	Richard.griffin@dot.stat.co.us	No APT
3.	Connecticut DOT	Connecticut	NA	Laine	Keith.laine@po.state.ct.us	No APT
4.	Georgia DOT	Georgia	NA	Geary	Georgene.Geary@dot.state.ga.us	No APT
5.	Hawaii DOT	Hawaii	NA	Choy	gary_choy@exec.state.hi.us	No APT
6.	Idaho DOT	Idaho	NA	Smith	BSmith@itd.state.id.us	No APT
7.	Illinois DOT	Illinois	NA	Lipperdt	lippertdl@nt.dot.state.il.us	No APT
8.	Iowa DOT	Iowa	NA	MacGillivray	Ian.Macgillivray@dot.state.ia.us	No APT
9.	Maryland DOT	Maryland	NA	Smith	jsmith3@sha.state.md.us	No APT
10.	Missouri DOT	Missouri	NA	Donahue	donahj@mail.modot.state.mo.us	No APT
11.	Nebraska DOT	Nebraska	NA	Traynowicz	mtraynow@dor.state.ne.us	No APT
12.	Nevada DOT	Nevada	NA	Tedford/Weitzel	dtedford@dot.state.nv.us / dweitzel@dot.state.nv.us	No APT
13.	New Jersey DOT	New Jersey	NA	Vitillo	Nick.Vitillo@dot.state.nj.us	No APT
14.	New York DOT	New York	NA	Bernard	DBERNARD@gw.dot.state.ny.us	No APT
15.	Oregon DOT	Oregon	NA	Griffith	Andrew.S.Griffith@odot.state.or.us	No APT
16.	Pennsylvania DOT	Pennsylvania	NA	Moretz	jmoretz@dot.state.pa.us	No APT
17.	South Carolina DOT	South Carolina	NA	Zwanka	mzwanka@dot.state.sc.us	(via NCAT)
18.	Tennessee DOT	Tennessee	NA	Egan	began2@mail.state.tn.us	(via NCAT)
19.	Utah DOT	Utah	NA	Anderson	danderso@dot.state.ut.us	No APT
20.	West Virginia DOT	West Virginia	NA	Roush	nroush@state.dot.wv.us	No APT

International Programs from whom no responses were received						
Ref.	Entity	Acronym/Location	Year	Respondent		Status 2001
				Name	E-mail	
1.	Ecole Polytechnique Federale de Lausanne	EPFL/Switzerland	1977	Perret	Jacques.perret@epfl.ch	A
2.	Port and Harbor Research Institute	PHRI/PW RI—Japan	1969			A
3.	Canadian Transportation Innovation Center	C-TIC—Saskatchewan, Canada	1978			Not known
4.	Laboratory of Japan Highway Public Corporation	JHPC—Japan	1979			A
5.	Vuis – Cesty	S-KSD—Slovakia	1994	Cesty	vuis.cesty@inecnet.sk	A
6.	Institute of Engineering – The Universidad Nacional Autonome de Mexico	UNAM—Mexico	1970			A
7.	Bundesanstalt fur Strassenwesen	BASt—Germany	1963		hess@bast.de / golkowski@bast.de	Not applicable

APPENDIX C

Graphical Representation of Answers to Selected Questions by Respondents to the Questionnaire Survey (see Appendix A)

RIOH-ALF				
WesTrack				
RRT-Rom				
NCAT				
MnROAD	TRACKER	RIOH-ALF		
LCPC-Fr	RRT-Romania	TRL-PTF		
ISETH	PRF-La	PRF-La	TRACKER	
In-APLF	MnROAD	NCAT	TRL-PTF	
HVS-SA	LINTRACK	LINTRACK	MnROAD	
HVS-Nordic	K-ATL	K-ATL	LCPC-Fr	
FHWA-PTF	ATLaS	ATLaS	ATLaS	
NAPTF	ISETH	ISETH	ISETH	
DRTM	HVS-SA	In-APLF	HVS-SA	
HVS-CRREL	DRTM	FDOT-HVS	NAPTF	HVS-A
CEDEX	HVS-CRREL	HVS-CRREL	DRTM	TxMLS
CAPTIF-NZ	CAPTIF-NZ	CAL/APT	CAL/APT	ISETH
ARRB-ALF	CAL/APT	ARRB-ALF	ARRB-ALF	HVS-SA
Oh-APLF	Oh-APLF	Oh-APLF	Oh-APLF	CAL/APT
National research program	Academic research program	State research program	Partnership with others in private sector	Service rendered for others; e.g., state DOTs, military, etc.

FIGURE C1 Nature of your APT program. (Source: Significant findings from full-scale/APT testing, Question 1.1).

RIOH-ALF					
HVS-A		RIOH-ALF			
TxMLS		WesTrack			
TRL-PTF		HVS-A			
RRT-Rom		TRACKER	RIOH-ALF		
PRF-La		TxMLS	WesTrack		
NCAT		TRL-PTF	HVS-A		
MnROAD	HVS-A	RRT-Rom	TxMLS		
LINTRACK	TxMLS	PRF-La	PRF-La		HVS-A
LCPC-Fr	TRL-PTF	NCAT	NCAT		TxMLS
K-ATL	MnROAD	MnROAD	MnROAD		MnROAD
ATLaS	LINTRACK	LINTRACK	LINTRACK		LINTRACK
ISETH	LCPC-Fr	LCPC-Fr	LCPC-Fr	HVS-A	LCPC-Fr
In-APLF	ATLaS	K-ATL	ATLaS	TRL-PTF	K-ATL
HVS-SA	ISETH	ATLaS	ISETH	PRF-La	ATLaS
HVS-Nordic	In-APLF	ISETH	INDOT	MnROAD	ISETH
FHWA-PTF	HVS-SA	In-APLF	HVS-SA	LCPC-Fr	In-APLF
FDOT-HVS	FHWA-PTF	HVS-SA	FHWA-PTF	K-ATL	HVS-SA
NAPTF	NAPTF	FHWA-PTF	NAPTF	ATLaS	HVS-Nordic
DRTM	DRTM	FDOT-HVS	DRTM	In-APLF	FHWA-PTF
HVS-CRREL	HVS-CRREL	HVS-CRREL	HVS-CRREL	HVS-SA	FDOT-HVS
CEDEX	CEDEX	CEDEX	CEDEX	FDOT-HVS	NAPTF
CAPTIF-NZ	CAPTIF-NZ	CAPTIF-NZ	CAPTIF-NZ	HVS-CRREL	HVS-CRREL
CAL/APT	CAL/APT	CAL/APT	CAL/APT	CEDEX	CEDEX
ARRB-ALF	ARRB-ALF	ARRB-ALF	ARRB-ALF	CAL/APT	CAL/APT
Oh-APLF	Oh-APLF	Oh-APLF	Oh-APLF	ARRB-ALF	ARRB-ALF
Pavement structural composition	Loading environment (traffic/climate)	Materials and tests	Performance models	Construction techniques	Rehabilitation strategies

FIGURE C2 Implementation of your APT is geared towards. (Source: Significant findings from full-scale/APT, Question 1.2).

		WesTrack			
		HVS-A			
		TxMLS			WesTrack
		RRT-Rom			HVS-A
		PRF-La			TxMLS
		NCAT			TRL-PTF
		MnROAD			RRT-Rom
		LINTRACK			NCAT
		LCPC-Fr			MnROAD
		ATLaS			LINTRACK
		ISETH			LCPC-Fr
RIOH-ALF		HVS-Nordic			K-ATL
WesTrack	TRACKER	FHWA-PTF			ATLaS
TxMLS	TxMLS	FDOT-HVS			ISETH
PRF-La	TRL-PTF	NAPTF			NAPTF
MnROAD	K-ATL	HVS-CRREL		RIOH-ALF	DRTM
HVS-SA	In-APLF	CEDEX	TxMLS	HVS-A	HVS-CRREL
FHWA-PTF	DRTM	CAPTIF-NZ	MnROAD	NCAT	CAL/APT
CAL/APT	HVS-CRREL	CAL/APT	CAL/APT	MnROAD	ARRB-ALF
ARRB-ALF	Oh-APLF	Oh-APLF	ARRB-ALF	ARRB-ALF	Oh-APLF
Field	Laboratory	Fixed site	In-service pavements	Test roads	Specially constructed

FIGURE C3 Type of APT application. (Source: Significant findings from full-scale/APT, Question 1.3).

RIOH-ALF									
PRF-La	HVS-A								
FHWA-PTF	TRACKER								
FDOT-HVS	DRTM								
TRL-PTF	TRL-PTF								
LINTRACK	LINTRACK								
K-ATL	K-ATL								
ATLaS	ATLaS								
In-APLF	In-APLF								
HVS-SA	HVS-SA								
HVS-Nordic	HVS-Nordic								
ARRB-ALF	FDOT-HVS								
HVS-CRREL	HVS-CRREL		HVS-A	RRT-Rom				Mn/ROAD	Mn/ROAD k
CAL/APT	CAL/APT	TxMLS	NAPTF	ISETH	LCPC-Fr			WesTrack	WesTrack
Oh-APLF	Oh-APLF	K-ATL	K-ATL	CAPTIF-NZ	CAPTIF-NZ	CEDEX		NCAT	NCAT
Unidirectional Single axles	Bidirectional Single axles	Unidirectional Multiple axles	Bidirectional Multiple axles	Single axles	Multiple axles	Single axles	Multiple axles	Single axles	Multiple axles
Linear				Circular		Elliptical (Oval)		Trucks	

FIGURE C4 Type of APT device/system. (Source: Significant findings from full-scale/APT, Question 1.4).

				HVS-A
	TxMLS		RIOH-ALF	MnROAD
	LINTRACK		WesTrack	LCPC-Fr
TRACKER	K-ATL		TRL-PTF	In-APLF
ISETH	HVS-Nordic	RRT-Rom	NCAT	HVS-SA
FDOT-HVS	NAPTF	PRF-La	CEDEX	FHWA-PTF
HVS-CRREL	Oh-APLF	CAPTIF-NZ	CAL/APT	ARRB-ALF
1-5	6-10	11-20	21-50	>50*

FIGURE C5 Number of pavement sections tested. (Source: Significant findings from full-scale/APT, Question 1.5).

*Upper limit not defined in questionnaire.

TRACKER	RIOH-ALF			
TRL-PTF	TxMLS			
LCPC-Fr	LINTRACK			
K-ATL	LCPC-Fr	HVS-A		
In-APLF	FHWA-PTF	NAPTF		
HVS-SA	FDOT-HVS	DRTM		
HVS-Nordic	HVS-CRREL	CEDEX	RRT-Rom	WesTrack
CAL/APT	CAL/APT	CAPTIF-NZ	PRF-La	MnROAD
Oh-APLF	ARRB-ALF	CAL/APT	NCAT	ISETH
1-3	4-6	7-11	12-24	>24*

FIGURE C6 Typical duration of an APT test per test section in months. (Source: Significant findings from full-scale/APT, Question 1.6).

*Upper limit not defined in questionnaire.

	RIOH-ALF		
	TRL-PTF		
	ATLaS	PRF-La	WesTrack
RRT-Rom	HVS-SA	FHWA-PTF	MnROAD
LINTRACK	CAPTIF-NZ	FDOT-HVS	LCPC-Fr
K-ATL	ARRB-ALF	CEDEX	NAPTF
In-Oh-APLF	Oh-APLF	CAL/APT	HVS-CRREL
<\$1 M	\$1-2 M	\$2-5 M	>\$5 M*

FIGURE C7 Estimated capital cost of APT facility equipment. (Source: Significant findings from full-scale/APT, Question 1.7).

*Upper limit not defined in questionnaire.

	RIOH-ALF				
	TRL-PTF				
	RRT-Rom			WesTrack	
	ISETH	LINTRACK		FDOT-HVS	
	CAPTIF-NZ	K-ATL	TxMLS	NAPTF	NCAT
In-APLF	ARRB-ALF	HVS-Nordic	PRF-La	HVS-CRREL	MnROAD
HVS-Nordic	Oh-APLF	FHWA-PTF	HVS-SA	CEDEX	CAL/APT
<\$0.1 M	\$0.1-0.2 M	\$0.2-0.4 M	\$0.4-0.8 M	\$0.8-1.6 M	>\$1.6 M*

FIGURE C8 Yearly APT budget without pavement construction cost. (Source: Significant findings from full-scale/APT, Question 1.8).

*Upper limit not defined in questionnaire.

									WesTrack
									HVS-A
									TxMLS
									TRL-PTF
									PRF-La
									LINTRACK
			WesTrack	HVS-A	RIOH-ALF				K-ATL
			TxMLS	TRACKER	TRL-PTF				ATLaS
			TRL-PTF	NCAT	RRT-Rom				ISETH
			RRT-Rom	ATLaS	PRF-LA				In-APLF
	PRF-La		NCAT	HVS-SA	LINTRACK				FHWA-PTF
	ATLaS		K-ATL	FHWA-PTF	K-ATL				NAPTF
	In-APLF		ISETH	FDOT-HVS	ISETH				CAPTIF-NZ
	FHWA-PTF		CAPTIF-NZ	CAL/APT	INDOT				CAL/APT
TRACKER	FDOT-HVS		CAL/APT	ARRB-ALF	NAPTF			RRT-Rom	ARRB-ALF
LINTRACK	Oh-APLF	NAPTF	ARRB-ALF	Oh-APLF	CAPTIF-NZ	FDOT	NCAT	DRTM	Oh-APLF
<10%	10-20%	20-30%	>30%*	<10%	10-20%	<10%	10-20%	20-30%	>30%
Operational				Maintenance			Staff		

FIGURE C9 Breakdown of budget (N/A). (Source: Significant findings from full-scale/APT, Question 1.9).

*Upper limit not defined in questionnaire.

RIOH-ALF			
WesTrack			
HVS-A			
TRACKER			
TRL-PTF			
RRT-Rom			
NCAT			
LINTRACK			
LCPC-Fr			
K-ATL			
ATLaS			
ISETH			
In-APLF			
HVS-SA			
HVS-Nordic			
FHWA-PTF			
DRTM			
HVS-CRREL			
CAPTIF-NZ	TxMLS		
ARRB-ALF	PRF-La		
Oh-APLF	FDOT-HVS	CEDEX	
<\$0.5 M	\$0.5-1 M	\$1-2 M	>\$2 M*

FIGURE C10 Average (typical) operational cost/test section. (Source: Significant findings from full-scale/APT, Question 1.10).

*Upper limit not defined in questionnaire.

RIOH-ALF					RIOH-ALF	
HVS-A					HVS-A	
TxMLS					TRACKER	
TRL-PTF					TxMLS	
RRT-Rom					TRL-PTF	
PRF-La		RIOH-ALF			RRT-Rom	
NCAT		HVS-A			PRF-La	
LINTRACK		TRACKER			NCAT	
K-ATL		TRL-PTF			LINTRACK	
ATLaS		RRT-Rom			K-ATL	
ISETH		PRF-La			ATLaS	
In-APLF		NCAT			In-APLF	
HVS-SA		LINTRACK			FHWA-PTF	
HVS-Nordic		K-ATL			HVS-CRREL	
FHWA-PTF		ATLaS			CEDEX	
FDOT-HVS		In-APLF			CAPTIF-NZ	
NAPTF		FHWA-PTF				
HVS-CRREL		HVS-CRREL				
CEDEX		CEDEX	HVS-SA			
CAPTIF-NZ	WesTrack	CAPTIF-NZ	HVS-Nordic	WesTrack	CAL/APT	TxMLS
ARRB-ALF	MnROAD	ARRB-ALF	FDOT	MnROAD	ARRB-ALF	MnROAD
Oh-APLF	CAL/APT	Oh-APLF	NAPTF	CAL/APT	Oh-APLF	HVS-Nordic
<5	>5*	<5	5-10	>10*	<5	>5*
Professional		Technical			Administrative	

FIGURE C11 Number of direct APT personnel. (Source: Significant findings from full-scale/APT, Question 1.11).

*Upper limit not defined in questionnaire.

					WesTrack
					HVS-A
					NCAT
					MnROAD
					NAPTF
					CAPTIF-NZ
					CAL/APT
					ARRB-ALF
			ISETH		
<\$100 k	\$100-200 k	\$200-500 k	\$0.5-1 M	\$1-2 M	>\$2 M*

FIGURE C12 Overall estimated savings/benefits in monetary terms for the respective programs. (Source: Significant findings from full-scale/APT, Question 1.12).

*Upper limit not defined in questionnaire.

RIOH-ALF	
WesTrack	
HVS-A	
TxMLS	
RRT-Rom	
PRF-La	
NCAT	
MnROAD	
LINTRACK	
LCPC-Fr	
ATLaS	WesTrack
ISETH	HVS-A
HVS-SA	TxMLS
HVS-Nordic	RRT-Rom
FHWA-PTF	NCAT
FDOT-HVS	MnROAD
NAPTF	LINTRACK
HVS-CRREL	LCPC-Fr
CAPTIF-NZ	ISETH
CAL/APT	In-APLF
ARRB-ALF	HVS-CRREL
Oh-APLF	ARRB-ALF
Structural performance	Functional performance

FIGURE C15 Purpose of the structural compositions used in APT programs. (Source: Significant findings from full-scale/APT, Question 2.1).

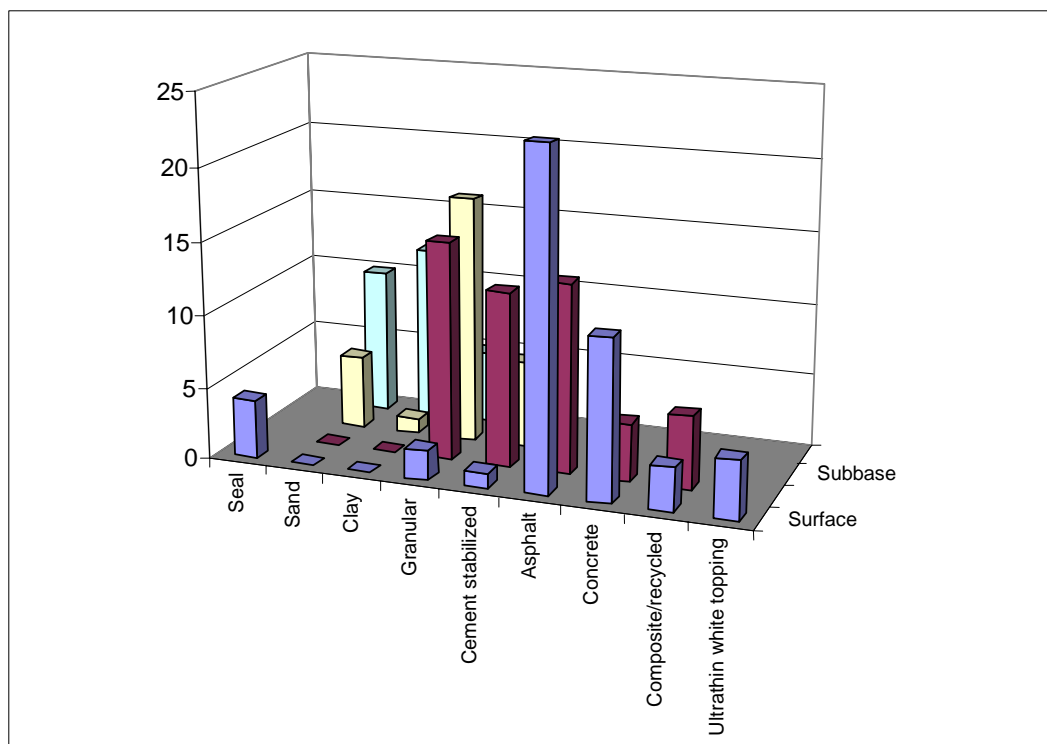


FIGURE C16 Pavement layers evaluated/validated in the structural performance tests. (Source: Significant findings from full-scale/APT, Question 2.2).

				PRFL-La
				WesTrack
				HVS-A
				TxMLS
				TRL-PTF
				NCAT
				LINTRACK
				K-ATL
				FHWA-PTF
				FDOT-HVS
			MnROAD	NAPTF
MnROAD	MnROAD	MnROAD	ISETH	DRTM
HVS-SA	HVS-SA	HVS-SA	HVS-SA	CAL/APT
ARRB-ALF	ARRB-ALF	CAPTIF-NZ	ARRB-ALF	Oh-APLF
Ravelling	Bleeding	Other	Aggregate loss	Not applicable

FIGURE C17 Distress criterion evaluated for seals. (Source: Significant findings from full-scale/APT, Question 2.3).

				RIOH-ALF	
				HVS-A	
				TxMLS	
				TRL-PTF	
				MnROAD	
				LINTRACK	
				K-ATL	
				ISETH	
				HVS-SA	
				HVS-Nordic	
				NAPTF	
				DRTM	
				HVS-CRREL	FHWA-PTF
				CEDEX	WesTrack
	HVS-A	MnROAD	CAPTIF-NZ	NCAT	
	HVS-SA	DRTM	CAL/APT	FDOT-HVS	MnROAD
ISETH	ARRB-ALF	HVS-CRREL	ARRB-ALF	Oh-APLF	NAPTF
Collapsing	Swelling	Freeze/thaw	Permanent deformation	Not applicable	Other

FIGURE C18 Distress criterion evaluated for pavements with clay/sand material. (Source: Significant findings from full-scale/APT, Question 2.4).

RIOH-ALF				
HVS-A				
TxMLS				
TRL-PTF				
PRF-La				
MnROAD				
LCPC-Fr				
K-ATL				
ISETH				
HVS-SA				
HVS-Nordic				
NAPTF		RIOH-ALF		
DRTM		HVS-A		
HVS-CRREL		MnROAD		
CEDEX		HVS-SA		WesTrack
CAPTIF-NZ	MnROAD	HVS-CRREL		NCAT
CAL/APT	DRTM	CAPTIF-NZ		FDOT-HVS
ARRB-ALF	HVS-CRREL	ARRB-ALF	K-ATL	Oh-APLF
Permanent deformation	Frost/thaw damage	Shear failure	Other	Not applicable

FIGURE C19 Distress criterion evaluated for pavements with granular materials. (Source: Significant findings from full-scale/APT, Question 2.5).

RIO-ALF				
HVS-A				
TxMLS				
TRL-PTF				
RRT-Rom				
PRF-La				
MnROAD				FHWA-PTF
LCPC-Fr				WesTrack
ISETH	RIOH-ALF			NCAT
HVS-SA	HVS-A			LINTRACK
NAPTF	TRL-PTF			FDOT-HVS
DRTM	ISETH		MnROAD	HVS-CRREL
CEDEX	HVS-SA	RRT-Rom	CAL/APT	CAPTIF-NZ
ARRB-ALF	ARRB-ALF	HVS-SA	ARRB-ALF	Oh-APLF
Cracking	Crushing	Carbonation	Other	Not applicable

FIGURE C20 Distress criterion for pavements with stabilized or cemented materials. (Source: Significant findings from full-scale/APT, Question 2.6).

RIOH-ALF						
WesTrack						
HVS-A						
TxMLS						
TRL-PTF	RIOH-ALF					
RRT-Rom	WesTrack					
PRF-La	TxMLS					
NCAT	TRL-PTF					
MnROAD	RRT-Rom					
LINTRACK	PRF-La					
LCPC-Fr	NCAT					
K-ATL	MnROAD					
ISETH	LINTRACK					
In-APLF	LCPC-Fr					
HVS-SA	K-ATL					
FHWA-PTF	ISETH					
FDOT-HVS	In-APLF		RIOH-ALF			
DRTM	HVS-SA		WesTrack			
HVS-CRREL	FHWA-PTF		TxMLS			
CEDEX	DRTM		NCAT	TxMLS		
CAPTIF-NZ	CEDEX	RIOH-ALF	MnROAD	RRT-Rom	WesTrack	
CAL/APT	CAPTIF-NZ	WesTrack	In-APLF	MnROAD	MnROAD	
ARRB-ALF	CAL/APT	MnROAD	HVS-SA	HVS-SA	K-ATL	
Oh-APLF	ARRB-ALF	HVS-CRREL	CAL/APT	FHWA-PTF	Oh-APLF	NAPTF
Rutting	Fatigue	Low temperature cracking	Moisture damage/ stripping	Aging	Other	Not applicable

FIGURE C21 Distress criterion evaluated for pavements with asphaltic materials. (Source: Significant findings from full-scale/APT, Question 2.7).

HVS-A												
TRL-PTF												
RRT-Rom												
MnROAD												
LCPC-Fr												
K-ATL												
ATLaS			HVS-A	HVS-A								
In-APLF			MnROAD	TRL-PTF								
HVS-SA	HVS-A		LCPC-Fr	MnROAD								
HVS-Nordic	MnROAD	TRL-PTF	ATLaS	LCPC-Fr	TRL-PTF					MnROAD		WesTrack
NAPTF	ATLaS	MnROAD	In-APLF	ATLaS	MnROAD	TRL-PTF				K-ATL		TxMLS
DRTM	HVS-SA	ISETH	HVS-SA	In-APLF	K-ATL	MnROAD				ATLaS		NCAT
CAL/APT	HVS-Nordic	HVS-SA	NAPTF	CAL/APT	ATLaS	K-ATL	TRL-PTF	TRL-PTF		HVS-SA		FDOT-HVS
ARRB-ALF	DRTM	CAL/APT	CAL/APT	ARRB-ALF	HVS-SA	HVS-SA	MnROAD	MnROAD		CAL/APT		HVS-CRREL
Oh-APLF	CAL/APT	ARRB-ALF	ARRB-ALF	Oh-APLF	CAL/APT	ARRB-ALF	ARRB-ALF	ATLaS	TRL-PTF	ARRB-ALF	RRT-Rom	CAPTIF-NZ
Cracking	Stress ratio	Joint failure	Fatigue	Curling and warping	Load transfer failure	Faulting	Spalling	Punchouts	Steel rupture	Erosion of subbase	Other	Not applicable

FIGURE C22 Distress criterion evaluated for pavements with concrete. (Source: Significant findings from full-scale/APT, Question 2.8).

	PRF-La					
	PRF-La					
	HVS-A					
	TxMLS					
HVS-A	TRL-PTF					
TxMLS	RRT-Rom			HVS-A		
TRL-PTF	NCAT		TxMLS	TxMLS		
RRT-Rom	MnROAD		TRL-PTF	TRL-PTF		
NCAT	K-ATL		NCAT	MnROAD		FDOT-HVS
ISETH	ISETH		ISETH	In-APLF		NAPTF
DRTM	In-APLF		In-APLF	FHWA-PTF	RRT-Rom	HVS-CRREL
CAL/APT	FHWA-PTF	NCAT	FHWA-PTF	DRTM	MnROAD	CAPTIF-NZ
ARRB-ALF	ARRB-ALF	DRTM	ARRB-ALF	ARRB-ALF	FHWA-PTF	Oh-APLF
Rutting	Cracking	Slippage	Fatigue	Debonding	Other	Not applicable

FIGURE C23 Distress criterion evaluated for pavements with composite materials. (Source: Significant findings from full-scale/APT, Question 2.9).

			WesTrack		
			PRF-La		
			HVS-A		
			TxMLS		
			RRT-Rom		
			NCAT		
			LCPC-FR		
	NCAT		ISETH		TRL-PTF
	MnROAD		CEDEX		In-APLF
	LINTRACK				FDOT-HVS
	HVS-SA				
	HVS-CRREL	WesTrack	CAPTIF-NZ		
	CEDEX	NCAT	ARRB-ALF	K-ATL	NAPTF
Safety	Environment	User cost	Roughness	Other	Not applicable

FIGURE C24 Which aspects of functional performance were addressed? (Source: Significant findings from full-scale/APT, Question 2.10).

RIOH-ALF							
WesTrack							
TxMLS							
TRL-PTF							
RRT-Rom							
PRF-La							
NCAT							
MnROAD							
LINTRACK		WesTrack					
LCPC-Fr		HVS-A					
ISETH	WesTrack	TxMLS					
HVS-SA	TxMLS	RRT-Rom					
FHWA-PTF	TRL-PTF	PRF-La					
FDOT-HVS	PRF-La	NCAT					
HVS-CRREL	NCAT	MnROAD					
CAPTIF-NZ	MnROAD	LCPC-Fr					K-ATL
CAL/APT	CEDEX	ISETH	RIOH-ALF				NAPTF
Oh-APLF	ARRB-ALF	ARRB-ALF	HVS-SA	HVS-SA	MnROAD	MnROAD	DRTM
Rutting	Skid resistance	Roughness	Punchouts	Delamination	Spalling	Other	Not applicable

FIGURE C25 Which safety aspects were addressed in your APT program? (Source: Significant findings from full-scale/APT, Question 2.11).

			WesTrack
			HVS-A
			TRL-PTF
			RRT-Rom
			PRF-La
			LINTRACK
			K-ATL
			ISETH
			FHWA-PTF
		NCAT	FDOT-HVS
		LINTRACK	NAPTF
TxMLS		HVS-CRREL	CAPTIF-NZ
HVS-SA	MnROAD	Oh-APLF	ARRB-ALF
Noise	Dust pollution	Other	Not applicable

FIGURE C26 Which environmental aspects were addressed in your APT program? (Source: Significant findings from full-scale/APT, Question 2.12).

	RIOH-ALF							
	WesTrack							
	HVS-A							
	TxMLS							
	TRL-PTF							
	RRT-Rom							
	PRF-La							
	NCAT							
RIOH-ALF	MnROAD							
WesTrack	LCPC-Fr							
TxMLS	K-ATL							
RRT-Rom	ISETH					HVS-A		
PRF-La	In-APLF					PRF-La		
NCAT	HVS-SA	RIOH-ALF				MnROAD		
MnROAD	HVS-Nordic	TxMLS				LCPC-Fr		
ISETH	FHWA-PTF	PRF-La				ISETH	HVS-A	
In-APLF	NAPTF	NCAT				HVS-SA	TxMLS	
HVS-SA	DRTM	MnROAD			WesTrack	HVS-Nordic	NCAT	
DRTM	HVS-CRREL	LCPC-Fr			PRF-La	DRTM	MnROAD	
HVS-CRREL	CEDEX	HVS-SA	PRF-La		MnROAD	HVS-CRREL	K-ATL	
CEDEX	ARRB-ALF	CEDEX	NCAT	HVS-SA	CEDEX	HVS-SA	TxMLS	MnROAD
ARRB-ALF	APLF	ARRB-ALF	MnROAD	FHWA-PTF	ARRB-ALF	ARRB-ALF	MnROAD	K-ATL
Air temperature	Pavement temperature	Rainfall	Relative humidity	Aging	Water table	Drainage	Depth to bedrock	Other

FIGURE C28 Environment/weather data that have been related to APT performance. (Source: Significant findings from full-scale/APT, Question 3.2).

	RIOH-ALF							
	HVS-A							
	TRL-PTF							
	RRT-Rom							
HVS-A	LINTRACK				RIOH-ALF			
RRT-Rom	LCPC-Fr				HVS-A			
LCPC-Fr	K-ATL				LCPC-Fr			
K-ATL	In-APLF				K-ATL			
In-APLF	HVS-SA				HVS-Nordic			
HVS-SA	HVS-Nordic				DRTM			
HVS-Nordic	FHWA-PTF				HVS-CRREL			
DRTM	DRTM				CEDEX			
HVS-CRREL	HVS-CRREL				CAPTIF-NZ		WesTrack	
Oh-APLF	ARRB-ALF	Oh-APLF	Oh-APLF	Oh-APLF	ARRB-ALF		K-ATL	
Air temperature	Pavement temperature	Relative humidity	Subgrade moisture	Aging		HVS-SA	NAPTF	
							Other	

FIGURE C29 Environment/weather conditions that are controlled. (Source: Significant findings from full-scale/APT, Question 3.3).

	RIOH-ALF			
	WesTrack			
	HVS-A			
	TRACKER			
	TxMLS			
	TRL-PTF			
	RRT-Rom			
	PRF-La			
	NCAT			
	LINTRACK			
RIOH-ALF	LCPC-Fr			
WesTrack	K-ATL			
TxMLS	ISETH			
PRF-La	HVS-SA	WesTrack		
NCAT	HVS-Nordic	TxMLS		
LCPC-Fr	FHWA-PTF	NCAT		
K-ATL	FDOT-HVS	LINTRACK-NL		
In-APLF	NAPTF	LCPC-Fr		
HVS-SA	DRTM	HVS-SA	WesTrack	
FHWA-PTF	HVS-CRREL	HVS-CRREL	TxMLS	
FDOT-HVS	CEDEX	CEDEX	NCAT	
CEDEX	CAPTIF-NZ	CAPTIF-NZ	K-ATL	
ARRB-ALF	ARRB-ALF	ARRB-ALF	DRTM	
Oh-APLF	Oh-APLF	Oh-APLF	HVS-CRREL	
Hot (>40°C) (>104°F)	Moderate (>10°C <40°C) (>50°F <104°F)	Cold (<10°C) (<50°F)	Freezing (<5°C) (<41°F)	

FIGURE C30 APT test temperatures used. (Source: Significant findings from full-scale/APT, Question 3.4).

		TRACKER						
		TxMLS						
		TRL-PTF						
		RRT-Rom						
RIOH-ALF		PRF-La						
HVS-A		NCAT						
TxMLS		MnROAD						
TRL-PTF	RIOH-ALF	LINTRACK						
MnROAD	TxMLS	LCPC-Fr						
LCPC-Fr	TRL-PTF	K-ATL						
K-ATL	RRT-Rom	ISETH						
ISETH	PRF-La	In-APLF						
HVS-SA	MnROAD	HVS-SA				HVS-A		
HVS-CRREL	LCPC-Fr	FHWA-PTF	MnROAD	TRL-PTF		TRL-PTF		MnROAD
CEDEX	ISETH	CEDEX	LCPC-Fr	RRT-Rom	TRL-PTF	MnROAD	TRL-PTF	HVS-SA
CAPTIF-NZ	HVS-SA	CAL/APT	K-ATL	MnROAD	MnROAD	HVS-CRREL	RRT-Rom	FDOT-HVS
CAL/APT	CEDEX	ARRB-ALF	ISETH	LCPC-Fr	In-APLF	CEDEX	ISETH	CAL/APT
ARRB-ALF	ARRB-ALF	Oh-APLF	HVS-SA	HVS-SA	FHWA-PTF	ARRB-ALF	CEDEX	ARRB-ALF
Granular materials	Stablized/cemented materials	Asphalt (Hot mix)	Asphalt (Cold mix)	Concrete	Whitetopping	Geofabrics	Reinforcements	Other

FIGURE C31 APT has led to the improved characterization of: (Source: Significant findings from full-scale/APT, Question 4.1).

	RIOH-ALF								
	WesTrack								
	HVS-A				HVS-A				
	TxMLS				TRL-PTF				
	TRL-PTF				PRF-La				
	RRT-Rom				NCAT				
	PRF-La				MnROAD				
	NCAT	RIOH-ALF			LINTRACK				
	MnROAD	WesTrack			LCPC-Fr				
	LINTRACK	HVS-A			ISETH			RIOH-ALF	
TRACKER	LCPC-Fr	TRL-PTF			In-APLF			HVS-A	
TxMLS	K-ATL	NCAT			HVS-SA	HVS-A		PRF-La	
TRL-PTF	ISETH	MnROAD			FDOT-HVS	PRF-La		NCAT Auburn	
RRT-Rom	HVS-SA	LINTRACK			NAPTF	NCAT		MnROAD	
PRF-La	FDOT-HVS	HVS-SA			CEDEX	MnROAD		ISETH	
LCPC-Fr	CEDEX	FHWA-PTF			CAPTIF-NZ	HVS-SA		HVS-SA	
K-ATL	CAPTIF-NZ	CEDEX			CAL/APT	FDOT-HVS		CEDEX	
NAPTF	ARRB-ALF	CAL/APT	LCPC-Fr		ARRB-ALF	CEDEX	ARRB-ALF	HVS-SA	
Oh-APLF	Oh-APLF	ARRB-ALF	ISETH	MnROAD	Oh-APLF	ARRB-ALF	Oh-APLF	CAL/APT	
Direct tensile tests	Indirect tensile tests	Bending beam fatigue	Cantilever fatigue tests	Semi-circular bending test	Triaxial testing	Dynamic creep	Static creep	Other performance related tests	
Other performance related tests									

RIOH-ALF										
WesTrack										
HVS-A		WesTrack						RIOH-ALF		
RRT-Rom		HVS-A						WesTrack		
PRF-La		TRACKER						TxMLS		
NCAT		PRF-La						RRT-Rom		
MnROAD		NCAT						NCAT		
K-ATL		MnROAD						MnROAD		
ISETH		LCPC-Fr		WesTrack	WesTrack			LCPC-Fr	RIOH-ALF	RIOH-ALF
In-APLF		K-ATL		NCAT	RRT-Rom			K-ATL	MnROAD	TxMLS
HVS-SA		In-APLF		In-APLF	MnROAD			ISETH	K-ATL	TRL-PTF
NAPTF		HVS-SA	HVS-A	HVS-SA	LCPC-Fr			HVS-SA	ISETH	MnROAD
DRTM		FDOT-HVS	LCPC-Fr	FHWA-PTF	HVS-SA			FHWA-PTF	HVS-SA	ISETH
CEDEX		CAL/APT	HVS-SA	CEDEX	FHWA-PTF	MnROAD	DRTM	CEDEX	HVS-SA	
ARRB-ALF		ARRB-ALF	CAL/APT	CAPTIF-NZ	CEDEX	K-ATL	CEDEX	ARRB-ALF	CEDEX	TxMLS
Oh-APLF	HVS-SA	Oh-APLF	ARRB-ALF	CAL/APT	ARRB-ALF	FDOT-HVS	ARRB-ALF	Oh-APLF	ARRB-ALF	MnROAD
Marshall	Modified Marshall (Hugo)	Gyratory	Roller	Other compaction tests	Short or long term aging	Permeability	Basic aggregate tests	Unconfined compressive strength	California bearing ratio	Seismic measurements
Laboratory compaction										

FIGURE C34 (Continued).

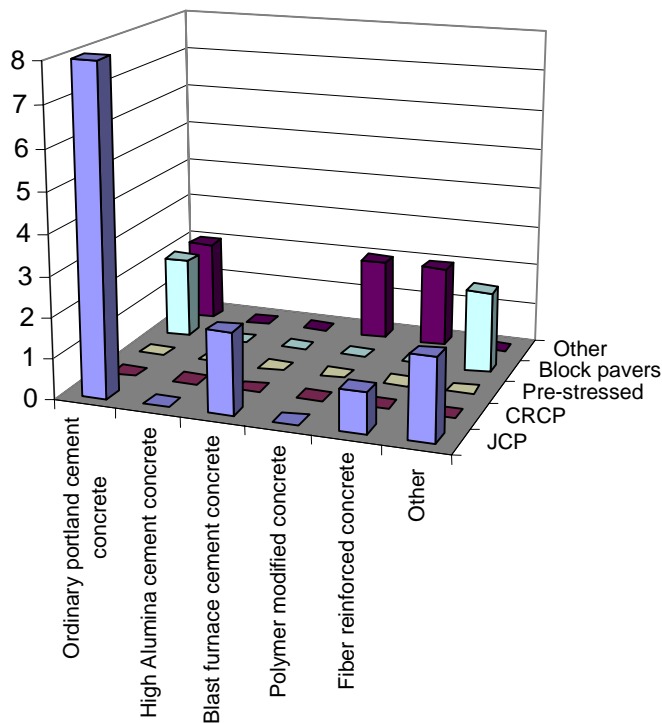


FIGURE C35 Concrete materials/structures tested with APT. (Source: Significant findings from full-scale/APT, Question 4.5).

	HVS-A		HVS-A	
	RRT-Rom		TRL-PTF	
	MnROAD	HVS-A	RRT-Rom	
	LCPC-Fr	MnROAD	MnROAD	
	K-ATL	K-ATL	LCPC-Fr	
HVS-A	FHWA-PTF	HVS-SA	K-ATL	
MnROAD	NAPTF	FHWA-PTF	FHWA-PTF	
LCPC-Fr	CAL/APT	CAL/APT	CAL/APT	MnROAD
K-ATL	ARRB-ALF	ARRB-ALF	Oh-APLF	Oh-APLF
Tensile strength	Flexural strength	Compressive strength	Stiffness modulus	Other

FIGURE C36 Properties that have been related to APT performance of concrete pavements. (Source: Significant findings from full-scale/APT, Question 4.6).

RIOH-ALF				RIOH-ALF				
WesTrack		RIOH-ALF		WesTrack				
HVS-A	RIOH-ALF	HVS-A		HVS-A				
TRACKER	HVS-A	TxMLS		TxMLS				
MnROAD	TxMLS	RRT-Rom		PRF-La				
LINTRACK	RRT-Rom	PRF-La		MnROAD				
LCPC-Fr	MnROAD	MnROAD	RIOH-ALF	LINTRACK				
In-APLF	LINTRACK	LINTRACK	WesTrack	LCPC-Fr				
HVS-SA	LCPC-Fr	LCPC-Fr	PRF-La	ISETH				
HVS-Nordic	ISETH	In-APLF	MnROAD	In-APLF	RIOH-ALF			
FHWA-PTF	HVS-SA	HVS-SA	LINTRACK	HVS-SA	TxMLS			
NAPTF	NAPTF	FHWA-PTF	LCPC-Fr	HVS-Nordic	RRT-Rom			
DRTM	DRTM	NAPTF	In-APLF	DRTM	PRF-La			
HVS-CRREL	HVS-CRREL	DRTM	HVS-SA	HVS-CRREL	MnROAD	HVS-A		
CEDEX	CEDEX	HVS-CRREL	FHWA-PTF	CEDEX	LINTRACK	TxMLS		
CAPTIF-NZ	CAPTIF-NZ	CEDEX	HVS-CRREL	CAPTIF-NZ	In-APLF	PRF-La		
CAL/APT	CAL/APT	CAPTIF-NZ	CEDEX	CAL/APT	HVS-SA	MnROAD		
ARRB-ALF	ARRB-ALF	CAL/APT	CAL/APT	ARRB-ALF	CAPTIF-NZ	ISETH	RIOH-ALF	
Oh-APLF	Oh-APLF	ARRB-ALF	ARRB-ALF	Oh-APLF	ARRB-ALF	ARRB-ALF	MnROAD	DRTM
Stress/strain modeling	Deflection modeling	Deformation modeling	Fatigue modeling	Back-calculation of modulus	Load equivalency	Pavement serviceability	Cracking	Other

FIGURE C39 Aspects of modeling studied using APT. (Source: Significant findings from full-scale/APT, Question 5.1).

RIOH-ALF					
WesTrack					
HVS-A					
TxMLS					
PRF-La					
MnROAD					
LINTRACK					
LCPC-Fr	RIOH-ALF				
K-ATL	HVS-A				
ISETH	TxMLS				
In-APLF	PRF-La				
HVS-SA	MnROAD				
HVS-Nordic	LCPC-Fr				
FHWA-PTF	K-ATL				
NAPTF	HVS-Nordic				
DRTM	NAPTF				
HVS-CRREL	DRTM	RIOH-ALF			
CEDEX	HVS-CRREL	HVS-A			
CAL/APT	CEDEX	TxMLS			
ARRB-ALF	CAPTIF-NZ	PRF-La			
Oh-APLF	ARRB-ALF	MnROAD			
Strain gauges	Pressure cells	Load cells	Displacement gauges	Subgrade moisture sensors	Other*
*Other instruments cited by respondents:					
Temperature sensors—Oh-APLF; CAL/APT			Temperature gauge—DRTM		
Emu & Bison strain coils—CAPTIF-NZ					
LVDT—FHWA-PTF					
Several attempts for measurement of asphalt sublayers: LINTRACK-NL					
MnROAD—see website (http://mnroad.dot.state.mn.us/research/Mnresearch.asp) and beyond the surface handout.					

FIGURE C40 Instrumentation used to gather modeling data. (Source: Significant findings from full-scale/APT, Question 5.2).

	RIOH-ALF			RIOH-ALF	
	WesTrack			WesTrack	
	HVS-A			HVS-A	
	TxMLS			TxMLS	
	RRT-Rom			PRF-La	
	PRF-La			MnROAD	
	NCAT			LINTRACK	
	LINTRACK			LCPC-Fr	
	LCPC-Fr			In-APLF	
	K-ATL			HVS-SA	
	ISETH			FHWA	
	HVS-SA			NAPTF	
	HVS-Nordic	WesTrack		DRTM	
	NAPTF	TxMLS		HVS-CRREL	
	DRTM	PRF-La		CEDEX	
	HVS-CRREL	MnROAD			
	CEDEX	LINTRACK			
	CAPTIF-NZ	LCPC-Fr	TxMLS	CAPTIF-NZ	PRF-La
	CAL/APT	ISETH	MnROAD	CAL/APT	MnROAD
	ARRB-ALF	FHWA-PTF	HVS-SA	ARRB-ALF	In-APLF
	Oh-APLF	CEDEX	CAL/APT	Oh-APLF	DRTM
None	Elastic layer analysis	Visco-elastic analysis	Elasto-plastic analysis	Finite element analysis	Other

FIGURE C41 Models used with APT studies. (Source: Significant findings from full-scale/APT, Question 5.3).

HVS-A					RIOH-ALF				
TxMLS					WesTrack				
TRL-PTF					HVS-A				
RRT-Rom					NCAT				
MnROAD					MnROAD				
LCPC-Fr	MnROAD			RRT-Rom	In-APLF	HVS-A			
ISETH	K-ATL			MnROAD	HVS-SA	TRL-PTF		NCAT	
HVS-SA	ISETH			LCPC-Fr	HVS-CRREL	RRT-Rom	RIOH-ALF	MnROAD	
CEDEX	HVS-SA	TRL-PTF	ISETH	CAPTIF-NZ	LCPC-Fr	TxMLS	HVS-SA		
CAL/APT	ARRB-ALF	MnROAD	HVS-CRREL	CAL/APT	HVS-Nordic	MnROAD	CEDEX	MnROAD	
ARRB-ALF	Oh-APLF	ISETH	CEDEX	ARRB-ALF	HVS-CRREL	ARRB-ALF	ARRB-ALF	HVS-SA	
Unconventional materials	Joints	Buried pipes	Durability	Compaction	Reinforcement	Preventive maintenance	Surface texture	Surface drainage	

									PRF-La	
									NCAT	
				MnROAD		WesTrack	HVS-A		MnROAD	PRF-La
	PRF-La	MnROAD		HVS-SA	HVS-A	NCAT	NCAT		CAL/APT	MnROAD
Oh-APLF	CEDEX	CEDEX	ARRB-ALF	ARRB-ALF	LCPC-Fr	MnROAD	CEDEX	NCAT	ARRB-ALF	HVS-Nordic
Gradients	Slippage	Road marking	Traffic accommodation	Patching	Risk management	QA/QC	Surface tolerance	Layers	Subsurface drainage	Other

FIGURE C42 Aspects of pavement engineering that enhance construction and rehabilitation through APT. (Source: Significant findings from full-scale/APT, Question 6.1).

RIOH-ALF					
WesTrack					
TRL-PTF					
NCAT					
K-ATL					
ISETH					
HVS-SA		WesTrack			
CEDEX		HVS-A			
CAL/APT	WesTrack	NCAT			
ARRB-ALF	NCAT	CAL/APT	ARRB-ALF	Oh-APLF	MnROAD
Performance-related specifications	Warranties	Pay factors	Risk management	Not applicable	Other

FIGURE C43 APT aids in development of construction specifications and contracts with regards to: (Source: Significant findings from full-scale/APT, Question 6.2).

APPENDIX D

Summary of Answers to Selected Questions by Respondents to the Questionnaire Survey

(SEE APPENDIX A—QUESTION 1.13)

Note: Summaries should be read in context with the rest of the text where further details have been provided in many instances.

Table D1. Process used to determine B/C ratio	
Oh-APLF	No economic benefits calculated to date.
ARRB	B/C ratios have varied from 1:1 to 15:1. Processes vary from full whole of life type analyses to discussions with clients regarding direct applications resulting from the trial and savings made on specific projects.
CAL/APT	Benefit/cost ratio of CAL/APT equals 10:1. Savings in hundreds of millions of dollars. Costs are for two machines, two sites, two crews, etc. Test section construction estimated at \$60 K/year. Most staff not full-time APT.
CAPTIF	Various outcomes are predicted; associated probabilities and savings for each outcome are combined to determine overall expected value. This sum is divided by actual cost of the project to give overall benefit/cost ratio for the project. The benefits are summed over 5 years and factored back to the present worth using a 10% discount rate.
FAA	Rehabilitation avoided plus material cost savings in new construction and rehabilitation.
FHWA-PTF	We have not done any benefit/cost determinations for our Pavement Test Facility (PTF) experiments.
HVS-SA	The impact and management of the HVS fleet in South Africa (Ref., Horak 1992): In total the quantifiable benefits obtained from HVS testing expressed as an annual benefit that should continue year after year at about US \$17 million per year (exchange rate R 2,65/US\$ and 15% inflation rate). If the present total cost per year of running the HVS fleet of US \$1,358,490 is used, the benefit/cost ratio is 12.8 to 1. This is obviously only a rough guide, but clearly indicates the extent of the benefits possible from the application of HVS research technology.
ISETH	Reduction of layer thickness, reduction of time needed for research.
IUT2	The B/C ratio is expected in excess of 20:1. This ratio compares the cost of placement of a typical HMA pavement in the APT compared with the cost of field placement of the same mix.
KDOT	Savings/benefits not yet estimated. Continued financial support by pooled fund member states indicates that states are receiving some benefits from the facility.
LCPC	The cost of the LCPC carousel itself was practically written off in less than 5 years. We might even say that one experiment alone has been sufficient to recoup the cost of the facility. The inverted structure motorway section saved approximately \$100,000 per km compared with classical construction.
TxDOT	Although guesses can be made to obtain the B/C ratio, there are insufficient data to back them up.
MnRoad	Currently not calculated.
NCAT	Total cost of sponsor participation compared with sponsors' annual paving costs and anticipated improvements in the life of their pavements.
PRF-LA	B/C ratio analyses have not been conducted; field performance and life-cycle cost has not been varified. B/C ratio is expected to be high, based on cost estimation and expected life expectancy shown by APT.
RRT	Overall estimated savings and B/C ratio of APT programs not available.
ERDC-GSL	The ERDC-GSL airfield design criteria were developed with the help of APT (load carts). Rapid methods for military road construction were developed with APT.
WesTrack	Benefit/cost results for the WesTrack experiments have not yet been published.

Table D2. Significant APT findings related to pavement structural composition	
Oh-APLF	<ul style="list-style-type: none"> - Magnitude of vertical deformation during curling of PCC slabs. - Effect of curling/warping on dowel bar stresses.
ARRB	<ul style="list-style-type: none"> - Guidelines for the construction of pavements incorporating cemented layers (prevention of erosion and pumping of fines). - Guidelines for the use of geotextile-reinforced seals on expansive clay subgrades subject to periodic inundation, including traffic operations. - Guidelines for the most appropriate use of marginal materials (lateritic gravel, sandstone, etc.) in pavements. - Guidelines for the use of industrial by-products (blast furnace slag, fly ash, etc.) in pavements. - Guidelines for the rehabilitation of asphalt pavements using thin asphalt overlays incorporating modified binders. - Use of cemented and unbound subbases under plain concrete bases. - Use of granite set pavements under tourist bus and similar traffic.
CAL-APT	<ul style="list-style-type: none"> - Recommendation for use of "rich-bottom" design. - The results of the study support the current Caltrans practice of the 2 to 1 thickness equivalency of ARHM-GG to DGAC for overlays on fatigue-cracked asphalt pavements. - Stripping of and intrusion of fines into ATPB test results support recommendations resulting from ATPB laboratory test study pertaining to clogging and the use of modified binders such as asphalt rubber. - Shrinkage and environmental effects on the performance of FSHCC pavements at Palmdale, California. - Dowels and tie-bars were effective in restricting curling movements along transverse and longitudinal joints resulting from daily temperature changes. - Evaluate adequacy of structural design options for concrete pavements under consideration by Caltrans for LLPR strategies. - To minimize slab thickness, higher than current required flexural strengths and small coefficients of thermal expansion should be used. - For heavier truck traffic conditions, dowels should be used at transverse joints.
FAA	<ul style="list-style-type: none"> - New data for six-wheel gears on flexible pavements. - Current thickness requirement for stabilized base materials in flexible pavement found to be over-conservative.
FHWA-PTF	<ul style="list-style-type: none"> - The stiffness of the underlying asphalt layer affects the performance of ultra-thin whitetopping (UTW) overlays significantly. - That stiffness appears to be more important than the primary UTW variables studied (overlay thickness, joint spacing, and the addition of polypropylene fibers to the concrete).
HVS-Nordic	<ul style="list-style-type: none"> - In dry condition even a thin pavement structure could carry rather high wheel load (sand subgrade). - Pavement life (10-mm rut depth) in dry condition was 2.5 to 5 times longer compared with wet condition. - Most of the surface rutting before rehabilitation could be found as deformation of the sand subgrade, whereas after rehabilitation up to half of the surface rutting was due to deformation of the asphalt layers.

Table D2. (Continued)	
HVS-SA	<ul style="list-style-type: none"> – Effective use of granular layers as a structural component. – Development of the balance pavement concept. – Development of the “inverted” pavement structure. – Effective use of innovative materials (i.e., emulsion mixes, large aggregate mixes for bases, fly ash, and foamed asphalt). – Development of the South African Mechanistic Design Method. – Field-verified fatigue and rutting performance prediction. – Field verification of mechanistic approaches, and verification that the exponent “<i>n</i>” of the well-known equivalency formula $F = (P/80)^n$, is not constant. – TRH4—structural design manual and catalogue of designs (portland cement concrete, granular bases, cemented bases, etc.). – TRH12—rehabilitation design manual. – More cost-effective pavements.
IUT2	Please see list of publications provided at end of this survey.
KDOT	<ul style="list-style-type: none"> – PCCP with epoxy-coated (1 in.) steel dowels perform the same as PCCP with 1.5-in. fiber-reinforced polymer (FRP) dowels. – The performance of 127 mm (5 in.) of asphalt concrete on 127 mm (5 in.) of asphalt concrete millings with fine-grained subgrade is the same with that of a 203-mm (8-in.) layer of asphalt concrete on fine-grained silt-clay subgrade. As a result of these findings, NDOR established a structural number for RAP and made a design change that should realize up to a 20% cost savings. – The above structures should have the same performance even after rehabilitation. The rehabilitation consisted of milling 51 mm (2 in.) from the surface and replacing it with a 51-mm (2-in.) asphalt overlay.
LINTRACK	<ul style="list-style-type: none"> – For thin asphalt pavement structure on sand subbase/subgrade confirmation of classical models, such as decrease of asphalt stiffness modulus with increasing number of load repetitions, and Shell subgrade deformation design criterion. – For thin asphalt pavement not only structural fatigue cracking in asphalt, but also considerable amount of surface cracking. – From rutting performance tests on asphalt motorway structures, compared with dual tire 315/80: <ul style="list-style-type: none"> • Dual tire 295/60 gave about the same rutting; • Wide base tire 495/45 gave 1.1 to 1.6 times more rutting, dependent on pavement structure; • Wide base tire 385/65 gave 1.4 to 2.0 times more rutting, again dependent on pavement structure; • Actual rutting significantly greater than rutting calculated on basis of triaxial test results.
TxDOT	<ul style="list-style-type: none"> – Any rehab or overlay must be done atop a solid base or underlying structure. – Remixed pavements may be too stiff to prevent reflected cracking and stripping, a problem exacerbated by insufficient support as above. – Temperature is the most influential factor on rutting of AC layers.
MnRoad	<ul style="list-style-type: none"> – MnPAVE flexible pavement design (ME Design). – Spring load restrictions policy. – Winter overload policy (starting fall/winter of 2001/2002). – Developing a PCC ME Design (future plan after 2002 comes out)—We are participating in this. – Developing a whitetopping design method. – Participate in the AASHTO 2002 design guide with materials and performance data for both HMA and PCC. – Education of Minnesota city/county/state engineers in pavement design and management. This includes providing in-house experts to assist them in their work. – Web page: http://mnroad.dot.state.mn.us/research/Mnresearch.asp.

Table D2. (Continued)	
NCAT	<ul style="list-style-type: none"> – Possible establishment of a structural coefficient for SMA that is different from conventional mixes.
PRF-LA	<ul style="list-style-type: none"> – Thicker/weaker cement-treated base courses were proven to be as effective as thinner layers with higher cement contents (10% vs. 4%). – Stone interlayer or inverted pavements had five times the life of our conventional pavements.
RRT	<ul style="list-style-type: none"> – The APT studies have been included in the research program necessary to elaborate the Flexible Pavements Catalogue in Romania, 1977.
ERDC-GSL	<ul style="list-style-type: none"> – Design criteria for both flexible and rigid pavements. – Analysis techniques for predicting pavement response and performance. – Innovative materials for rapid road construction. – Improved nondestructive test methods.
ERDC	<ul style="list-style-type: none"> – Subgrade failure criterion is a function of soil type. – Geogrids have potential for reinforcement of base course layers over weak subgrade soils.

Table D3. Significant APT findings related to loading environment	
ARRB	<ul style="list-style-type: none"> – Axle load equivalencies for unbound pavement materials. – Relative pavement damaging effects of dual and wide-based single tires. – Influence of tire type and tire pressure on pavement response. – Demonstration of curling and warping behavior of plain concrete pavements with and without shoulders and with and without dowels.
CAPTIF	<ul style="list-style-type: none"> – Exclusion of moisture greatly increases pavement life when compared with the expected design life. – Suspension type changes the spatial location and severity of damage, but not the average levels of damage.
FAA	<ul style="list-style-type: none"> – Four-wheel gear versus six-wheel gear pavement performance and response data.
FDOT	<ul style="list-style-type: none"> – Both loading direction and wander, including the magnitude of wander increments, are important in simulating in-service rut performance.
FHWA-PTF	<ul style="list-style-type: none"> – Tire pressure was not nearly as important a factor in fatigue damage of hot-mix asphalt test sections as were load magnitude and pavement temperature. – Wide-based single tires (“super-singles”) generated significantly more damage in hot-mix asphalt test sections than dual tire pairs carrying the same load. This was true in terms of both fatigue cracking and rutting.
HVS-Nordic	<ul style="list-style-type: none"> – In dry conditions even a thin pavement structure could carry rather high wheel load (sand subgrade). – Pavement life (10-mm rut depth) in dry condition was 2.5 to 5 times longer compared with wet condition. – Most of the surface rutting before rehabilitation could be found as deformation of the sand subgrade, whereas after rehabilitation up to half of the surface rutting was due to deformation of the asphalt layers.
HVS-SA	<ul style="list-style-type: none"> – Quantification of nonuniform contact stresses. – Investigation into the dynamic effects of vehicle loading. – Quantification of the damaging effects of channelized traffic versus that of normal wander. – Quantification of the differences in bidirectional and unidirectional loading. – Mechanistic determination of equivalent damage factors for multiple load and axle configurations.

Table D3. (Continued)

LINTRACK	<ul style="list-style-type: none"> – From rutting performance tests on asphalt motorway structures, compared with dual tire 315/80: <ul style="list-style-type: none"> • Dual tire 295/60 gave about the same rutting; • Wide base tire 495/45 gave 1.1 to 1.6 times more rutting, dependent on pavement structure; • Wide base tire 385/65 gave 1.4 to 2.0 times more rutting, again dependent on pavement structure. – Actual rutting significantly greater than rutting calculated on basis of triaxial test results.
TxDOT	<ul style="list-style-type: none"> – AC temperature is not controlled under the MLS; it is only measured. It is one of the uncontrollable and confounding variables relating to the rutting performance under the MLS. The MLS may later go to a fixed or temperature-controlled facility to eliminate this problem. – Temperature is one of the most important factors that effects rutting observed on the MLS test sites. It was observed that the rate of the rutting decrease significantly during wintertime.
MnRoad	<ul style="list-style-type: none"> – Spring load restriction policy. – Winter overload policy. – Seasonal material properties defined for use in a ME design. – Seasonal pavement response (stress, strain, warp/curl, etc.). – Rutting (surface and base) related. – Top down cracking. – Thermal cracking effects based on loadings. – Base failures. – Superpave binder effects.
PRF-LA	<ul style="list-style-type: none"> – The duration of test (time-to-failure) was accelerated when loading was increased. Tests were started at deadweight of 4432 kg and additional plates each weighing 1045 kg were added for this purpose.
ERDC-GSL	<ul style="list-style-type: none"> – Typically, environment is controlled for the purpose of limiting the number of variables. However, moisture migration measurements have permitted refinement in 2-D FEM model predictions of same.
ERDC	<ul style="list-style-type: none"> – Reduction factors during thaw weakening developed from FWD tests not the same as from in situ stress/strain measurements.
WesTrack	<ul style="list-style-type: none"> – Driverless vehicle technology is far enough advanced to allow 24/7 operation of multi-truck loading on a closed test track with a single operator. The driverless vehicle operation at WesTrack provided safety advantages and was cost competitive with trucks driven by human drivers. The instrumentation, control, and monitoring systems required in a driverless system allows for a variety of additional experiments in areas such as truck dynamics, effect of vehicle wander on pavement performance, and vehicle operating costs. – An increase in pavement roughness increased fuel consumption of trucks applying load to WesTrack pavement sections. Under otherwise identical conditions, trucks used 4.5% less fuel per kilometer on smooth pavement than on rough pavement. – An increase in pavement roughness increased the frequency of fatigue failures of truck and trailer components during WesTrack loading.
Oh-APLF	<ul style="list-style-type: none"> – Polymer modifiers improve the stability of AC mixes.
ARRB	<ul style="list-style-type: none"> – Development of laboratory test methods for the characterization of asphalt and unbound materials. – Demonstration of the applicability of these tests to stabilized, recycled, and marginal materials.
CAL-APT	<ul style="list-style-type: none"> – Comparison of measured and predicted results demonstrate the validity of the fatigue analysis and design system developed during the SHRP program and refined within the CAL/APT program. – Preliminary results have demonstrated feasibility of this methodology to measure in situ water contents in untreated materials in the pavement sections.

Table D3. (Continued)

CAPTIF	<ul style="list-style-type: none"> – Small-scale field testing (in situ CBR, nuclear density, Loadman, etc.) very dependent on surface conditions beneath the instrument.
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Table D4. Significant APT findings related to materials and tests

FHWA–PTF	<ul style="list-style-type: none"> – For unmodified binders in surface mixes, the Superpave binder parameter, $G^*/\sin\delta$, correlates well with PTF Accelerated Load Facility (ALF) pavement rutting. Higher $G^*/\sin\delta$ values generally correspond to less rut depth under the ALF for a given number of loads. – For two modified binders (Styrelf and Novophalt), the same correlation did not hold. Although the $G^*/\sin\delta$ of the Styrelf binder after rolling thin film oven aging was higher than that of the Novophalt binder at each pavement test temperature, the pavement with Novophalt was always more resistant to rutting under the ALF.
HVS–SA	<ul style="list-style-type: none"> – Improved materials design: <ul style="list-style-type: none"> • TRH8—asphalt mix design manual, • TRH14 materials selection for roads, • Large-stone asphalt (new design method), • Modified binders in mixes, and • Treated bases (cement, lime, and emulsion treated). – Evaluation of innovative materials: <ul style="list-style-type: none"> • Drainage layers, • Roller-compacted concrete, • Geotextiles, • Block pavements, • Coarse power station generator ash as a road-building material, • Slag as a granular base material, • Bitumen–rubber asphalt mixture as an overlay material, • Emulsion treatment of recycled granular bases, • Waterbound macadam coarse aggregated bases, • Recycled asphalt base material, • Marginal natural aggregates with various additives, and • Styrene–butadiene–rubber (SBR) asphalt mixture in an overlay.
IUT2	<ul style="list-style-type: none"> – The findings are summarized in several research projects. – List of publications is provided at the end of this summary.
KDOT	<ul style="list-style-type: none"> – Superpave (SM-2C) mix performs better than a Marshall (BM-2C) mix when used as overlay mixes over a distressed PCCP, under radiant heat condition. The two AC mixes are the most used in Kansas. – Superpave mixture with optimum binder content performs better than those with optimum + 0.5%. – Fiber-reinforced concrete performs the same as the ordinary concrete when used in a nondoweled, nonreinforced PCC overlay on a highly distressed PCCP. – Superpave asphalt mix with reduced ratio of river sand (15%) has a much better rutting performance than the mixes with higher (20% and 30%) river sand ratio. – PCCP performed better on a drainable base than on a semi-drainable base.
LCPC	<ul style="list-style-type: none"> – Heat during fatigue test in lab with rest leads causes field tests to exhibit a shorter life.
TxDOT	<ul style="list-style-type: none"> – DCP tests correlate well to FWD back-calculated moduli. – The equation from Corps of Engineers provides good relationship between CBR and modulus. – Seismic tests also correlate well to FWD after adjustment for strain rate and temperature. – GPR is great for finding layer thickness, stripping, subsurface moisture. – FWD results depend highly on AC temperature; some correction equations were developed. – Bedrock depth equation was developed.

MnRoad	<ul style="list-style-type: none"> – Seasonal characteristics of materials for ME designs (surface, base, subgrade). – Field tests to support ME design in the field for users. – ASR testing of materials. – Seasonal loadings (spring and winter) policies. – HMA materials to work to eliminate thermal cracking. – Superpave binder effects on performance.
NCAT	<ul style="list-style-type: none"> – Relating laboratory performance to field performance, comparing field performance to binder grade and modifier type, relating aggregate properties to field performance, etc.
PRF-LA	<ul style="list-style-type: none"> – Variability of moisture contents in the foundation/embankment material influenced pavement support when deflection tests were conducted. – Localized failure caused separation of asphalt pavement layer. – In-place mixing of soil-cement and plant mixing had similar pavement performance.
ERDC-GSL	<ul style="list-style-type: none"> – APT was used during our development of DCP. – FWD on test sections provided data helpful for refining back-calculation algorithms. – Test sections were used during development of seismic analysis surface wave techniques.
WesTrack	<p>Premature rutting failures of test sections containing coarse-graded Superpave mixes at WesTrack led to a number of recommendations for such mixes:</p> <ul style="list-style-type: none"> – Design for any mix should be based on a 20-year design life, regardless of the actual expected life. – For high-volume roads, a laboratory performance test (wheel tracker or other) is necessary after the volumetric mix design is completed. – The upper end of the allowable range for the dust-to-binder ratio should be increased for coarse-graded mixtures. – Specifications include requirements on minimum values for the voids-in-mineral aggregate (VMA); for coarse aggregate mixes they should also have maximum value requirements (2% above the minimum value). – Results with the ignition oven for asphalt content determination emphasized the importance of careful calibration of the equipment, especially when the mix design includes hydrated lime as an anti-stripping additive.

Oh-APLF	<ul style="list-style-type: none"> – Validation of curling/warping models.
ARRB	<ul style="list-style-type: none"> – CIRCLY. – EFROMD2 (back-calculation). – STRAND2. – Various generic rutting models.
CAL-APT	<ul style="list-style-type: none"> – The subgrade strain criteria used by the Asphalt Institute can be used by Caltrans as a part of a mechanistic-empirical design procedure. – Evaluate adequacy of structural design options for concrete pavements under consideration by Caltrans for LLPR strategies. – To minimize slab thickness, higher than current required flexural strengths and small coefficients of thermal expansion should be used. – For heavier truck traffic conditions, dowels should be used at transverse joints.
DRTM	<ul style="list-style-type: none"> – Plastic strain at top of subgrade and functional condition index are related to number of load repetitions and dynamic vertical stress and strain at top of subgrade: $mep = A \cdot N^a \cdot (s/p)^b \cdot m^g$ – e.g., $A = 0.087$, $a = 0.33$, $b = 0.333$, $g = 1$, $p = 0.1$ MPa – IRI (or rutting) = $A \cdot (N/106)^a \cdot (s/p)^b \cdot (m e/1000)^g$ – For IRI (m/km) $A = 0.87$, $a = 0.333$, $b = 0.333$, $g = 1$, $p = 0.1$ MPa – For rutting (mm) $A = 5.54$, $a = 0.333$, $b = 0.333$, $g = 1$, $p = 0.1$ MPa

Table D5a. (Continued)

FHWA-PTF	<ul style="list-style-type: none"> - Calibrating mechanistic flexible pavement rutting models (VESYS-5) from full-scale accelerated pavement tests. - Calibrating response/load capacity models for ultra-thin whitetopping from accelerated tests.
HVS-SA	<ul style="list-style-type: none"> - The development of the South African Mechanistic Design Method <ul style="list-style-type: none"> • Mechanistic Empirical Modeling of the Permanent Deformation of Unbound Pavement Layers. • Elasto-Plastic Modeling of Granular Layers.
TxDOT	<ul style="list-style-type: none"> - MLS has been run over pressure cells and strain gauges to find actual pressures and strains within pavement. No models obtained, as cells and gauges unreliable. - Back-calculation of layer moduli done regularly using both surface deflections measured by an FWD and at-depth deflections measured by Multi-Depth Deflectometers (MDDs). - MDD deflections used to refine the back-calculation through an iterative elastic layer analysis. - MDDs also used to measure motion of underlying bedrock. - MDDs invaluable for deformation modeling, as they can measure permanent deformation of each layer, eliminating uncertainties about each layer's contribution to overall (surface) rutting. - Field measured layer rutting match well with VESYS model.
MnRoad	See web page: http://mnroad.dot.state.mn.us/research/MnROAD_Project/products90.asp .
NCAT	- Pending.
RRT	<ul style="list-style-type: none"> - APT studies have been included in the research program for the design methods (calculation and dimensioning) of flexible and semi-rigid pavements based on the allowable elastic deflection, 1968. - APT studies have been included in the program for elaboration of the design method for reinforcement of existent flexible and semi-rigid pavements, 1971.
ERDC-GSL	<ul style="list-style-type: none"> - Layered elastic is now a standard design procedure. - FEM is several years away from implementation.
ERDC	- In progress.
WesTrack	<ul style="list-style-type: none"> - Empirical and mechanistic-empirical models developed for predicting rutting and fatigue cracking from traffic and materials (percent asphalt content, percent air voids, and gradation). - Models are suitable for inclusion in a system of performance-related specifications for hot-mix asphalt (HMA) and for generating pay factors for HMA construction based on relationship between materials and construction property test results and subsequent pavement performance.

Table D5b. Significant APT findings relating to modeling

ARRB	<ul style="list-style-type: none"> - The cost and effort associated with pavement instrumentation is often not worth it. - Demonstration of the use of Time Domain Reflectometry (TDR) gauges to monitor moisture movement and to measure moisture content. - Back-calculation is a useful tool; however, it must be used widely and can be difficult to manage, particularly with respect to unbound, stress-dependent, materials and thin asphalt surfacing layers. - Roughness data useful in developing maintenance intervention strategies.
CAPTIF	- Measured stresses and strains under thin surfaced unbound granular pavements are 2 to 3 times higher than values predicted by elastic theory.

Table D5b. (Continued)

CAL-APT	<ul style="list-style-type: none"> – Use fatigue analysis/design system (calibrated with HVS tests) to evaluate effects of <i>binder loss modulus</i>, $G^*\sin\delta$, on pavement performance in fatigue lead to a recommendation that $G^*\sin\delta$ be eliminated from PG specification for binders. – Development of CalCool, computer software for determining pavement temperatures during AC placement, a program that determines the temperature profile for multilift AC paving operations. Inputs include AC lifts (up to 9), mix and underlying mat characteristics, and environment characteristics; e.g., ambient temperature, wind speed, etc.
DRTM	<ul style="list-style-type: none"> – For the strains at the bottom of the asphalt, reasonably good agreement was mostly found with Layered Elastic Theory with linear elastic materials. – The method where any layer may be nonlinear elastic, although some comparisons gave very large differences. For the strains at the subgrade top, the assumption of linear elastic materials gave very poor agreement. A reasonably good agreement could be obtained with a nonlinear elastic subgrade. In most cases the best agreement (and the most reasonable values for layer moduli) was found using the Method of Equivalent Thicknesses.
FAA	<ul style="list-style-type: none"> – Developing failure models for thickness design procedures. – Asphalt strain response as a function of travel speed for heavy aircraft loading.
HVS-SA	<ul style="list-style-type: none"> – Development of the South African Mechanistic Design Method. – Development of the Elasto-Plastic Modeling of Granular Layers. – Development of the Mechanistic Empirical Modeling of the Permanent Deformation of Unbound Pavement Layers.
LINTRACK	– See Table D2.
TxDOT	– See Table D5a.
NCAT	– Pending.
PRF-LA	– VESYS 3A-M and flexpass can be used to model and predict the performance of the pavements consisting of HMA wearing course over crushed stone base. These included prediction of rutting and PSI of test lanes.
ERDC-GSL	– Recently developed a granular model for FEM that accumulates permanent deformation—now extending the capability of the theory (“multi-mechanical model”) for asphalt concrete and soil.
ERDC	– Subgrade failure criteria as a function of soil type and moisture content.

Table D6a. Significant APT findings related to construction

ARRB	<ul style="list-style-type: none"> – Development of maintenance intervention strategies for unbound granular pavements with thin bituminous surfacings. – Guidelines for the construction of pavements incorporating cemented layers (prevention of erosion and pumping of fines). – Guidelines for the use of geotextile-reinforced seals on expansive clay subgrades subject to periodic inundation, including traffic operations. – Guidelines for the most appropriate use of marginal materials (lateritic gravel, sandstone, etc.) in pavements. – Guidelines for the use of industrial by-products (blast furnace slag, fly ash, etc.) in pavements.
CAL-APT	<ul style="list-style-type: none"> – Importance of mix compaction conclusively demonstrated. – Recommendation for “tightening” Caltrans compaction requirements. – The lack of bond between compacted lifts of asphalt concrete observed in the HVS tests suggests reexamination by Caltrans of the use of a tack coat between lifts to improve the bond. – Dry density and degree of saturation have significant impact on stiffness, strength, and permanent deformation resistance. – Recommendation that Caltrans change the method of compaction control for untreated granular materials from current procedure to Modified AASHTO Test (T-180).
HVS-SA	<ul style="list-style-type: none"> – The design and construction of emulsion-treated bases. – The design and construction of large aggregate mixes for bases. – The design and construction of porous asphalt wearing courses. – The importance of granular layer compaction. – The effective use of cemented layers.

Table D6a. (Continued)

KDOT	– Above the forbidden zone (fine, low permeability) Superpave mixes have adequate rutting resistance to be used in pavements on moderate-to-low traffic roadways.
MnROAD	– Whitetopping procedures. – Large stone base construction.
NCAT	– Impact of varying asphalt content on life-cycle costs.
PRF-LA	– Two most-APT-proven-effective construction techniques, the construction of the weaker and thicker cement-treated base layers, were used in construction of several experimental and full-scale field projects.
ERDC-GSL	– Density requirements for asphalt concrete and granular layers. – Airfield base course proof-rolling techniques and equipment requirements.
WesTrack	– Combined full-scale testing and performance monitoring on pavement sections at WesTrack with a comprehensive laboratory testing program of component materials and analysis of pavement response to develop a performance-related specification with realistic pay factors for hot-mix asphalt.
ARRB	– Guidelines for the most appropriate rehabilitation treatments for asphalt pavements. – Use of in situ stabilization using bitumen/cement and slag/lime blends.

Table D6b. APT findings related to rehabilitation

HVS-SA	– Deep in situ recycling using emulsion- or foam-treated bases. – The effective use of pothole fillers. – Structural evaluation and determination of optimum rehabilitation options. – Evaluation of AC hot-mix and bitumen-rubber overlay.
KDOT	– Pavements constructed partial depth with RAP can perform as well as new full-depth new mixes.
TxDOT	– Same as APT findings related to pavement structural composition. – Closer attention needs to be paid to the effective gradation and binder viscosity of remixed pavements. Since the operation reuses old asphalt and mills (crushes) the original aggregate, the final product tends to have a too-fine gradation and overly stiff binder, which makes it prone to cracking. – The recycled content should be lowered and the new materials should use a lower asphalt grade. – The remixer provides excellent rut resistance, but does poorly on stopping reflected cracking. The remixer should be placed on where there are rutting problems.
MnRoad	– Micro-surfacing. – Sealing effects on moisture movement in base layer and edge drains from rainfall. – Whitetopping rehabilitation procedures.
PRF-LA	– Some of the thicker and weaker cement-treated base layers were implemented in rehabilitation jobs.
ERDC-GSL	– Bomb crater damage repair techniques.
WesTrack	– Two repair procedures used at WesTrack have potential for in-service pavements. – The procedure for rutting involved milling the rutted areas and replacing the milled-out sections with a rut-resistant mix. – The other, to repair sections with extensive fatigue cracking, used a patching procedure referred to as a “T-patch.”

APPENDIX E

Characteristics of Accelerated Pavement Testing Facilities Established Since 1996

E1 CHARACTERISTICS OF CRREL HVS MK IV FACILITY

ENTITY ACRONYM	ERDC
FACILITY ACRONYM	CRREL HVS Mk IV
LOCATION	U.S. Army Corps of Engineers Cold Regions 72 Lyme Road, Hanover, N.H.
Commissioned	1997
Costs	>\$5 million (costs includes facility)
PAVEMENT CONFIGURATION	
Size of test area	12 test cells each 6.4 m wide - 8 cells are 7.6 m long and 2.4 m deep - 4 cells are 11.4 m long and 3.7 m deep
Size of test section	6.1 m long × 1.5 m wide
Wheel path width	1.5 m with lateral wander ±900 mm in 50 mm increments
Testing length	6.1 m
TRAFFICKING DETAILS	
Loading device	Tractor drawn structure: 30 m × 4.9 m × 4.3 m (length × width × height) indoors in 2508 m ² building
Wheel configuration	Single, dual, or aircraft
Wheel load	20 kN to 100 kN on super singles or duals/up to 200 kN on C141 tires
Wheel suspension	Airbag
Wheel velocity	13 km/h
Wheel passes	700/h unidirectional
Load propulsion	Cable
Power	Single electric motor
Housing	Mobile unit in a 2700 m ² environmentally controlled building
ENVIRONMENTAL CONTROL	Air temperature, pavement temperature, and subgrade moisture (water table) controlled drainage, freeze/thaw (6 cycles/year). See Appendix F
Instrumentation	Strain gauges, pressure cells, displacement gauges, subgrade moisture sensors, temperature sensors, soil suction



E2 CHARACTERISTICS OF HVS-A (BIGFOOT) FACILITY

ENTITY ACRONYM	ERDC-GSL
FACILITY ACRONYM	HVS-A (Bigfoot)
LOCATION	U.S. Army Corps of Engineers Research and Development Center 3909 Halls Ferry Road (attn: GM-A) Vicksburg, MS 39180-6199
Commissioned	1998
Costs	~\$3 million
PAVEMENT CONFIGURATION	
Size of test area	76 m × 24 m
Size of test section	23 m × 3 m
Wheel path width	1.5 m, including lateral wander
Testing length	12.2 m
TRAFFICKING DETAILS	
Loading device	Tractor-drawn structure housed indoors: 36.6 m × 4.9 m × 4.3 m (length × width × height)
Wheel configuration	Single, dual-wheel, and single-twin aircraft
Wheel load	45–445 kN
Wheel suspension	The test wheel carriage uses its own independent hydraulic system, which generates and regulates the load that is applied to the test surface
Wheel velocity	13 km/h
Wheel passes	10,000/day—bidirectional
Load propulsion	Chain—unidirectional and bidirectional
Power	480 volt 3-phase power or the onboard 228 kW <i>Caterpillar</i> generator that produces 240/480 volts
Housing	60 Hz at 1,800 rpm Operated in a open-ended hangar: 116 m × 46 m (approximately 5,300 m ²)
ENVIRONMENTAL CONTROL	See Appendix F



E3 CHARACTERISTICS OF NAPTF FACILITY

ENTITY ACRONYM	FAA
FACILITY ACRONYM	NAPTF
LOCATION	William J. Hughes Technical Center, Atlantic City, N.J.
Commissioned	1999
Costs	\$21 million
PAVEMENT CONFIGURATION	
Size of test area	274.3 m x 18.3 m
Size of test section	Variable depending on the test plan. Typically 9 to 12 independent sections, each 12 to 30 m long
Wheel path width	13.5-m width of pavement can be loaded. Typical test plan has two wheel paths 3.6 m wide and 9 m apart. Aircraft wander can be simulated
Testing length	274.3 m
TRAFFICKING DETAIL	
Loading device	Gantry structure supported on rails 23.2 m apart
Wheel configuration	Two complete landing gears with one to six wheels per undercarriage—adjustable 6.1 m forward and sideways
Wheel load	Maximum 334 kN/wheel
Wheel suspension	Rail-based with rubber springs
Wheel velocity	0.1–24 km/h. Typical test speed is 4 km/h
Wheel passes	Number of repetitions 15/h to 40/h at a specific location. Depends on test plan
Load propulsion	Variable frequency electric drives
Power	Active hydraulic servo-system
Housing	Located in-house in a building 365 m long, 30.5 m wide, 12 m high
ENVIRONMENTAL CONTROL	Building environmentally controlled
Instrumentation	Heavy-Weight Deflectometer (HWD), comprehensive instrumentation system, strain gauges, pressure cells, displacement gauges, temperature and subgrade moisture sensors
Instrumentation	Typically kept simple. The following are monitored at various depths: moisture, temperature, vertical stress, vertical deflection. Horizontal strain has also been monitored at the bottom of HMA



E4 CHARACTERISTICS OF FDOT—APTF—HVS FACILITY

ENTITY ACRONYM	FDOT
FACILITY ACRONYM	FDOT-APTF-HVS
LOCATION	Florida Department of Transportation, 5007 NE 39th Avenue, Gainesville, FL
APT Devices	HVS-Mk IV
Commissioned	1999
Costs	\$2–5 million
PAVEMENT CONFIGURATION	
Size of test area	45 m × 3.6 m (10 test sections)
Size of test section	6 m × 1.6 m
Wheel path width	1070 mm with lateral wander 0 to 760 mm
Testing length	6 m
TRAFFICKING DETAILS	
Loading device	Tractor drawn structure: 30 m × 4.9 m × 4.3 m (length × width × height)
Wheel configuration	Super single and dual tire
Wheel load	32 kN–205 kN, mass of device 50 tons
Wheel suspension	Fixed load hydraulically applied
Wheel velocity	13 km/h
Wheel passes	29,000 bidirectional and 14,000 unidirectional/24 h
Load propulsion	Chain
Power	Electrical (external power or on-board diesel generator)
Housing	Mobile vehicular unit: 30 m × 4.9 m × 4.3 m (length × width × height)
ENVIRONMENTAL CONTROL	Heating using a detachable insulation chamber. See Appendix F
Instrumentation	As needed
Ancillary Equipment	Automated laser profilometer



E5 CHARACTERISTICS OF ATLAS FACILITY

ENTITY ACRONYM	JUT2
FACILITY ACRONYM	ATLaS
LOCATION	Advanced Transportation Research & Engineering Laboratory University of Illinois 205 N. Mathews MC-250 Urbana, IL 61801
Commissioned	2002
Costs	\$2 million including site development
PAVEMENT CONFIGURATION	
Size of test area	168 m × 81 m
Size of test section	26 m × [wheel carriage width + 1.8 m]
Wheel path width	Bogie ± 900 mm
Testing length	26 m with constant speed over central 19.8 m
Mobile shed size	42 m × 15.2 m × 7.3 m
TRAFFICKING DETAILS	
Loading device	Tractor drawn mobile structure: 26 × 3.7 × 3.7 m. Load applied by means of a hydraulic ram attached to the wheel carriage capable of accommodating a single truck wheel, a dual-truck wheel, an aircraft wheel or a single axle rail bogie
Wheel configuration	Single-tire/dual-tire/aircraft- tire/single-axle rail bogie
Wheel load	0–358 kN can be varied by computer control while traveling, uni- or bidirectional, velocity variable over length of test section but constant over central 20 m of test section
Wheel suspension	Hydraulic
Wheel velocity	16 km/h
Wheel passes	10,000/24 h (bidirectional)
Load propulsion	Cable and winch motor assembly
Power	Electrical
Housing	Operated within a movable structure enclosing the unit with allowance for maneuvering inside
ENVIRONMENTAL CONTROL	
Instrumentation	See Appendix F As need arises



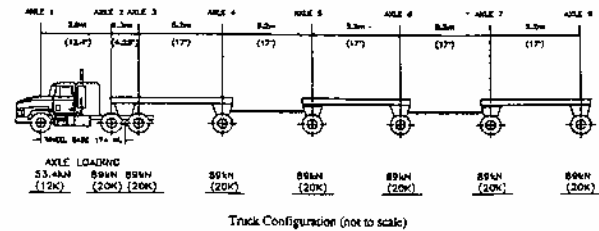
E6 CHARACTERISTICS OF K-ATL HVS FACILITY

ENTITY ACRONYM	KSU-CISL
FACILITY ACRONYM	K-ATL
LOCATION	Kansas State University Civil Engineering Infrastructure Laboratory 2112 Fiedler Hall, Manhattan, KS
Commissioned	1997
Costs	<\$1 million
PAVEMENT CONFIGURATION	
Size of test area	418 m ²
Size of test section	Two test pits both 1.8 m deep: one is 9.7 m long × 1.8 m wide, the other is 6.1 m long × 1.8 m wide; the later is used for environmental control testing
Wheel path width	Dependent on selected tire configuration. No wander capability
Testing length	9.75 m and 6.1 m, respectively
TRAFFICKING DETAILS	
Loading device	Regular tandem axle truck bogie loaded by pushing against a reaction frame suspended along the test section. Loading can also be applied to one tandem axle to simulate a single axle
Wheel configuration	Dual tandem (4–8 wheels) and single axle (2–4 wheels)
Wheel load	Adjustable with a maximum of 178 kN for the whole bogie assembly
Wheel suspension	Air bags
Wheel velocity	11 km/h constant over central 5 m of test section
Wheel passes	313 cycles/h unidirectional 626 cycles/h bidirectional
Load propulsion	A wide, flat conveyor belt driven by a 15-kW variable-speed electric motor with an energy absorption/release system at each end
Power	Electrical (480 V, 3-phase)
Housing	Located in-house in a building: 537 m ²
ENVIRONMENTAL CONTROL	
	Air temperature, pavement temperature, and subgrade moisture by means of water sprinklers consisting of three soaker hoses buried at three positions in the pavement structure. Also see Appendix F
Instrumentation	Strain gauges, pressure cells, displacement gauges, subgrade moisture sensors



E7 CHARACTERISTICS OF NCAT FACILITY

ENTITY ACRONYM	NCAT
FACILITY ACRONYM	NCAT
LOCATION	NCAT Pavement Test Track 1600 Lee Road 151, Opelika, AL
Commissioned	1996
Costs	\$15 million including site development
PAVEMENT CONFIGURATION	
Size of test area	46 test sections, each 3.4 m × 61 m lanes in the outer lane of the test track
Size of test section	Two tangent sections each of 1.2 km linked through curved sections at both ends
Wheel path width	Trucks wander in the wheelpath within a range of 1.2–1.3 m
Testing length	2700 m oval track
TRAFFICKING DETAILS	
Loading device	Four conventional truck tractor-trailer vehicle trains
Wheel configuration	Triple-trailer and tractor (front axle plus tandem axle plus five single axles)
Wheel load	53.4 kN + 623 kN (89 × 7) = 676.4 kN per vehicle train unit. Taken to be equivalent to 10.4 ESALs per vehicle train
Wheel suspension	Steel spring
Wheel velocity	76 km/h
Wheel passes	28 axle trains/h of trafficking
Load propulsion	Driven and towed axles (tractor/trailer assembly)
Power	Truck engine
Housing	None
ENVIRONMENTAL CONTROL	
Instrumentation	None but air temperature, pavement temperature, rainfall, relative humidity monitored continuously. Also see Appendix F
	Subgrade moisture sensors. Other measurements include FWD, 3-point laser profilometer, Australian automated dipstick, and ARAN



E8 CHARACTERISTICS OF APLF FACILITY

ENTITY ACRONYM	ORITE
FACILITY ACRONYM	APLF
LOCATION	1570 Granville Pike Ohio University—Lancaster Branch Lancaster, OH 43130
Commissioned	1997
Costs	\$1.35 million
PAVEMENT CONFIGURATION	
Size of test area	13.7 m long × 11.6 m wide × 2.4 m deep
Size of test section	13.7 m long × 1.8 m wide × 2.4 m deep (5 off-max) 13.7 m long × 3.7 m wide × 2.4 m deep (2 off-normal)
Wheel path width	350 mm ± 254 mm or 535 mm ± 254 mm incl. wander
Testing length	10.7 m
TRAFFICKING DETAILS	
Loading device	Rolling wheel load mechanism pushing against reaction steel girders, spanning along the length of the test pit
Wheel configuration	Single wide-base or dual
Wheel load	22 kN–134 kN
Wheel suspension	Hydraulic
Wheel velocity	2–8 km/h
Wheel passes	250/h for unidirectional and 500 for bidirectional
Load propulsion	Cable driven
Power	Electric motor
Housing	Inside specially constructed building: 24 m long × 11.6 m wide × 5.4 m high
ENVIRONMENTAL CONTROL	
Instrumentation	Humidity—0–100%. Moisture can be added to the subgrade on the floor of the test pit. Also see Appendix F. TMW transducers, Dynatest gauges, Carlson gauges, pressure cells, linear variable differential transformers, resistivity, time domain reflectometer, thermistor, and thermal conductivity probes



E9 CHARACTERISTICS OF HVS-Nordic FACILITY

ENTITY ACRONYM	VTT, Finnra, and VTI
FACILITY ACRONYM	HVS-Nordic
LOCATION	VTI 58195 Linköping
Commissioned	1997
Costs	\$2–5 million
PAVEMENT CONFIGURATION	
Size of test area	36 m long × 4 m wide × 2.5 m deep. Test pit narrows to 3 m width at bottom
Size of test section	2 test pits: one concrete with thermal insulation and water table control and one excavated in rock with no cladding or control of water table. Two or three test sections are possible in a pit
Wheel path width	1070 mm with lateral wander 0 to 760 mm
Testing length	36 m × 4/3
TRAFFICKING DETAILS	
Loading device	Tractor drawn structure: 30 m × 4.9 m × 4.3 m (length × width × height)
Wheel configuration	Dual/single with standard/wide-based tires
Wheel load	20 kN–110 kN (linear) Can vary dynamically(±20%) sinusoidly
Wheel suspension	Fixed load hydraulically applied
Wheel velocity	15 km/h
Wheel passes	25,000 per day including maintenance time
Load propulsion	Chain
Power	Diesel/electrical
Housing	A test can be used to cover the test section to reduce environmental impact
ENVIRONMENTAL CONTROL	
Instrumentation	Heating and cooling using a detachable insulation chamber with controlled air/pavement temperature and subgrade moisture. Also see Appendix F. Strain gauges in asphalt layers, temperature sensors, suction sensors. Pore water pressure, moisture content, frost depth, and density is also measured.



APPENDIX F

Accelerated Pavement Testing Systems with Artificial Cooling and/or Heating Control Units

Entity/APT Acronym	Capacity to Cool	Capacity to Heat	Capacity to Control Chamber Temperature	Range of temperature	Capacity to Control Pavement Temperature	Range of Temperature
ARRB ALF	No	Yes	n/a	n/a	Yes	Ambient up to 60°C
CAL/APT HVS Richmond	Yes	Yes	Yes	Not monitored since heating and cooling is controlled by thermocouples in the pavement. In general, must run hotter than pavement at hot temperatures, colder than pavement at cold temperatures.	Yes	Surface Temperatures: To date facility has operated at 10°C (very short time); 20°C most of the time; 55°C for several months at a time.
CAL/APT HVS Palmdale	Yes	Yes	Yes	The HVS maintained 20°C (with a small variation), despite large variations in external air temperatures.	Yes	Mostly operated at 20°C, or without temperature control on concrete. Temperature controlled slabs are influenced by adjacent slabs not temperature controlled. Accordingly, it is being used less often on concrete.
DRTM Denmark	Yes	Yes	Yes, building enclosure with air conditioning units.	-10°C to +40°C	Yes	-4°C at subgrade level after 2 months. Temperature then raised to 25°C in stages for testing after thawing.
ERDC-CRREL HVS Mk IV	Yes	Yes, building enclosure only. No infra-red heaters attached to the HVS.	Yes, building enclosure only.	-3.9°C to 24°C ($\pm 2^\circ\text{C}$)	Yes, surface panels used to freeze/heat. Brine at -37°C is used to freeze pavement to given depth. Frosting 25 mm per 24 h is feasible. When frost penetration depth is reached, panels are removed and APT is done during thawing.	-37°C to +49°C
ERDC-GSL HVS-A (Bigfoot)	Yes	Yes	Yes, the compartment under the HVS	4°C to 38°C	Yes, limited, depending upon environmental conditions.	Asphalt temperature of 25°C has been maintained year round.
FAA NAPTF	No	No	Yes, building enclosure only.	-1°C to 35°C	Not controlled, but measured.	2°C to 27°C

Entity/APT Acronym	Capacity to Cool	Capacity to Heat	Capacity to Control Chamber Temperature	Range of Temperature	Capacity to Control Permanent Temperature	Range of Temperature
FDOT HVS Mk IV	No	Yes	Yes, using air conditioning with a detachable insulation chamber.	Ambient to 70°C	Yes	Ambient to 70°C (six heating zones independently controlled using resistance-type radiant heaters).
FHWA PTF ALF 1	No	Yes	n/a	n/a	Yes	Tests have been conducted between ambient (10°C) and 76°C at mid-depth of the pavement. Upper limit is higher.
FHWA PTF ALF 2	No	Yes	n/a	n/a	Yes	10°C–76°C
KSU–CISL K–ATL	Yes	Yes	No	–20°C to +60°C	Not to a very exact value	–10°C to +45°C
LCPC France	No	Yes	n/a	n/a	Yes	Approximately 10°C above ambient temperature.
ORITE OHIO APLF	Yes	Yes	Yes	–12°C to 54°C	Yes, through air temperature	–12°C to 54°C
SA–Gautrans/CSIR HVS Mk III	Yes	Yes	Yes	–26°C air temperature in chamber –5°C pavement temperature	Yes	–5 to 40°C. 50°C maximum pavement temperature is achievable, possibly even higher.
SA–Gautrans/CSIR HVS Mk VI+	Yes	Yes	Yes	–26°C air temperature in chamber –5°C pavement temperature	Yes	–5 to 40°C. 50°C maximum pavement temperature is achievable, possibly even higher.

Entity/APT Acronym	Capacity to Cool	Capacity to Heat	Capacity to Control Chamber Temperature	Range of Temperature	Capacity to Control Permanent Temperature	Range of Temperature
TRL PTF	No	Yes	No	Up to about 25°C above ambient	Pavement temperature can be controlled by feedback from sensors in pavement	Ambient to 45°C
TUDelft–DWW/LINTRACK	No	Yes	Surrounded by a mobile chamber used to insulate the machine. Heat accomplished by radiant heaters.	n/a	Yes	30–35°C above ambient temperature (depending on wind); until now maximum applied temperature was 40°C at pavement surface.
University of Illinois/IUT2 ATLaS	Yes	Yes	No, but environmental cover used to protect the machine.	n/a	No	n/a
VTT, Finnra and VTI HVS–Nordic	Yes	Yes	Yes, using airconditioning with a detachable insulation chamber	–5°C to +30°C	Not controlled but measured	

APPENDIX G

Summary of Accelerated Pavement Testing Objectives and Applications

Table G1 Structural Design Applications (refer to chapter two)		
Acronym/Location	Objectives	Applications
ALF Australia	Proof trial ALF. Evaluate macadam base.	Structural adequacy of Somersby pavement confirmed. ALF confirmed as reliable and effective.
	Compare <i>thin</i> (200 mm) and <i>standard</i> (300 mm) cement-treated base (CTB).	Failure mode was debonding of CTB layers, ingress of water at interfaces, and subsequent erosion of bottom of upper layer, leading to break-up of top CTB layer.
	Compare pavements with and without a bitumen heavy-cure coat interlayer and constructed in one lift instead of two or three lifts.	Failure mechanism of adjacent National highway found to be the same. Major changes to construction practice implemented.
	Determine the relative fatigue characteristics of various types of asphalt rehabilitations including geotextiles, modified asphalt, and high asphalt content mixes in the “tensile” zone applied to a distressed pavement.	Overlay trials demonstrated improved performance, for a modified binder compared with conventional binder; a significant impact on treatment for urban rehabilitation. SAMI successfully delayed crack propagation.
CAPTIF New Zealand	Inaugural testing: four thicknesses of unbound granular pavements under chip seals.	Proving trials and assessment of traditional pavements.
	Lime-stabilized subbases: three thicknesses.	An experiment with lime-stabilized subbase course showed that an increase in thickness from 150 to 250 mm would increase life by 15 times (Pidwerbesky 1995a).
	Life-cycle performance of a thin-surfaced unbound granular pavement.	Assessment of traditional pavement configuration.
FHWA–PTF USA	To evaluate accuracy of AASHTO designs used.	Good agreement was reached on one section; the second section failed prematurely by cracking.
HVS South Africa	Reduction of pavement cost by improved designs.	New designs incorporated in the catalogue resulting in construction cost savings.
ISETH Switzerland	Comparison of pavement configurations.	Effective ranking procedure developed.
	Evaluation of design procedure.	Existing practice shown to be conservative.
LCPC France	Performance of doweled concrete pavements and different cements.	Revision of design procedure.
	Trafficking of three thick structures (up to 200 mm) of bitumen-treated materials.	Adjustment of the circular test track.
	Evaluation of four structures: CTM/CTM, CTM/CTM, BTM/CTM, and CTM/UTM.	Heavily traveled pavements with road bases treated with hydraulic binders.
	Comparison of bitumen-treated materials on WRM and cement-treated sand subbases.	Demonstration of separating layer of WRM to reduce reflective cracking.
	Two very thin rolled asphalt overlays assessed.	For maintenance motorway pavements.

Table G1 (Continued)

RIOH-ALF China	Reduce pavement costs by using stabilized bases and thin asphalt surfacing.	A 90–150-mm asphalt layer over a stabilized base was equivalent to 200-mm full-depth asphalt.
	Compare the performance of 10 different asphalt pavement configurations.	New asphalt pavement structures were recommended for the national specifications.
TRL United Kingdom	Forest road design.	Pavement design methods for specialized log traffic developed.

Table G2 Vehicle–Pavement–Environment Interaction (refer to chapter three)		
Acronym/Location	Objectives	Applications
ALF Australia	To determine the axle load equivalency for a typical crushed-rock pavement, 300 mm thick, subjected to accelerated loading under ALF single-axle dual-wheel loads of 40, 60, and 80 kN.	Load equivalency factors of 10 and 8, respectively, were estimated for a maximum surface deformation of 10 mm.
	Compare the performance of crushed-rock pavements, constructed at different moisture/compaction conditions at sealing and after drying-back and wetting-up after sealing.	At Beerburrum the low-plasticity, highly permeable crushed-rock bases, when placed on a CTSB having a 3% cross-fall, quickly dried back in the dry environment operating at that time.
CAPTIF New Zealand	Comparative rutting: dual and wide-base single tires.	Tire studies, which compared single low-profile, wide-based, radial ply to standard dual tires, and showed 92% greater rutting for the singles.
	Strain response of subgrades and unbound granular pavements: wheel load, tire pressure, and tire type.	Development of subgrade strain criteria for design.
	Dynamic wheel loads and pavement wear: single-unit and multi-leaf spring suspensions.	Vehicle–pavement interaction studies.
	DIVINE project; air bag and multi-leaf suspensions.	Vehicle–pavement interaction studies.
EPFLa Switzerland	Evaluation of frost protection design.	Existing practice shown to be conservative.
	Evaluation of drainage layer.	Shown to be very effective in freeze/thaw environments.
	Effects of temperature and loading pattern.	Dependence of rutting on temperature and transverse distribution of wheel path shown.
FHWA-PTF USA	To assess the impact of tire pressure on pavement response and performance.	Tire pressure effects shown to be less significant than load and temperature on flexible pavement response and performance.
HVS South Africa	Characterization of tire/pavement interface stresses.	As part of the HVS program it was possible to develop a 3-D load cell. This provided a means of accurately characterizing and modeling the tire/pavement interface.
	Improved understanding of response and performance.	Improved load equivalency factors.

Table G2 (Continued)

LCPC France	Comparison of the effects of 13-t and 10-t axles and of an 80 mm against two successive 40 mm overlays.	To design of WRM and CTM road bases and overlay practice.
	To compare: design methods and performance models; tandem axles versus standardized European axle.	Working group 14 of the OECD tested two flexible and one semi-rigid pavement.
	Observation of rutting behavior of bituminous concrete.	Evaluation of high-performance mixes, influence of speed-temperature and wheel load effects.
PTI USA	Determine structural damage of tri-axles.	Approximate load equivalency factor of 2.6 established, varying with load and pavement configuration.
	Evaluation of free draining base course.	Shown to be compaction-sensitive and best used deep in a pavement.
	Structural coefficient of surface mixes.	New materials and mixes performed in a similar manner to existing materials.
RIOH-ALF China	Determine the failure mechanism investigation of axle-load equivalencies for this type of pavement.	Surface seal maintenance was important to prevent water entering cracks and precipitating failure.
	Determine the relative damaging effects of different axle loads in terms of structural failure and surface rutting.	The current equivalent "exponent" was increased.
TRL United Kingdom	Single versus dual tire damage evaluation.	Single tires cause twice the damage on the thick pavements typical of the UK and Europe.

Table G3 Materials and Tests (refer to chapter four)		
Acronym/Location	Objectives	Applications
ALF Australia	Validate ERDC-GSL-WES tentative classification for lateritic gravel for road and airfield pavements.	Performance of both materials constructed to both compaction standards was excellent when tested soon after construction. When the pavements were retested after a <i>wet season</i> , the performance of the <i>good</i> material was still satisfactory but the <i>poor</i> material failed very quickly under traffic.
	Determine the effects of bitumen and bitumen/cement stabilization on the performance of a reconstructed high-quality crushed-rock pavement.	Recycling existing crushed-rock bases by stabilizing with 2% bitumen and 2% cement could improve performance and resistance to water penetration. Performance was very sensitive to additive content and compaction level.
	Evaluate high-quality dense crushed-rock base pavement for heavy traffic.	Structural adequacy of Benalla pavement confirmed.
	Compare performance of this pavement (double-chip seal surface) with similar pavement tested at Somersby (asphaltic concrete surface).	Heavy compaction and prompt seal maintenance shown to be essential.
	Assess the use of unbound and stabilized slag as base materials.	Specification for road base materials adjusted to permit wider use of slag materials.

Table G3 (Continued)

ALF Australia	Compare performance of different thicknesses of two qualities of recycled marginal unbound bases.	When subgrade in existing pavement is adequate for the design traffic, existing sandstone base can be reconstructed to support the seal and provide additional load capacity. Reconstructed sandstone base thicker than 125 mm may not enhance pavement performance, particularly for traffic with low axle loads (<40 kN). Recycling existing sandstone bases by stabilizing with 2% bitumen and 2% cement could improve performance and resistance to water penetration.
	Validate ERDC–GSL–WES tentative classification for lateritic gravel for road and airfield pavements.	Performance of both materials constructed to both compaction standards was excellent when tested soon after construction. When the pavements were retested after a <i>wet season</i> , the performance of the <i>good</i> material was still satisfactory, but the <i>poor</i> material failed very quickly under traffic.
	Quantify relative rut resistance of new and conventional mixes.	The performance of the <i>AUSTROADS</i> mix was contrary to expectations because laboratory creep testing had indicated that this mix was more rut-resistant than the <i>control</i> mix.
	To quantify rut resistance of experimental mixes developed by industry compared with a conventional mix of known performance, both in the field and under accelerated loading.	The results associated with the <i>control</i> mix are yet to be analyzed.
CAL–APT California	To compare rutting of a dense-graded asphalt under channelized and normal traffic.	Channelized traffic doubled the rutting surface rut rates. This compared well with previous HVS trials at about 100,000 repetitions.
	To compare the fatigue performance of a rubber–bitumen mix to a conventional mix.	Life to cracking failure compared well with that calculated by the Caltrans overlay design procedure, a reduction of 50% in layer thickness is justified for the rubber–bitumen mix.
CAPTIF New Zealand	Effect of particle shape and gradation on base course. Performance: nine pavements.	New Zealand specifications currently limit the rounded aggregate content in base course to a maximum of 30%. The research showed that, while the best performance was obtained with this mix content, up to 50% could be tolerated (Pidwerbesky 1995a) and that mixes with greater than 70% rounded aggregate could not be compacted.
	Asphalt mixes with four modified and two conventional binders.	Six asphaltic concrete layers compared high and conventional stiffness mixes (Pidwerbesky 1995a). The sections showed little deterioration and the tests were truncated at a surface deformation of 4 mm; at this stage the stiffer asphalt mixes were performing better than a thicker layer with conventional binder.
HVS South Africa	Use of nonstandard materials.	Use of sands and sandstones in stabilized subbase specifications for: emulsion-treated bases, use of blast furnace slag, use of water-bound macadam.

Table G3 (Continued)

HVS South Africa	Investigation of porous asphalt.	Performance of bitumen–rubber porous asphalt, with void contents in excess of 20%, investigated in terms of deformation. Findings used in porous asphalt design manual (SABITA 1996).
	Comparison of HVS predicted behavior with actual pavement performance.	Performance of a road 15 years after HVS testing investigated. Good agreement was found with this study, the first such comparison of any extent. Number of important issues relate to effective long-term pavement performance monitoring.
JHPC Japan	To compare low-volume road base courses.	Base course materials were ranked in order of performance; a manual for low-volume roads was prepared.
LCPC France	Tests of four free-draining coated materials.	Ranking of performance in relation to rutting, cracking, drainage, and frictional characteristics.
	Evaluation of four structures of untreated materials having very different characteristics.	Funded by aggregate producers.
	Evaluation of special materials.	To acceptance of commercial mixes.
	Study of high-performance mixes and fatigue behavior.	Comparison with normal mixes and laboratory tests.
	Observation of rutting behavior of bituminous concrete.	Evaluation of high-performance mixes, influence of speed-temperature, and wheel load effects.
	Comparison of hot and cold bituminous mixes.	Development of maintenance techniques.
	Test commercial emulsion-bound composite material.	Validated performance.
PTI USA	Determine in situ moduli from surface deflection.	Moduli higher than laboratory estimates and affected by many variables.
	Evaluation of free-draining base course.	Shown to be compaction-sensitive and best used deep in a pavement.
RIOH–ALF China	Investigate the performance of low-cost, heavy-duty pavements with lime-stabilized soil bases.	Asphalt surfaced lime-stabilized soil base pavement had a life in excess of 6 million ESALs.
	Determine the fatigue performance of stabilized base materials using tensile strains.	Pavement life models using laboratory tensile (beam) tests did not correlate closely to behavior under ALF.

TABLE G4 Modeling (refer to chapter five)		
Acronym/Location	Objectives	Applications
ALF Australia	Establish relationships between back-calculated asphalt stiffness and CTCR modulus, determined from FWD deflection bowl data, pavement temperature, and the severity and extent of surface cracking.	Asphalt fatigue relationships derived. Potential benefits much higher as use of heavy-duty asphalt pavements in urban applications increases.
FHWA-PTF USA	To compare estimated and measured pavement responses.	There was general agreement between peak deflection, back-calculated moduli, and strain data. Cracking was not a good indicator of failure unless the cracks propagate to the surface.
	To establish load equivalencies.	Not yet complete.
HVS South Africa	Improved understanding of response and performance.	Improved mechanistic models.
	Improvements in modeling permanent deformation.	Contributions of the various rock types in the pavement structure.
LCPC France	To compare: design methods and performance models; tandem axles versus standardized European axles.	Working group 14 of the OECD tested two flexible and one semi-rigid pavement.
	To test cold mix.	Two phases were used. The first load cycles were applied at 45 kph with a reduced load. The second trafficking took place after a few months with full load and speed. This allowed for maturing.
PTI USA	Develop structural equivalency factors.	Layer coefficients recommended.
	Develop estimates of remaining service life.	Remaining service life can be predicted from Surface Curvature Index; effect of layer thickness considered in terms of structural number.
RIOH-ALF China	Compare field measurements of stresses and strains and evaluate the theoretical model.	A theoretical linear elastic model and back-analysis procedure were amended to allow for conditions from full to no layer bonding.

Table G5 Rehabilitation, Construction, and Maintenance (refer to chapter six)		
Acronym/Location	Objectives	Applications
ALF Australia	Compare pavements with and without a bitumen heavy-cure coat interlayer and constructed in one lift instead of two or three lifts.	Failure mechanism of adjacent National highway found to be the same. Major changes to construction practice implemented.
	Compare the performance of two thicknesses of gravel pavements and the geotextile-reinforced seal pavements.	Guidelines for the design, construction, maintenance, and management of geotextile-reinforced seal pavements prepared. Major long-term benefit is more effective use of local materials and scant resources in a location where it is imperative to maintain road links during the <i>wet</i> season.

Table G5 (Continued)

ALF Australia	Compare performance of different thicknesses of two qualities of recycled marginal unbound bases.	When subgrade in existing pavement is adequate for the design traffic, existing sandstone base can be reconstructed to support the seal and provide additional load capacity. Reconstructed sandstone base thicker than 125 mm may not enhance pavement performance, particularly for traffic with low axle loads. Recycling existing sandstone bases by stabilizing with 2% bitumen and 2% cement could improve performance and resistance to water penetration.
	Compare the performance of crushed-rock pavements, constructed at different moisture/compaction conditions at sealing and after drying-back and wetting-up after sealing.	At Beerburrum the low-plasticity, highly permeable crushed-rock bases, when placed on a CTSB having a 3% cross-fall, quickly dried back in the dry environment operating at that time.
	Establish the performance of deep-lift recycled pavements using a slag/lime binder over subgrades of relatively low and relatively high strengths.	At Cooma, deep-lift recycled pavements tested on a low-strength subgrade (CBR = 4) had fatigue lives at least twice that estimated for the adjacent National highway. The findings suggest that this type of pavement recycling is suitable for moderate rural arterial traffic.
HVS South Africa	Development of low-risk maintenance strategies.	Better use of cemented materials for heavy traffic roads. Use of crushed-stone bases for heavy traffic—15–20 ESALs. Reduced cost of bituminous bases for heavy traffic. Extended use of natural gravel. Importance of proper maintenance.
	Evaluation of rehabilitation.	Recycling of asphalt pavement. Advantages of early rehabilitation of crushed-stone bases. Prediction of remaining life and recommended rehabilitation procedure for concrete pavement affected by alkali–aggregate reaction. Rehabilitation of a deformed bitumen premix.
	Materials test methods.	HVS testing resulted either directly or indirectly in the development or refinement of several material test methods and associated design criteria. It included the erosion test for cementitious materials, the crack movement simulator for evaluating crack reflection, and the refinement of the dynamic creep test for asphalt deformation. The link between laboratory test results and APT test results is vital to ensure full benefit from the program.
	Comparison of bases constructed by labor-enhanced techniques.	Labor-enhanced, or labor-intensive, construction techniques. The construction covered different bases including penetration macadam, emulsion-treated natural gravel, slurry bound macadam, and clinker ash.

Table G5 (Continued)

HVS South Africa	Rehabilitation measures for cemented-base pavements.	A long-term HVS investigation into the selection of rehabilitation measures for lightly cemented-base pavements concluded (Steyn et al. 1997).
ISETH Switzerland	Evaluation of failures.	Construction quality shown to be a common factor.
LCPC France	Comparison of hot and cold bituminous mixes.	Development of maintenance techniques.
	Comparison of very high modulus bituminous and cement-treated materials.	Rehabilitation techniques.
PTI USA	Rigid pavement repair.	Techniques validated.
	Evaluation of recycled asphalt.	Technique validated.
	Overlay design.	Simplified mechanistic procedure based on Road Rater deflections.
TRL United Kingdom	Trench reinstatement techniques.	Present methods shown to be conservative and thus legal requirements realistic.
	Ecopave evaluation.	New concrete paving technology proven and patented.
	Nu-pave evaluation	Thin fiber-reinforced concrete overlay technique designed to crack without “failing.”

Table G6 Pavement Engineering Applications and Issues (refer to chapter seven)

Acronym/Location	Objectives	Applications
ALF Australia	Compare the performance of two thicknesses of gravel pavements and the geotextile-reinforced seal pavements.	Guidelines for the design, construction, maintenance, and management of geotextile-reinforced seal pavements prepared. Major long-term benefit is more effective use of local materials and scant resources in a location where it is imperative to maintain road links during the <i>wet</i> season.
	Establish relationships between back-calculated asphalt stiffness and cement-treated crushed-rock (CTCR) modulus, determined from FWD deflection bowl data, pavement temperature, and the severity and extent of surface cracking.	Asphalt fatigue relationships derived. Potential benefits much higher as use of heavy-duty asphalt pavements in urban applications increases.
	Assess the use of unbound and stabilized slag as base materials.	Specification for road base materials adjusted to permit wider use of slag materials.
FHWA-PTF USA	To establish load equivalencies.	Not yet complete.
HVS South Africa	Improved understanding of response and performance.	Improved mechanistic models.
	Improvements in modeling permanent deformation.	Contributions of the various rock types in the pavement structure.
	Enhancement of PMS procedures.	Visual cracking was adopted as a trigger for resealing. The HVS showed that cracking in the thin surfacing used in South Africa would lead to rapid pavement deterioration with ingress of water, before any significant change in deflection.

Table G6 (Continued)

JHPC Japan	To rank the durability of overlay treatments	Findings were used in a maintenance manual.
LCPC France	To test cold mix.	Two phases were used. The first load cycles were applied at 45 kph with a reduced load. The second trafficking took place after a few months with full load and speed. This allowed for maturing.
	Evaluation of four structures of untreated materials having very different characteristics.	Funded by aggregate producers.
	Evaluation of special materials.	Towards acceptance of commercial mixes.
PTI USA	Skid resistance.	Calibration service provided.
	Develop structural equivalency factors.	Layer coefficients recommended.
	Develop estimates of remaining service life.	Remaining service life can be predicted from Surface Curvature Index; effect of layer thickness considered in terms of structural number.
	Roughness measurement.	Calibration technique developed using sinusoidal blocks.
RIOH-ALF China	Reduce reflective and thermal cracking of asphalt pavements by using a rubber asphalt interlayer.	Life to the onset of cracking was much improved.
	Evaluate the performance of the prototype desert pavements.	A design for a desert highway was recommended and has been used.
	Compare field measurements of stresses and strains and evaluate the theoretical model.	A theoretical linear elastic model and back-analysis procedure were amended to allow for conditions from full to no layer bonding.
TRL United Kingdom	Sidewalk damage by heavy vehicles.	Damage to sidewalks evaluated because of legal liability issues.
	Industrial by-products.	Specifications developed to permit use of several materials shown to be structurally adequate and environmentally safe.

(Source: Metcalf 1996, with some referenced supplements.)

APPENDIX H

Implementation of the Results of Accelerated Loading Facility Trials into Practice and the Relationship Between Accelerated Pavement Testing and Long-Term Pavement Performance Trials

Prepared for Synthesis Report on Significant Findings from Accelerated Pavement Testing, November 2001

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Relationship Between Accelerated Loading Facility Trials and Long-Term Pavement Performance Testing

The weakest element of Pavement Management Systems currently in place or being developed in Australia is the prediction of pavement performance. The use of long-term pavement performance (LTPP) monitoring results will improve our understanding of the performance of pavements and lead to cost savings and more appropriate construction and rehabilitation practices.

To address this issue, and to take advantage of the opportunity to be directly involved in the U.S. Strategic Highway Research Program (SHRP), an Austroads-funded project was established that had, as its primary aim, the monitoring of the performance of a range of Australian test sections that both the quantity and quality of pavement performance data could be enhanced and prediction models improved.

The overall objectives of the LTPP study are to:

- Enhance asset management strategies through the use of improved pavement performance models based on an improved understanding of the behavior of pavement structures (SHRP–LTPP program), and
- Compare the results of accelerated pavement testing (APT) studies with actual road pavement performance (ALF–LTPP program).

Pavement monitoring of 19 Australian test sections has been under way for 5 continuous years; two more sites were established during 1999/2000 and the addition of further sites is planned. These sections include those set up specifically as LTPP sites, and also sites specifically established in tandem with ALF trials. The preliminary analysis conducted to date has produced significant findings and clearly demonstrated the need to continue this long-term study. The benefits of the LTPP studies as identified by the findings of the comparative analysis and related recommendations are as follows:

- Excavations in the pavement adjacent to the Beerburum LTPP test pavement (spray seal surface over ce-

ment-treated base and cement-treated subbase) revealed a similar failure mechanism to that observed during the ALF trial, viz. pumping of fines from the cement-treated subbase through the surface seal.

- The environmental effects that are being experienced in the Beerburum LTPP test section and that were not experienced in the Beerburum ALF trial have possibly contributed to the occurrence of transverse cracking not observed during the ALF trial.
- The mean rut depths recorded in the Beerburum LTPP test section were comparable to those measured during the ALF trial. However, it is too early in the loading of the LTPP test section to draw any long-term conclusions. The LTPP test section has allowed the environmental affects to be examined, by means of the ingress of moisture through surface cracks.
- The findings of the Beerburum ALF trial were that the mean surface deflections did not reflect the performance of the CTCR, as the mean surface deflection remained relatively low, despite the evident structural damage to the CTCR. The surface deflection of the LTPP test pavement has generally increased slightly, and if load-related fatigue cracking of the CTCR layers is occurring, then it is not evident from the deflection data.
- Early comparative analysis between the Benalla ALF trial and the Benalla LTPP test pavement section (spray seal surface and unbound granular base) showed that there was an excellent correlation between maximum surface deflection, rutting, and overall pavement surface condition.
- Analysis of the data from the Callington LTPP trial and the related ALF trial (asphalt pavements) has proven inconclusive to date. There has been a poor correlation between the development of rutting and the pavement surface performance for the two sets of data. However, there was a better correlation for surface deflection. The differences are probably related to the differing visco-elastic behavior of the asphalt in the two tests. This points to the difficulties associated with the use of accelerated pavement testing to accommodate the range of environmental conditions

encountered over the life of the pavements, especially when the properties of the materials within the pavement also change over time (binder hardening, curing, etc.).

- One of the primary aims of the ALF–LTPP study is to verify the fundamental purpose of ALF; namely, its ability to predict the behavior of a pavement structure. To this effect, the analysis to date has suggested that ALF has been able to predict in-service behavior, especially with respect to loading effects. The comparative analysis has also highlighted the significant effect of the interrelationship between environment, age, and traffic loading on the performance of pavements and the inability of ALF to predict them.
- The comparative analysis has clearly demonstrated the need to continue the long-term studies on pavements in conjunction with the ALF studies, so that the results of ALF experiments can be fully interpreted and thus fully implemented into design and rehabilitation or asset management strategies. To this end, new sites have recently been established so that the results of more recent ALF trials can be compared with observed in-service performance.
- Because of the need for consistency in data collection and storage, a draft guideline document for the establishment of sites, and the data to be collected from them, has now been produced. This document sets out the requirements for the establishment of a site for on-going pavement condition monitoring in terms of site-selection criteria. Although the guidelines were developed in terms of the requirements of the LTPP studies, they can also be used as the basis for monitoring the condition of other trial or experimental pavements.

Implementation of Findings of ALF Trials into Practice

- Changes to construction practice associated with cement-treated crushed-rock pavements to avoid observed debonding, followed by erosion at the interface. The behavior observed under ALF duplicated that which had been observed on the adjacent National highway, which led to an increased confidence in the ability of ALF to duplicate field behavior.
- The use of unbound and stabilized slags in place of unbound and stabilized crushed rock provided they were protected from excessive tensile strains by the provision of an adequate subgrade and that an adequate wearing course, preferably asphalt, was used to prevent surface wear. This trial also led to the development and publication of guidelines for the most appropriate use of slag materials in pavements.
- Changes to rehabilitation practice based on the findings that, at high temperatures, deformation on asphalt overlays were mainly confined to the upper asphalt layer, indicating that only this layer needed to be replaced with a more rut-resistant product when repairs owing to rutting were carried out. An associated outcome was the more widespread use of high-bitumen-content asphalt mixes and, in thinner layers than previously adopted, the addition of bitumen was shown to result in improved fatigue life.
- Guidelines for the design and management of all-weather low-cost pavements involving the use of geotextile-reinforced seals over expansive clay subgrades, and the more effective use of local materials and scant resources in a location where it is imperative to maintain road links during the *wet season*.
- Changes to road widening and pavement rehabilitation projects associated with the confirmation that nonstandard sandstone materials could be used—and in thinner layers than previously thought—in many regions of Australia. This resulted in savings of approximately 15% of total project costs. The concept was also to be transferred to different climatic regions (up to 500 mm mean annual rainfall) using different nonstandard paving materials and subgrades on a trial basis.
- Changes to specifications for the compaction, and moisture content at sealing, of crushed rock based, specifically: (1) the control of compaction and moisture content at sealing to maximize base performance, (2) the risk of early pavement failure at combinations of high level of compaction and high degree of saturation, and (3) the risk of large errors in Optimum Moisture Content and Maximum Dry Density values of low-plasticity crushed rocks determined using the current standard compaction techniques.
- Revision of the U.S. Army Corps of Engineers tentative classification scheme for the use of lateritic gravels in airfield pavements constructed in tropical areas and the more widespread use of these materials in low-cost pavements constructed in tropical areas of Queensland. An associated finding was the confirmation of laboratory testing protocols—based on repeat load triaxial testing—for these materials.
- Confirmation of the superior deformation-resistance performance of asphalt mixes incorporating polymer-modified and multigrade binders compared with mixes incorporating conventional binders. The analysis of the laboratory creep test results suggested that the minimum creep slope could rank the relative performance of mixes having the same composition but different binder type, but not the relative performance of mixes having different gradings and compositions, which had implications in terms of the use of this test in an asphalt mix design. These results were made possible because of the development of a pavement heating system to ensure that all testing was conducted at the same (and high) asphalt temperatures.
- Confirmation that materials recycled in situ with slag/lime blends to a depth up to 350 mm would per-

form satisfactorily under moderate rural traffic loadings up to about 107 ESALS. The results suggested that, for high subgrade strengths, the pavements would also provide adequate service at higher traffic loading. An associated finding was that the Austroads fatigue relationship generally under-predicted the fatigue life of this material but that there was justification in using a conservative approach for the design of in situ stabilized pavements because of the variability of the properties of the parent material, constructed thickness, binder quantity, levels of compaction and curing regimes.

- The development of design charts for pavements incorporating cement-stabilized fly ash material as a base or subbase layer based on *crushing* life per-

formance data collected during the trial. In the case of cement-stabilized fly ash base pavements, the failure mechanism was fatigue followed by crushing of the material. However, when the material was used as a subbase under a granular base, the pavements rutted after a relatively low number of loading cycles, with rutting of the granular base being the principal distress mechanism.

- Guidelines for the most appropriate use of materials stabilized in situ with bitumen/cement and slag/lime blends, including the effect of curing time on performance. The preparation of these guidelines has resulted in a wider range of options being available with respect to the most appropriate strategy for the rehabilitation of pavements.

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Abbreviations used without definition in TRB Publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation