CALTRANS ACCELERATED PAVEMENT TEST

(CAL/APT) PROGRAM

SUMMARY REPORT

SIX YEAR PERIOD: 1994–2000

Report Prepared for

CALIFORNIA DEPARTMENT OF TRANSPORTATION

by

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EXECUTIVE SUMMARY

This report provides a summary of the Phase II portion (1994-2000) of the Caltrans Accelerated Pavement Testing (CAL/APT) Program. This research and development activity is a joint effort between Caltrans (California Department of Transportation), the University of California at Berkeley (UCB), the Division of Roads and Transport Technology of the Council of Scientific and Industrial Research (CSIR) of the Republic of South Africa, and Dynatest Consulting, Inc., of Ventura, California.

The program utilizes two Heavy Vehicle Simulators (HVS) developed in South Africa. One of the HVS units is used to test full-scale pavements in a controlled environment at the UCB Pavement Research Center, located at the University of California Berkeley Richmond Field Station, while the other is utilized for testing in-service pavements and is currently in operation on State Route 14 near Palmdale, California. An extensive laboratory testing program involving the laboratories of both UCB and Caltrans complements the full-scale accelerated testing. Table 1 provides a concise summary of the work completed during the six-year period July 1, 1994 to June 30, 2000.

Section 2 provides background for the development of the program and a description of modifications to the program in the period since July 1994, illustrating the ability of the program to adapt to the changing needs of Caltrans in a timely manner.

Section 3 contains a brief description of the HVS units and associated pavement instrumentation and evaluation equipment routinely used.

The pavement sections tested thus far are described in Section 4. These include asphalt concrete (AC) pavements tested at the Pavement Research Center, located at the University of California Berkeley Richmond Field Station (RFS), and concrete pavements tested at the RFS and near Palmdale, California on SR14.

Pavement sections at the RFS, constructed according to Caltrans specifications, included both "drained" [i.e., with an asphalt-treated permeable base (ATPB) layer] and "undrained" [with a standard aggregate base (AB) layer] sections.

Following loading to failure of these sections, they were overlaid with either dense-graded asphalt concrete (DGAC) or asphalt rubber hot mix gap-graded (ARHM-GG) to evaluate the current Caltrans method of overlay designs for these two materials.

At Palmdale, test sections were constructed using hydraulic cement concrete (HCC) to establish fatigue response of the material and to evaluate the influence of dowels, tied shoulders, and widened traffic lanes on pavement performance in the Long Life Pavement Rehabilitation (LLPR) Program. In preparation for the Palmdale test program, a portland cement concrete (PCC) pavement was constructed and tested at the RFS.

Section 5 provides a brief summary for each of the studies listed in Table 1. These studies have been grouped into several general areas: 1) AC (flexible) pavement studies; 2) PCC and HCC (rigid) pavement studies; 3) analytical developments related to both asphalt and concrete pavements; 4) construction issues for both asphalt and concrete pavements; 5) database considerations including development of CAL/APT program database and evaluation of Caltrans pavement management system (PMS) database for performance information; 6) development and interpretation of in-situ measurements for stiffness properties of pavement components and water contents of untreated base and subgrade materials using ground penetrating radar (GPR); and 7) economic analysis demonstrating potential benefits which might accrue with implementation of some of the initial results obtained from the asphalt pavement studies. Both the asphalt and concrete pavement studies include laboratory test programs, HVS tests, and pavement analysis and design considerations.

Section 6 provides a collective view of the results presented in Section 5 and provides the bases for important recommendations to Caltrans on a number of important issues.

In the asphalt (flexible) pavement area, the mix design and analysis system originally developed as part of the Strategic Highway Research Program (SHRP) has been extended to efficiently treat in-situ temperatures, calibrated to the Caltrans asphalt concrete pavement design system, extended to incorporate construction variability, and used to interpret the results of the first four HVS tests completed at the Richmond Field Station. Use of this system provides the basis for recommendations to Caltrans in the following areas: 1) AC pavement and mix design and analysis, 2) design and use of ATPB, 3) materials for overlays on existing AC pavements, and 4) construction practices and pay factors.

Similarly, in the concrete (rigid) pavement area, results of both the laboratory and HVS test programs provide the basis for recommendations in the following areas: 1) design considerations for concrete pavements including the use of dowels, widened truck lanes, joint spacing, and the use of non-erodable bases with low stiffness under long-time loading; and 2) concrete mix design considerations including control of cement shrinkage in hydraulic cements, use of higher flexural strengths than currently specified, control of sulfate resistance, and the development of an improved accelerated sulfate resistance (ASR) test.

In the pavement construction area, two computer programs have been developed which should prove useful in the LLPR program as well as for other construction projects. These are: 1) a program for constructability analysis for both concrete and AC pavement construction; and 2) *CalCool,* a program that determines the temperature profile for multi-lift AC paving operations.

Asphalt Concrete Pavement Design and Rehabilitation

Results indicate that the total pavement thicknesses developed by the current Caltrans pavement design procedure are generally adequate to preclude the incidence of rutting caused by permanent deformation occurring in the subgrade and untreated aggregate pavement layers. On the other hand, recommended thicknesses of the asphalt concrete layers (particularly for weaker subgrades and higher traffic levels) may lead to premature fatigue cracking. Utilization of the mix design and analysis systems developed during the CAL/APT program should reduce this propensity for fatigue cracking and generally improve pavement performance. Innovative pavement designs could extend fatigue lives substantially beyond conventional designs.

The mix design and analysis system permits the more effective utilization of materials, e.g., the use of the “rich bottom” concept as well as insuring the effective use of new materials such as modified binders. Such designs could extend fatigue lives substantially. Innovations in design and related improvements in construction quality will contribute significantly to the development of asphalt concrete alternatives to be used in the Caltrans Long Life Pavement Rehabilitation Strategies (LLPRS) program. This has been demonstrated by the application of the methodology to both mix and structural pavement design for the AC pavements to be used on the I-710 freeway in Long Beach, California.

The results of the overlay study support the current Caltrans practice of the 2-to-1 thickness equivalencies of ARHM-GG to DGAC for overlays on fatigue-cracked asphalt pavements. This practice must be carefully applied, however, to insure that rutting at the pavement surface from deformations in the untreated pavement components does not control performance.

Design and Use of Asphalt Treated Permeable Base

From the HVS tests on the pavement sections containing ATPB, laboratory tests on representative ATPB mixes, and associated analyses and surveys of the field performance of ATPB including the experience of district personnel with maintenance of pavement drainage systems, the general use of ATPB directly under the dense-graded asphalt concrete layer in the pavement section warrants reconsideration.

Improved compaction in the asphalt concrete layer will reduce its permeability. Improved compaction and increased asphalt concrete layer thickness, following the mix design and analysis system described herein, will also substantially delay crack initiation and propagation in the asphalt concrete layer. Reducing the permeability and cracking potential of the asphalt concrete will thus reduce the necessity for ATPB in this location—potentially the use of ATPB could even be eliminated. It is likely that the resistance to cracking and reduction in permeability will also be improved by the use of a “rich bottom” layer of asphalt concrete. Despite the steps to reduce the propensity for the surface water to enter the pavement, it must be recognized that drainage layers may still be required to help remove water seeping into the pavement structure through the subgrade.

If ATPB is used directly beneath the asphalt concrete, improvements should be made to the material to enhance its performance in the presence of water. Increasing binder content, using modified binders such as asphalt rubber, and using an additive such as lime or an anti-stripping agent are alternatives which should be considered. Associated with the changed mix design is the necessity for incorporation of properly designed geotextile filters adjacent to the ATPB layer in the pavement structure in order to prevent the ATPB from clogging. Results of the Goal 5 tests on saturated pavements reinforce these recommendations.

Finally, to insure continued effectiveness of the ATPB, effective maintenance practices for the clearing of edge and transverse drains should be established.

Following these and other performance enhancing recommendations would justify raising the gravel factor for ATPB from its current value of 1.4 to a value as high as 2.

Construction Practices—AC Pavements

Both the fatigue analyses and the fatigue performance of the asphalt concrete in the HVS tests emphasize the importance of proper compaction of these layers in the pavements structure. Accordingly, compaction requirements should be established to insure that in-place constructed mix air-void contents do not exceed 8 percent.

While the use of relative compaction requirements based on the laboratory density is satisfactory, a reduction in asphalt content from that selected in the laboratory could lead to an air-void content higher than 8 percent, even though the relative compaction requirements were met. Accordingly, the change from a relative compaction requirement to a maximum air-void requirement based on ASTM D2041 ("Rice" specific gravity) is strongly recommended.

In the construction (using the Caltrans method specification) of the ARHM-GG for the overlay study, relatively low compaction levels were obtained. The current specification (method specification) should be replaced by the compaction requirement stated above.

A weak bond was observed between the first two asphalt concrete lifts in the HVS test sections. In all cases, this lack of bond was found to significantly degrade pavement performance. While the extent to which weak bonding may be prevalent in California pavements is unknown, the fact that the HVS test pavements were constructed according to standard Caltrans procedures suggests that a weak bond may contribute to performance problems for in-service pavements under heavy traffic. Effects from weak bonding may become more evident in the pavement network as axle weights and freight traffic increase in the future. If additional investigations confirm such problems, recommended use of a tack coat will result in significant improvements in pavement performance and, hence, reduction in life-cycle cost.

With Caltrans moving toward the use of QC/QA procedures in pavement construction, CAL/APT data can provide the basis for a rational procedure for the development of pay factors. Using the calibrated mix analysis and design system, pay factors based on fatigue analysis—including the effects of degree of mix compaction (represented by relative compaction), asphalt content, and asphalt thickness—have already been developed.

These pay factors have been combined with those developed from rutting analyses for the WesTrack test road. This blending of the results from both projects provides an example of the synergistic effects that can result from the CAL/APT group being involved in other related projects.

The pay factor study also stresses the importance of proper compaction to insure improved fatigue and rutting performance. In addition, the study has highlighted the importance of thickness control for the asphalt concrete layer. Implementation of a bonus/penalty system based on this study as a part of a QC/QA program has the potential to significantly improve asphalt concrete pavement performance.

Concrete Pavement Design Considerations

Results of analytical studies, supported by the results of HVS tests at the RFS and in Palmdale, stress the importance of the use of dowels and non-erodable bases for heavily trafficked, jointed concrete pavements. Results from the Palmdale site also demonstrate the effectiveness of dowels in restricting curling movements along transverse joints from daily temperature changes. Tie bars produce similar results for longitudinal joints.

In order to minimize slab thicknesses for concrete sections, greater than current required flexural strengths along with small coefficients of thermal expansion should be used.

Concrete Mix Design Considerations

Some hydraulic cements considered for use in the LLPR program may be susceptible to sulfate attack. Accordingly, it is recommended that Caltrans enforce sulfate resistance guidelines for PCC and that contractors produce evidence that any HCC being considered for a project is sulfate resistant.

Test data developed thus far suggest that an improved test should be developed for alkali-silica reaction (ASR) given that this could be a problem with some aggregates and could impact pavement performance in the LLPR program.

High shrinkage hydraulic cement led to top-down premature cracking in longer slabs at the Palmdale test site. If this type of material is used, shorter slab lengths will be required.

Construction Management

Two computer programs have been developed to assist in pavement construction: 1) a program for constructability analysis for both concrete and AC pavements, and 2) *Cal Cool* for pavement temperature profile determinations during multi-lift AC construction.

The constructability program has provided guidelines for improved productivity in various alternatives under consideration for the LLPR-Rigid program. For example, it suggests that the current proposed strategy to rebuild 6 lane-kilometers within 55 hours of weekend closure has a very low probability of success. The program has also been of value in guiding the construction activities associated with the rehabilitation of a section of I-10 in Pomona, California.

Thus, it is recommended that this program be used to assist in scheduling LLPR program paving activities.

Section 7 provides a brief summary of the program. It concludes with an important observation that the project has demonstrated the efficacy of government, industry, and academia working together to provide solutions to critical pavement problems. Moreover, it demonstrates the benefits of international cooperation in which technology is transferred among the participants to the benefit of the involved organizations.

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1.0 INTRODUCTION

The Caltrans Accelerated Pavement Testing (CAL/APT) Program, a research and development activity, is a joint effort between Caltrans (the California Department of Transportation), the University of California at Berkeley (UCB), the Division of Roads and Transport Technology of the Council of Scientific and Industrial Research (CSIR) of the Republic of South Africa, and Dynatest Consulting, Inc. of Ventura, California.

The program utilizes two Heavy Vehicle Simulators (HVS) developed in South Africa. One of the HVS units is used to test full-scale pavements in a controlled environment at the UCB Richmond Field Station (RFS) while the other is utilized for testing in-service pavements. An extensive laboratory testing program involving the laboratories of both UCB and Caltrans complements the full-scale accelerated loading testing. Figure 1 illustrates a simplified framework within which the program operates.

This report summarizes results obtained from the Phase II portion of the program initiated July 1, 1994 (Phase I was accomplished in the period of April 1993–January 1994).[1] Table 1 provides a summary of the work completed during the six-year period July 1, 1994 to June 30, 2000 together with references for associated publications with each of the studies listed.

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[1] Results of this study are briefly described in the following summary report: Harvey, J., and C. L. Monismith. Accelerated Pavement Testing, Phase I, Field and Laboratory Evaluation of Dense-Graded Asphalt Concrete (DGAC) and Asphalt-Rubber Hot Mix Gap-Graded (ARHM-GG), Executive Summary and Recommendations. Report prepared for the California Department of Transportation. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley, 1994.

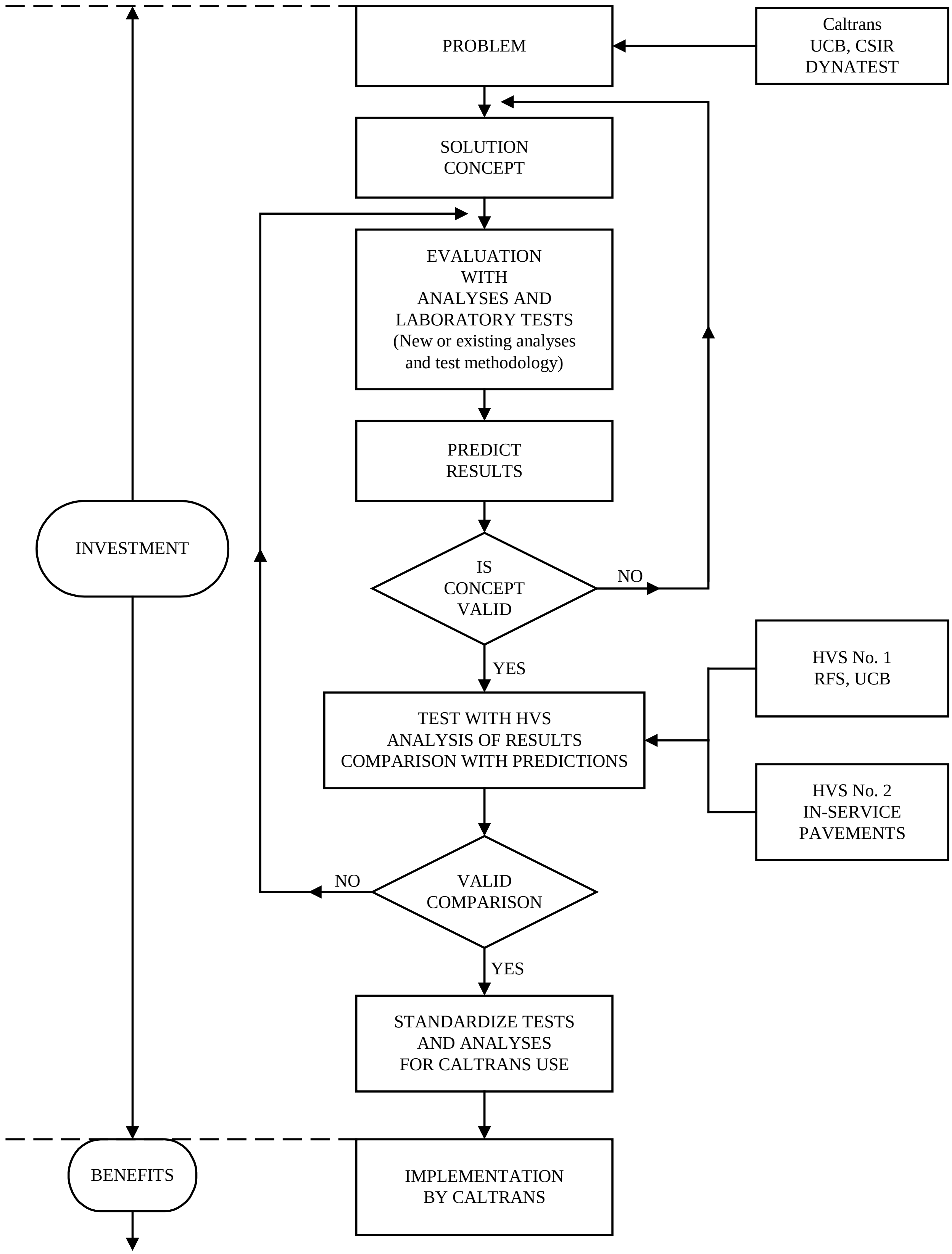

Figure 1. CAL/APT framework.

Table 1 Program Summary

Study	Type	Objective(s)	Results	References
1. Fatigue performance of asphalt concrete mixes and its relationship to pavement performance in California.	Laboratory study, analyses	• Evaluate effects of asphalt content and air-void content on fatigue response of a typical California asphalt concrete mix. • Demonstrate usefulness of SHRP-developed procedure for mix and pavement analysis and design to achieve improved fatigue performance.	• Used in interpretation of data obtained in Study (*2*). • Used in comparative analysis in Study (*8*). • Used in pay-factor Study (*9*). • Recommendation for use of "rich-bottom" design.	(*3*), (*4*)
2. Accelerated loading on four full-scale pavements with untreated aggregate and asphalt-treated permeable bases.	Accelerated pavement tests with HVS, laboratory tests, analyses	*Primary objective:* Develop data to quantitatively verify existing Caltrans design methodologies for asphalt treated permeable base (ATPB) pavements and conventional aggregate base pavements with regard to failure under traffic at moderate temperatures. *Other objectives:* • Quantify effective elastic moduli of various pavement layers • Quantify stress dependence of materials in pavement layers • Determine failure mechanisms in various layers • Determine and compare fatigue lives of the two types of pavement structures	• Importance of mix compaction conclusively demonstrated. • Recommendation for "tightening" Caltrans compaction requirements. • 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. • The lack of bond between compacted lifts of asphalt concrete observed in the HVS tests suggests re-examination by Caltrans of the use of a tack coat between lifts to improve the bond. • The subgrade strain criteria used by the Asphalt Institute can be used by Caltrans as a part of a mechanistic-empirical design procedure.	(*1*), (*6*), (*7*), (*8*), (*9*), (*10*), (*11*), (*12*)
3. Asphalt treated permeable base study	Laboratory study, analyses	• Measure effects of water on ATPB stiffness through laboratory testing. • Relate soaking performed in laboratory and its effects on ATPB stiffness to field conditions. • Provide "bridge" between HVS tests conducted with ATPB in dry state and in-situ performance with some likelihood of ATPB being saturated. • Evaluate design philosophy behind use of ATPB and its implementation to date. • From overall evaluation, provide recommendations pertaining to use of ATPB in California.	• Improved compaction of the asphalt concrete layer and proper structural design based on results of Studies (1) and (2) as well as reduced permeability of asphalt concrete resulting from improved compaction would eliminate the need for the ATPB directly beneath the asphalt concrete layer. • Because of the susceptibility of ATPB to the action of water as currently specified, an improved design is recommended using more asphalt and/or modified binders such as asphalt rubber. • To prevent clogging of the ATPB, if used, suitable filters should be incorporated in the structural section.	(*16*)

Study	Type	Objective(s)	Results	References
4. Tire pressure study using 3-D stress sensor [Vehicle-Road Surface Pressure Transducer Array (VRSPTA)]	HVS loading with different tire types, pressures, tire configurations (single, dual)	Define stress distributions, both vertical and horizontal, exerted by a range in tire types, pressures, and configurations including bias-ply, radial, wide-base radial, used aircraft, radial (new and used), and wide-base (off-road) radial.	Tire pressure analysis used in finite element analysis to: • evaluate crack patterns observed in HVS tests. • provide confirmation of the results of layered elastic analysis of HVS tests. • provide a basis for the use of the simple shear test for permanent deformation evaluation of mixes.	(*18*)
5. Mix rutting using accelerated loading at elevated pavement temperature(s)	Accelerated pavement tests with HVS, laboratory tests, analyses	Study mix rutting under radial, bias-ply, and wide-base tires at elevated temperatures.	• Test series on ten sections demonstrated the rapidity with which the influence of different tire types on asphalt concrete rutting can be evaluated. • Results demonstrate the increased rutting which can result with wide base single tires as compared to dual tires for same total load and tire pressure under channelized traffic conditions. For this reason, Caltrans should monitor usage of this tire on California pavements. • The 2 to 1 equivalency for ARHM-GG as an overlay must be carefully applied to insure that rutting at the pavement surface from deformations in the untreated materials does not control performance.	(*23*), (*24*), (*25*)
6. Accelerated loading on overlaid pavements	Accelerated pavement tests with HVS, laboratory tests, analyses	The principal objective of this study (Goal 3 of the Program) was the evaluation of the performance of two rehabilitation strategies: 1. conventional DGAC overlay, and 2. ARHM-GG overlay at one-half the thickness of the DGAC	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	(*29*)
7. Accelerated loading of two full-scale pavements (including ARHM-GG overlay) with saturated base conditions	Accelerated pavement tests with HVS, laboratory tests, analyses	Evaluate the behavior of the drained and undrained pavement sections in the wet condition under HVS loading	Stripping of and intrusion of fines into ATPB test results support recommendations resulting from ATPB laboratory test study	(*31*)

Study	Type	Objective(s)	Results	References
8. Comparison of AASHTO and Caltrans pavement design methods	Analyses	• Quantify differences in pavement thicknesses by two methods. • Compare predicted performance for pavement designs considered equal within Caltrans procedure. • Evaluate effect of drainage conditions on pavement structures designed by AASHTO procedure. • Demonstrate the usefulness of mechanistic-empirical design procedure.	Provides additional evidence to Caltrans to make the transition from their current design procedure to a mechanistic-empirical procedure.	(*32*)
9. Mix and structural pavement designs for LLPRS–Interstate 710, Long Beach, CA	Laboratory study, analysis, HVS tests (in progress)	Prepare mix and structural pavement designs for section of I-710 Freeway adjacent to the Port of Long Beach, CA	Designs prepared for mixes containing PBA-6A and AR8000 asphalt binders. Structural sections included: • full-depth asphalt section to be placed under overcrossings as replacements for existing PCC. • full-depth asphalt section as overlay on cracked and seated PCC.	(*34*), (*35*)
10. Pay-factor study	Analyses	Use fatigue analysis/design system (calibrated with HVS tests and rut depth information from WesTrack) to develop pay-factors for compaction control (air-void content), asphalt content, asphalt concrete thickness, and aggregate gradation.	Recommended that Caltrans uses factors on a trial basis for selected QC/QA projects currently underway (shadow projects).	(*36*)
11. Effects of binder loss stiffness (SHRP PG binder specification) on fatigue performance of pavements	Analyses	Use fatigue analysis/design system (calibrated with HVS tests) to evaluate effects of binder loss modulus, $G^*sin\delta$, on pavement performance in fatigue.	Recommendation that $G^*sin\delta$ be eliminated from PG-specification for binders.	(*38*)

Study	Type	Objective(s)	Results	References
12. Accelerated loading of full-scale concrete pavements at the RFS and on State Route 14, Palmdale, CA	Accelerated pavement tests with HVS, laboratory tests, and analyses	Construct a full-scale portland cement concrete (PCC) pavement test section at the RFS to evaluate instrumentation and data acquisition system in preparation for Palmdale experiment. On full-scale pavements at SR14 near Palmdale, CA: • identify potential problems in FSHCC construction • determine fatigue resistance of fast setting hydraulic cement concrete (FSHCC) pavements under HVS loading. • evaluate performance of concrete pavements with dowels, tied concrete shoulders, and widened traffic lanes under HVS loading and environmental stresses.	• Experience gained in installation of instrumentation and use of data acquisition system at RFS test permitted efficient operations at Palmdale. • Failure in the RFS PCC pavement stressed the importance of the use of non-erodable bases and dowels at transverse joints for heavy traffic loads. • *While the tests at Palmdale are still in progress*, it was observed that short term flexural strengths of the FSHCC did not meet specified strength requirements; field loading on the south tangent sections indicate the fatigue resistance of the FSHCC is similar to the fatigue resistance of PCC slabs tested in the laboratory	(*40*), (*41*), (*42*), (*43*)
13. Long-term durability of concrete mixes used in LLPRS Program	Laboratory study, analyses	• Evaluate the sulfate resistance of hydraulic cements in accelerated laboratory test as compared to conventional portland cements used in California (Type I/II). • Evaluate alkali-silica (ASR) susceptibility of hydraulic cements as compared to Type I/II portland cements	• Results showed that several hydraulic cements may be susceptible to sulfate attack • Recommendation that Caltrans enforce sulfate resistance guidelines for PCC and, for HCC, the contractor produce evidence that material is sulfate resistant. • Tests demonstrated that one hydraulic cement (calcium aluminate cement–CA) was highly resistant to ASR. • Recommendation that an improved ASR test be developed because of ambiguity in results for specimens containing three other cements including Type I/II portland cement.	(*50*), (*51*), (*52*)
14. Shrinkage and environmental effects on the performance of FSHCC pavements at Palmdale, CA	Field and laboratory studies, analyses	Determine the influence of temperature gradients and drying shrinkage on the performance of FSHCC pavement slabs.	• High shrinkage hydraulic cement led to top-down premature cracking in longer slabs. Analysis indicated that shorter slab lengths will reduce the chance of premature failure if high shrinkage cement is used. In addition, to reduce the potential for this type of cracking, bases which are flexible under long-term and stiff under short-term loading are preferred. • Dowels and tie-bars were effective in restricting curling movements along transverse and longitudinal joints resulting from daily temperature changes.	(*51*), (*55*), (*56*)

Study	Type	Objective(s)	Results	References
15. Evaluation of proposed LLPR strategies for rigid pavements; design and constructability considerations	Visual condition survey, analyses including that of historical Caltrans design and performance data	Evaluate adequacy of structural design options for concrete pavements under consideration by Caltrans for LLPR strategies.	• Faulting is the most prevalent form of distress in California concrete pavements. Transverse joint spacing should be made a function of climate. Non-erodable bases with low stiffness under long-time loading conditions desirable. • 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	(*57*), (*58*)
16. Constructability analyses for Long Life Concrete Pavement Rehabilitation	Analysis, computer program development	Perform constructability analyses for LLPR-Rigid Program.	Results of the analyses indicated that strategy to rebuild 6 lane-kilometers during 55 hour weekend closure has low probability of success. Existing pavement removal and new concrete supply were the major constraints. Construction productivity data obtained for rehabilitation operations on the I-10 freeway in Pomona provided validation for the approach.	(*63*), (*64*)
17. Computer program for determining pavement temperatures during AC placement (Cal Cool)	Analysis, computer program development	Develop computer program to determine pavement temperature profiles for multi-lift pavement construction throughout the duration of the paving operation.	Computer program Cal Cool with inputs including: AC lifts (up to 9); mix and underlying mat characteristics; and environment characteristics, e.g., ambient temperature, wind speed, etc.	(*65*)
18. Mechanistic-empirical pavement design and performance-based asphalt mix design and analysis	Analysis, computer program development	Develop mechanistic-empirical design procedures for new and rehabilitated pavements. (To date, the project has concentrated on the development of essential elements for the overall design methodology.)	• Identification 7of climate regions in California (in terms of temperature and moisture) for materials selection and pavement design • Multilayer elastic analysis computer program (LEAP) • Constitutive relation for permanent deformation response of AC mixes at high temperatures (>40ºC)	(*22*), (*67*), (*68*), (*69*), (*70*), (*71*)
19. Performance characteristics of compacted untreated granular materials	Laboratory tests, HVS tests, analysis	Definition of the stiffness, strength and permeability characteristics of untreated granular materials for use in mechanistic-empirical design procedures and for QC/QA in construction.	• 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)	(*76*), (*31*)

Study	Type	Objective(s)	Results	References
20. Nondestructive monitoring of water contents in untreated bases, subbases and subgrade soils of pavement structure using ground penetrating radar (GPR)	Laboratory tests, in-situ tests on RFS HVS pavements, analysis	Develop a reliable procedure to measure in-situ water contents of untreated materials in pavement sections.	Preliminary results have demonstrated feasibility of this methodology to measure in-situ water contents in untreated materials in the pavement sections.	(*77*)
21. Studies related to Caltrans pavement management system (PMS)	Analysis	Evaluate data in California PMS to develop performance models for the various types of pavements used on the state highway system.	• Recommendations for changes to *Caltrans Pavement Survey Manual* • Development of prioritized list of pavement test sections for inclusion in Caltrans condition survey network	(*78*), (*79*)
22. CAL/APT database development	Analysis	Develop CAL/APT database.	Database has been developed consisting of the following: 1. PRC Lab Database 2. HVS Asphalt Database 3. HVS PCC Database 4. Caltrans Database Uses MS Access and Oracle as relational database management system	(*80*)
23. Assessment of economic benefits from implementation of findings from CAL/APT Program	Analysis	Evaluate economic benefits of implementation by Caltrans of three changes in flexible pavement technology resulting from CAL/APT program: 1. increased AC compaction 2. use of tack coat between AC layers 3. use of "rich bottom layer" in thick AC pavements	Potential cost savings for use of these technology changes is substantial [approaching ~$590 million (1998 dollars)]	(*81*)

2.0 BACKGROUND

Pavement construction, including maintenance and rehabilitation, requires a significant portion of the Caltrans budget each year to insure that the extensive highway system will continue to serve the needs of both passenger and goods transport in order to maintain the economic viability of the State. It has been estimated that the value of the existing pavement system in California, including those at the State, County, and City levels, is about $35 billion—a sizeable investment.

Recognizing the potential benefits that could result from an accelerated pavement testing (APT) capability to insure the viability of these systems through both improved design and construction methodologies, Caltrans began serious investigation of full-scale APT in 1989. By 1992, Caltrans engineers had decided to further investigate the heavy vehicle simulators (HVS) developed and used by the CSIR of South Africa. This decision was supported by the long and productive operation by CSIR of the HVS equipment, improved pavement technologies and a database containing results from more than 400 pavement test sections, as well as validation of HVS predictions by documented performance of in-service pavements. Before purchasing the HVS equipment and services needed to implement an APT program in California, a pilot project (termed Phase I) was initiated and completed in 1993 that involved Caltrans, UCB, Dynatest Consulting, Inc., and CSIR.

Objectives of this project were to

1. demonstrate the capabilities of HVS technology to provide rapid information on pavement performance,
2. validate the Caltrans asphalt rubber hot mix gap-graded (ARHM-GG) overlay thickness design specification which allows up to 50-percent thinner layers than conventional dense-graded asphalt concrete (DGAC); and

3. evaluate pavement rutting from channelized traffic under laterally guided automated vehicle control systems (AVCS).

The logistics of the project were complex because the test pavements were built in South Africa by a local contractor. CSIR engineers ensured that Caltrans design and construction specifications were met. CSIR engineers also sampled the materials and conducted the HVS tests. Materials samples were shipped to California for testing by UCB (at the RFS laboratory) and Caltrans (at the Caltrans laboratory). Dynatest engineers provided substantial coordination and technical support.

Successful completion of the pilot project provided ample justification for Caltrans to proceed. The current program was approved in February 1994 and began with the purchase of two HVS units from CSIR and the Phase II contract with UCB in June 1994. By June 1995, both HVS units were accepted by Caltrans and the first HVS testing began.

Since June 1994, a fully functional accelerated pavement testing capability has been established at the Pavement Research Center (PRC) of UCB resulting from the successful partnership between Caltrans, UCB, Dynatest, and the CSIR of South Africa.

The initial activities developed for the Phase II program are described in the *CAL/APT Strategic Plan*.[2] After this program had been underway for about 18 months, an assessment was made of progress and additional activities were included.[3] In January 1998, in response to the Long Life Pavement Rehabilitation Program (LLPR) initiated by Caltrans, the program was further broadened to include investigations related to hydraulic cement concrete (HCC)

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[2] Adopted by CAL/APT Steering Committee, May 1995. This plan provides an overview; describes the program's vision, purpose, mission, and goals; and then outlines a schedule of objectives, tasks, and products for a 2-year period from 1995 to 1997.
[3] *Reviewing the Future Directions for the CAL/APT Program*. Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley, March 1996.

pavements. In addition, responsibility for operation of HVS2 was shifted from Caltrans to the PRC. Rapid assimilation and initiation of the concrete pavement research program demonstrated the ability of the CAL/ APT program to adapt to the changing needs of Caltrans in a timely manner.

3.0 HEAVY VEHICLE SIMULATOR

Figure 2 contains a diagram and specifications for the HVS Mark III developed by the CSIR. Two of these units were purchased by Caltrans in 1994; both units have been in almost continuous operation since spring of 1995.

Wheel loads of up to 200 kN (45,000 lb.) are applied on a half axle using dual, standard-size truck tires or a single aircraft tire. The loads move in either a bi-directional (for fatigue evaluation) or a unidirectional (for permanent deformation evaluation) mode at speeds up to 10 km/h. (6.2 MPH). At this rate, up to 18,000 load repetitions can be applied per day in the bi-directional mode. Longitudinal wheel travel is 8.0 m (26.2 ft.) and lateral travel is programmable over 1.5 m (4.9 ft.).

Once an HVS is at a test site, its full mobility enables it to maneuver to nearby test sections under its own power. Pavement instrumentation and evaluation equipment routinely used includes: multi-depth deflectometers (MDD), laser profilometer, road surface deflectometer (RSD), crack activity meter (CAM), thermocouples, photographic surface crack monitoring equipment, and a nuclear density gauge.

Overall weight:		59,646 kg (131,500 lbs.)
Load weight of the test wheel		20-100 kN (4,500-22,500 lbs.) with truck tire 20-200 kN (4,500-45,000 lbs.) with aircraft tire
Tire Pressure		690 kPa
Dimensions of tested area of pavement		1.5 m × 8 m (4.9 ft × 26.2 ft) maximum
Velocity of the test wheel		10 km/h (6.2 mph) maximum
Maximum trafficking rate		1000 repetitions/hr
Average trafficking rate		750 repetitions/hr
Average daily repetitions		16,000 (including daily maintenance)
Engines:	Hydraulic plant	10-cylinder diesel
	Electrical plant/hydraulic control	6-cylinder diesel
Dimensions:	Length	22.56 m (74 ft
	Width, overall	3.73 m (12 ft)
	Height	3.7 m (12 ft)
	Wheel base	16.7m (55 ft)
Number of axles		3 (1 in rear, 2 in front)

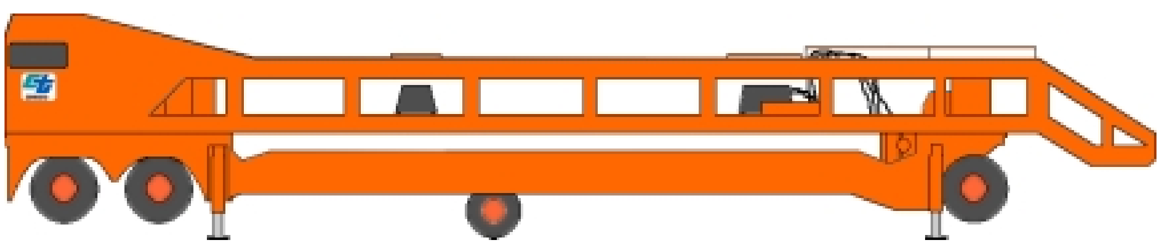


Figure 2. Diagram and specification of HVS.

4.0 PAVEMENT SECTIONS

Asphalt concrete (AC), portland cement concrete (PCC), and hydraulic cement concrete (HCC) pavements have been tested during the period covered by this report. The AC pavements were constructed and tested at the Richmond Field Station (RFS) while the HCC pavements were constructed at Palmdale, California on State Route 14. In preparation for the Palmdale tests, a PCC pavement was constructed and tested at the RFS.

4.1 Asphalt Concrete Pavement Test Section, RFS

Pavement structures tested thus far consist of a clay subgrade (AASHTO A-7-6), aggregate subbase (ASB), aggregate base (AB), asphalt treated permeable base, and asphalt concrete (AC) selected according to the Caltrans design procedure for a Traffic Index (TI) of 9 (approximately 1×10^6 ESALs) and a design stabilometer "R" value of 10 for the subgrade. Figure 3 illustrates schematically the various pavement structures and the locations of the four initial HVS test sections constructed according to Caltrans specifications by a local contractor. The sections containing the ATPB are also referred to as *drained* sections while those containing only AB are termed *undrained*.

When construction of the test pavements was completed in 1995, cores and slabs of the asphalt concrete were taken from the pavement for laboratory testing. Due to the total required thickness of 137 mm (5.4 in.), the AC was placed and compacted in two 68.5-mm (2.7-in.) lifts. When the cores were obtained, a weakness in (and even a lack of) the bond between the two asphalt-concrete lifts was observed. Reference (*1*) contains details of the initial design considerations, materials evaluations, and construction test data.

Following completion of the HVS tests on the four sections, overlays were placed. One overlay was a conventional dense-graded asphalt concrete (DGAC) with a compacted thickness

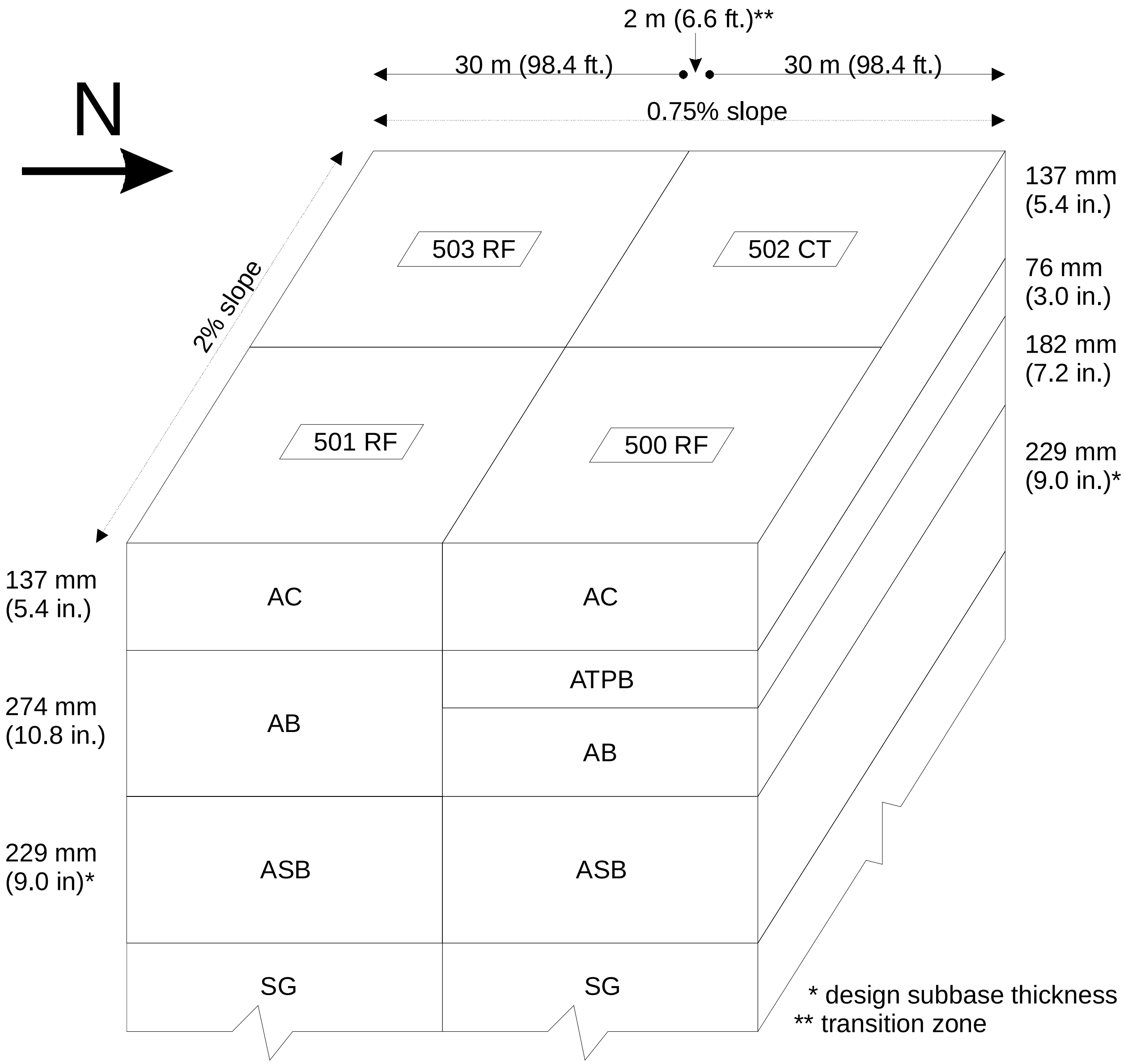


Figure 3. Structural pavement sections for first four HVS test sections at the Pavement Research Center.

of 60–75 mm (0.20–0.25 ft.) on Sections 500 and 501. The other was a gap-graded asphalt rubber hot mix (ARHM-GG) 37 mm (0.12 ft.) in thickness on Sections 502 and 503. A part of the ARHM-GG overlay was increased to 61 mm in thickness in order to provide cores with a thickness sufficient to provide specimens for permanent deformation evaluation testing in repeated simple shear test at constant height (RSST-CH). Construction of the overlays was accomplished in March, 1997. Unlike initial construction, a tack coat was applied before the overlay construction. Cores taken after this construction consistently showed good bonding between the overlay and upper lift of the original asphalt concrete.

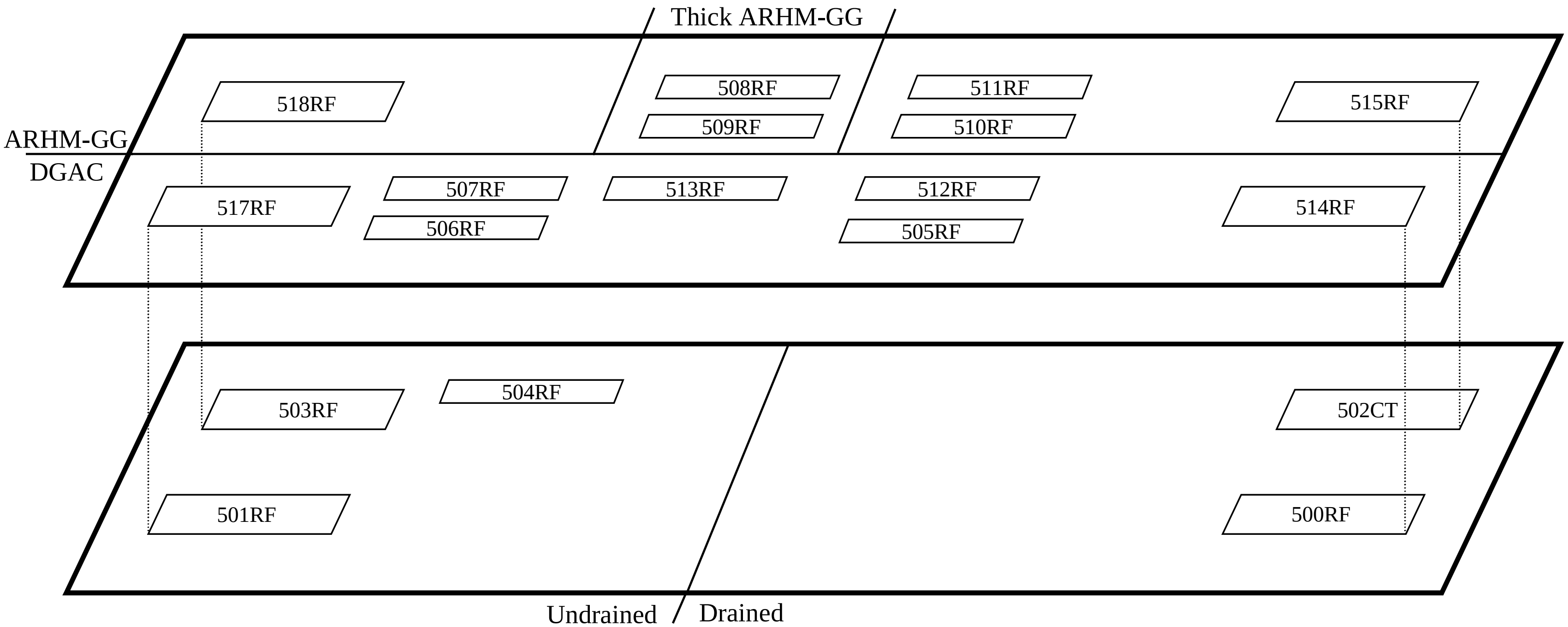
In addition to the four tests on the original surface and the four overlay test sections (514R–518RF), a series of rutting tests were performed with the pavement at a temperature of about 50°C (122°F) (504RF–513RF), and two tests were performed at 20°C on the ARHM-GG overlay with the ATPB and AB sections in the wet condition (543RF, 544RF). Locations of all of these sections, together with the original four (500RF–503RF) are shown schematically in Figure 4.

4.2 Portland Cement Concrete Test Section, Richmond Field Station

In preparation for the HCC pavement test program at Palmdale, a portland cement concrete (PCC) pavement test section was constructed at the RFS in December 1997. The PCC contained a Type II portland cement accelerated with 2 percent calcium chloride. The layout and cross-section for the test pavement (516 CT) is shown in Figure 5. The instrumentation is similar to that used in the field test sections in Palmdale.

4.3 Hydraulic Cement Concrete Pavement Test Sections, Palmdale

The test sections were constructed by Caltrans on State Route 14 just south of Palmdale, California in northeast Los Angeles County. The test sections are located in a high desert environment at an elevation of just over 800 m. The Palmdale area has a mean annual low air temperature of -8°C (18°F) with snowfall common in the winter, and summer high temperatures



500RF Fatigue test, dual bias, original AC, drained, “dry”
501RF Fatigue test, dual bias, original AC, undrained, “dry”
502CT Fatigue test, dual bias, original AC, drained, “dry”
503RF Fatigue test, dual bias, original AC, undrained, “dry”
504RF Rutting test, dual bias, AC, undrained
505RF Rutting test, dual bias, 61mm DGAC, drained
506RF Rutting test, dual radial, 76mm DGAC, undrained
507RF Rutting test, wide base single, 76mm DGAC, undrained
508RF Rutting test, wide base single, 61mm ARHM-GG, undrained
509RF Rutting test, dual radial, 61mm ARHM-GG, undrained
510RF Rutting test, dual radial, 37mm ARHM-GG, drained
511RF Rutting test, wide base single, 37mm ARHM-GG, drained
512RF Rutting test, wide base single, 76mm DGAC, drained
513RF Rutting test, aircraft tire, DGAC, undrained
514RF Fatigue test, dual radial, 62mm DGAC, drained
515RF Fatigue test, dual radial, 37mm ARHM-GG, drained
517RF Fatigue test, dual radial, 75mm DGAC, undrained
518RF Fatigue test, dual radial, 37mm ARHM-GG, undrained
543RF Fatigue test, dual radial, 37mm ARHM-GG, drained, “wet”
544RF Fatigue test, dual radial, 37mm ARHM-GG, undrained, “wet”

Figure 4. Test section locations at the Pavement Research Center.

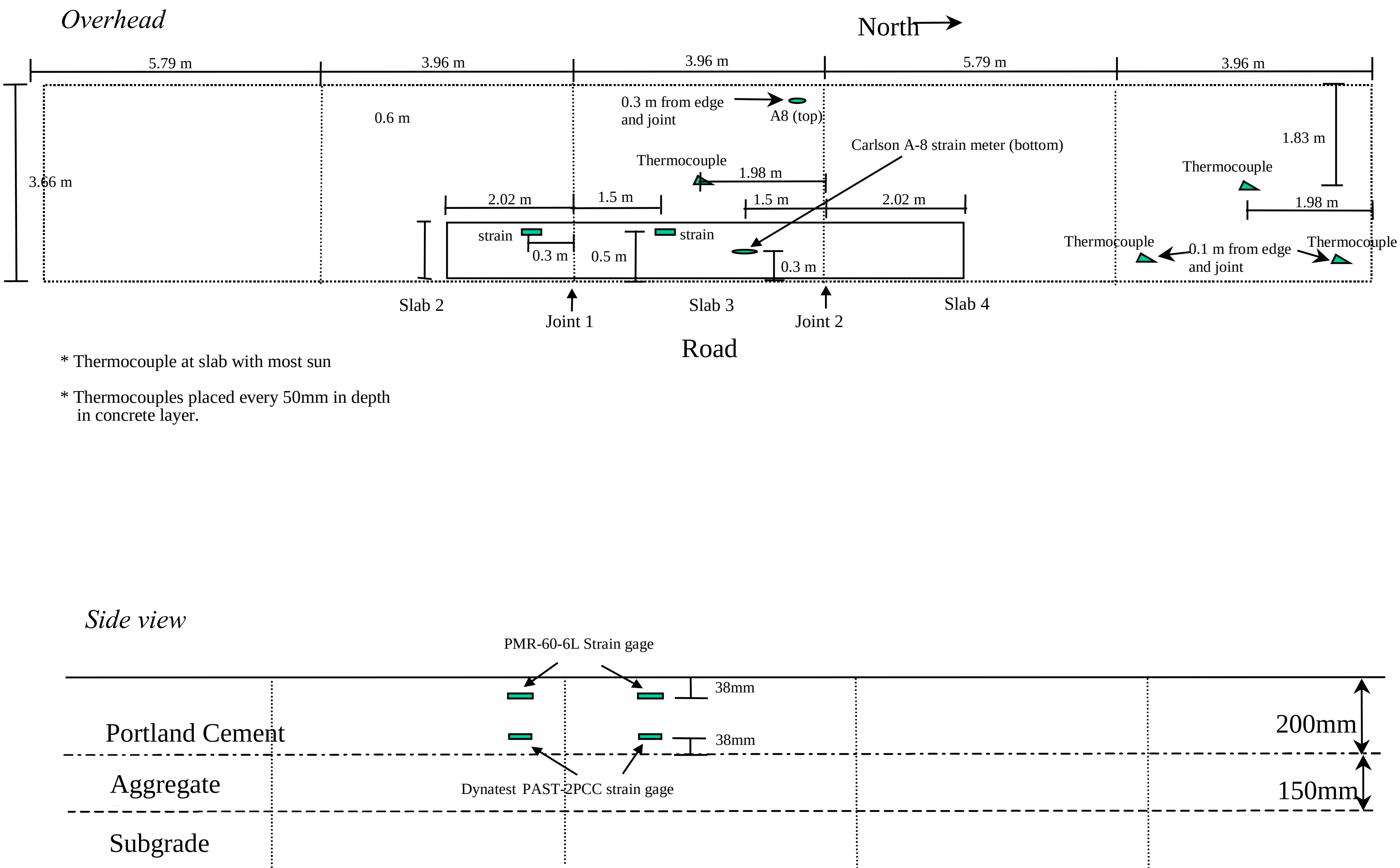


Figure 5. Portland cement concrete test section (516CT) with gage locations at the Pavement Research Center.

that can exceed 45°C (113°F). Diurnal temperature changes of more than 25°C (45°F) are not uncommon.(*2*)

The first three sections (South Tangent) were used to develop a fatigue relation for full-scale plain jointed concrete slabs. The second three test sections (North Tangent) include 200-mm thick slabs on cement-treated base (CTB), with dowels, tied shoulders, and a widened truck lane (4.3 m). All of the 200-mm (8-in.) thick sections are being continuously monitored for environmental responses. The North and South Tangents are each 210 m (689 ft.) long, each with three 70-m (230-ft.) test sections. The pavement structures for all six test sections are shown in Figure 6. Each test section has approximately 15 concrete slabs and can accommodate approximately four HVS load tests.

The subgrade material consists of uplifted alluvial deposits of sand and gravel. All test sections, except one, have asphalt concrete shoulders. All slabs have sawed, perpendicular transverse joints that match the 3.7-, 4.0-, 5.5-, and 5.8-m (12-, 13-, 18-, and 19-ft.) spacings of the adjacent slabs in the existing PCC pavement. All slabs widths are 3.7 m (12 ft.) except for Section 11, which is 4.3 m (14 ft.) wide.

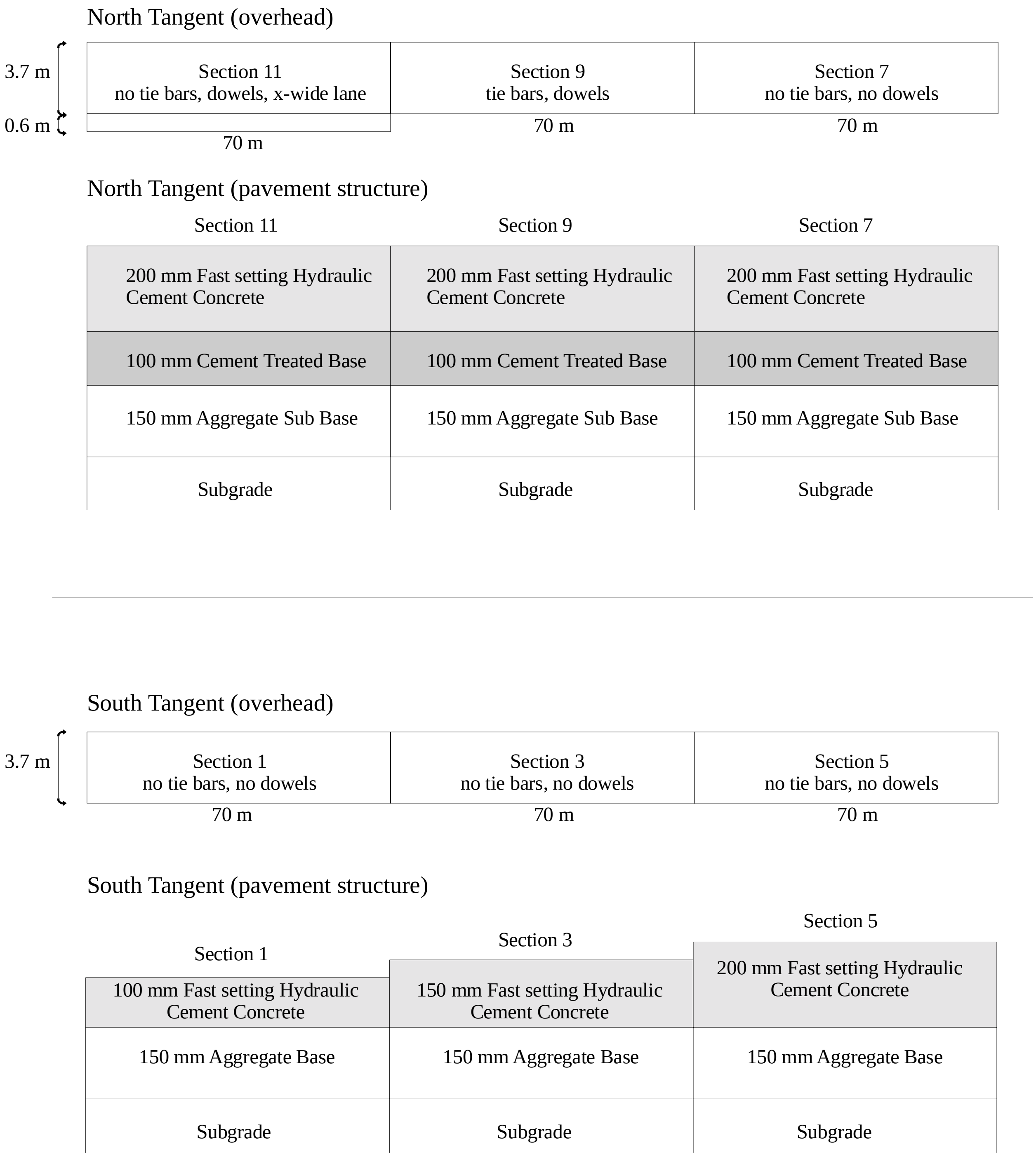


Figure 6. Palmdale pavement structures, North and South Tangents.

5.0 SUMMARY AND FINDINGS

This section provides a brief summary for each of the studies listed in Table 1. Some of the investigations are still in progress—for these, a brief description and reason(s) for inclusion in the program are discussed.

The studies are grouped into seven general areas:

1. AC (flexible) pavement studies,
2. PCC and HCC (rigid) pavement studies,
3. analytical developments related to both asphalt and concrete pavements,
4. construction issues for both asphalt and concrete pavements,
5. database considerations including development of CAL/APT program database and evaluation of Caltrans pavement management system (PMS) database for performance information,
6. development and interpretation of in-situ measurements for stiffness properties of pavement components and water contents of untreated base and subgrade materials using ground penetrating radar (GPR), and
7. economic analyses demonstrating potential benefits which might accrue with implementation of some of the initial results obtained from the asphalt pavement studies.

The studies of both the asphalt and concrete pavements include laboratory testing programs, HVS tests, and pavement analysis and design considerations.

The laboratory test program related to asphalt pavements includes stiffness, fatigue, and permanent deformation testing of both DGAC and ARHM-GG, behavior of ATPB under "wet" conditions, and stiffness testing and permeability of untreated pavement materials.

HVS tests associated with the asphalt pavement program have been performed at the RFS. Objectives of these tests include the following:

1. develop data to verify existing Caltrans design methodologies for drained asphalt treated permeable base (ATPB) pavements and undrained conventional aggregate base (AB) pavements with regard to failure under trafficking at moderate temperatures, and to create a uniform platform on which overlays could be constructed (Goal 1);
2. compare the fatigue performance of structural overlays of hot asphalt rubber gap-graded (ARHM-GG) mixes using Type 2 asphalt rubber binder with that of conventional dense-graded asphalt concrete (DGAC) mixes (Goal 3);
3. evaluate the rutting propensity of the mix used in the initial pavements and the two overlay mixes, the latter being subjected to wide base single and dual tires and a range in tire types (Goal4); and
4. evaluate the behavior of the drained and undrained pavement sections in the wet condition (Goal 5).

To determine the adequacy of the strategies[4] formulated in 1997 for the Caltrans Long Life Pavement Rehabilitation (LLPR) Program for rigid pavements, a multi-pronged approach was developed. This approach includes laboratory testing of the durability, strength, and fatigue characteristics of fast setting hydraulic cement concrete (FSHCC), pavement analyses, and

[4] The proposed approach is as follows (*44*):
"Remove existing concrete slabs from the one or two outside truck lanes using a saw and lift technique to preserve the integrity of the CTB. Slab thickneses would be the same as the removed slabs, typically 200 or 225 mm. New transverse joints would be perpendicular and joint spacing would match the existing lanes. Fast setting hydraulic cement concrete (FSHCC) would be used to reduce curing time needed before opening rehabilitated sections to traffic. To improve pavement performance, the rehabilitation would include construction of tied concrete shoulders, steel dowels at transverse joints, and wide truck lanes (4.26 m)."

accelerated pavement testing.

The accelerated pavement test program, using HVS2, includes the following objectives:

1. Construct a full-scale test section at the RFS (516CT) including instrumentation and subject it to HVS loading in order to provide experience and to insure that the instrumentation and data acquisition system will function at the test sections to be constructed on State Route 14 near Palmdale, California.
2. At Palmdale:
    a. Determine the fatigue resistance of FSHCC pavements in the field under HVS loading.
    b. Evaluate the performance of concrete pavements with dowels, tied concrete shoulders, and widened traffic lanes under HVS wheel loading and environmental stresses with respect to fatigue cracking, corner cracking, and joint faulting.

The studies, though listed in a numerical order, generally follow the sequence noted above. As noted earlier, Table 1 summarizes all of these investigations either completed or still in progress.

5.1 Fatigue Performance of Asphalt Concrete Mixes (*3, 4*)

This study, using multilayer elastic analysis and laboratory fatigue testing, examined the influence of mix proportions, specifically asphalt and air-void contents, on fatigue behavior both in the laboratory and in situ. It refined and recalibrated a mix design and analysis system developed as a part of the SHRP asphalt research endeavor.(*5*) This system is capable of quickly and easily determining the likely fatigue endurance of design mixes in specific pavement structures at specific locations and under anticipated traffic loading. Of particular significance is the integration of mix and structural components and the explicit treatment of both testing and construction variabilities which, in turn, permits selection of an acceptable level of risk for the pavement section. Specific results include the following:

- Construction control is an important consideration in mix design. With respect to fatigue performance, accurate control of air-void content is much more important than accurate control of asphalt content. Complicating this matter is the likelihood that smaller-than-specified asphalt contents will result in increased air-void contents unless compactive effect is increased to compensate.
- In-situ fatigue performance can be quite sensitive to construction variability and, by inference, to the caliber of the quality assurance program. To restrict the risk of premature failure to tolerable levels, mix design and/or structural design must recognize and, if possible, compensate for expected construction practice.
- Monte Carlo simulation is an effective technique for simulating fatigue-life distributions resulting from testing, extrapolation, and/or construction variabilities. The ability to quantify fatigue-life distributions has significant potential for a) establishing rational performance requirements, b) taking actions to reduce the risk of failure to meet performance requirements, and c) establishing performance-based contractor pay schedules. Figure 7 illustrates the results of such a simulation. In this figure, the pavement section listed as 11ab20 [TI of 11 (ESAL range $4.5–6.0\times10^6$), untreated aggregate base, 20 subgrade R-value], has a fatigue life at the targeted asphalt and air-void contents of approximately 4.4×10^6 ESALs; this corresponds to the median value shown in the figure. The mean fatigue life and its standard deviation are 5.4×10^6 and 3.9×10^6 ESALs, respectively.

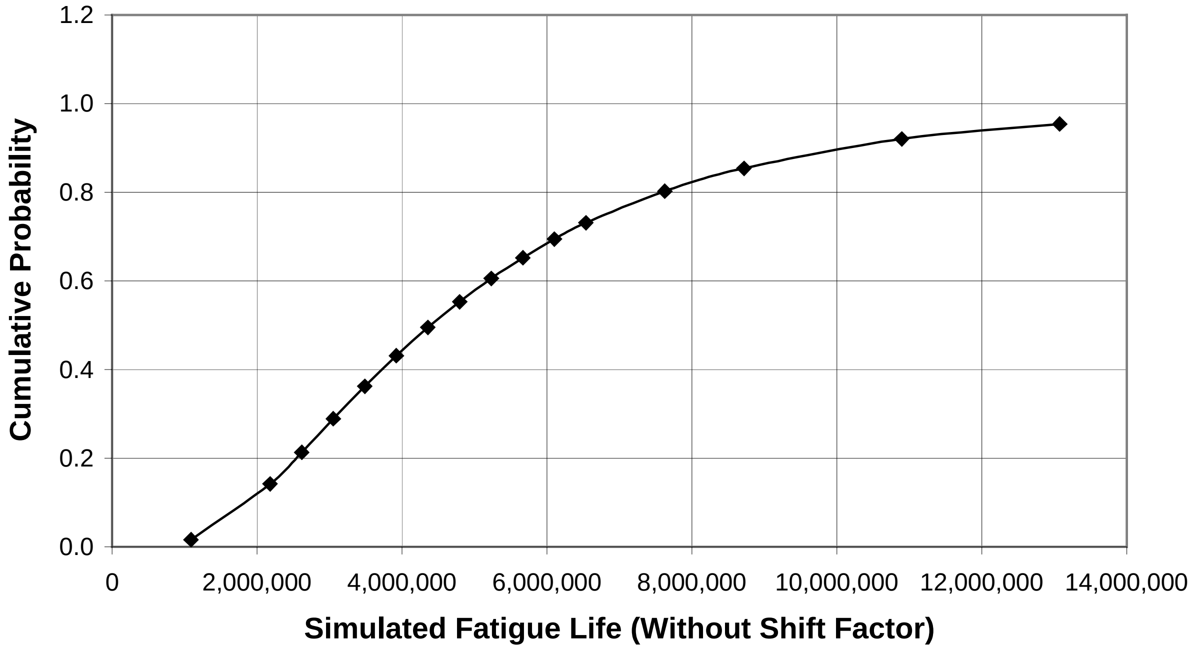


Figure 7. Dispersion of fatigue life (measured in ESALs) resulting from construction variability (Simulation 11ab20).

- The mix design and analysis system can be used to effectively determine the consistency of structural design procedures with respect to the control of fatigue distress. For example, conditions in which California practice is most likely to yield designs that are vulnerable to fatigue cracking appear to include:
  a. designs for large levels of traffic loading, specifically a TI of 15 (ESAL range 64.3–84.7×10^6);
  b. designs for subgrades of low and intermediate strength; and
  c. designs for coastal regions of the lower portion of the state.
- Rich-bottom designs, in which the bottom portion of the asphalt surface course is enriched with added asphalt and compacted with lower air-void contents, have the potential for enhancing fatigue performance, extending fatigue life by at least threefold beyond that of conventional structures in the absence of other adverse

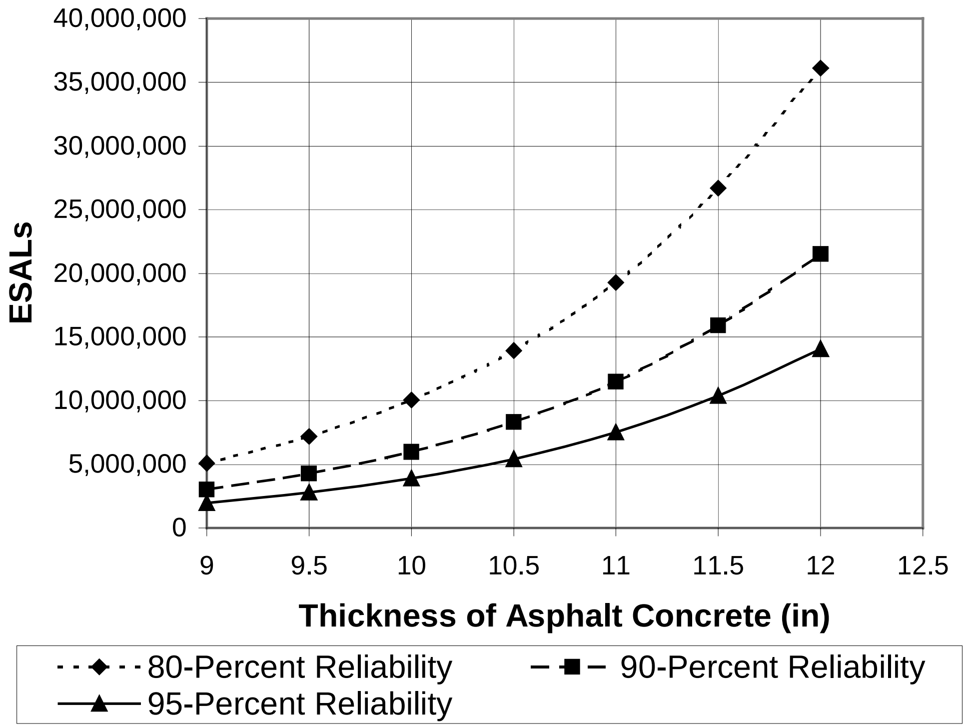
material, construction, and traffic influences. The investigation of rich-bottom pavements, the results of which are shown in Figure 8, is an example of the usefulness of the mix design and analysis system to quantitatively explore materials and structural alternatives that take advantage of improved fatigue properties at critical locations in the pavement structure.

5.2 Accelerated HVS Loading Tests on Four Full-Scale Pavements (Goal 1) (*1, 6–12*)

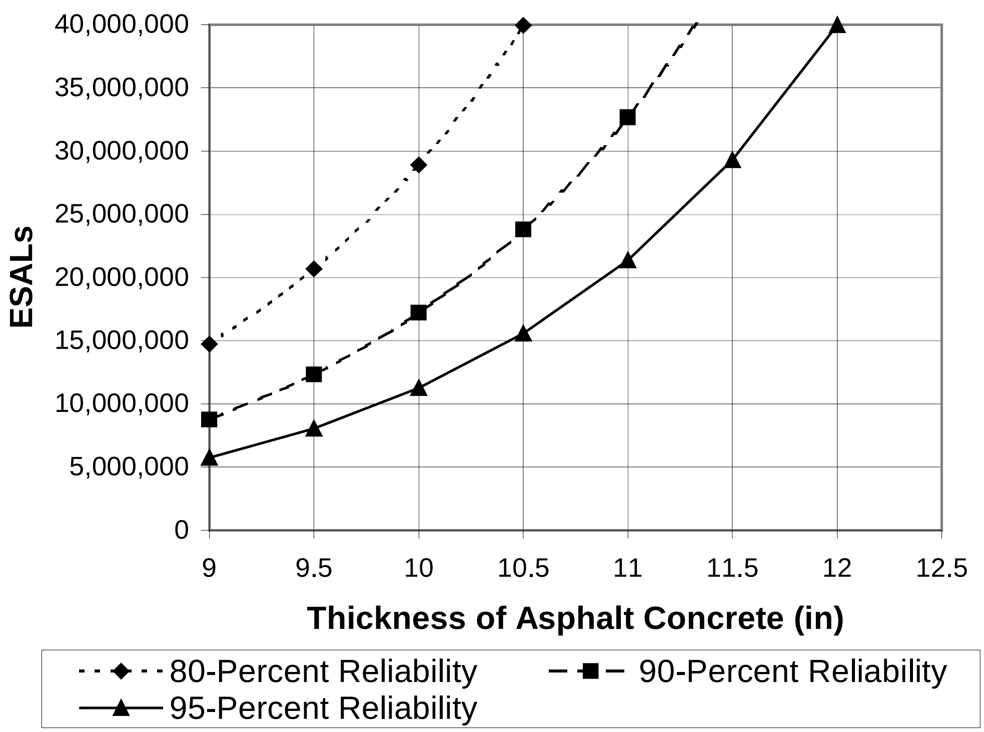
HVS tests associated with Goal 1 of the asphalt program commenced in May 1995. As stated above, one of the objectives of Goal 1 was *to develop data to verify existing Caltrans design methodologies for drained (ATPB) pavements and undrained (AB) pavements under trafficking at moderate temperatures.* Section 500RF, one of the drained sections, served as the first test. Table 2 provides a summary of the four HVS tests associated with Goal 1. In each test the loading consisted of 150,000 repetitions of a 40-kN (9000-lb.) load, 50,000 repetitions of an 80-kN (18,000-lb.) load, and the remainder with a 100-kN (22,500-lb.) load, all on dual tires.

At the termination of loading on each of the sections, the alligator-type cracking had reached a level which, according to Caltrans pavement management criteria, constituted fatigue failure. The density of cracking in the sections with untreated AB (undrained) was larger than that in the sections with ATPB (drained), as presented in Table 2.

To analyze the response of the four test sections, the fatigue analysis and design system referred to in Section 5.1 was utilized. The program CIRCLY (*13*) was selected for the multilayer elastic analysis since it has provisions for both full friction and no friction between the interface of the AC layers.



a. Conventional pavement.



b. Rich-bottom pavement.

Figure 8. Effect of surface thickness and design reliability on in-situ fatigue resistance.

Table 2 Summary of Results of First Four HVS Tests at

Section	**Base type**	**Loading period**	**Repetitions at which first load-associated cracks were observed**	**Total HVS repetitions to failure**	**Estimated ESALs[a]**	**Crack length/Area (m/m^2)**
500RF	ATPB	5/3/95–11/8/95	6.5×10^5	2.57×10^6	112×10^6	2.5
501RF	AB	11/20/95–2/26/96	5.5×10^5	1.43×10^6	59×10^6	9.6
502CT[b]	ATPB	12/5/95–9/20/96	1.3×10^6	2.67×10^6	117×10^6	4.0
503RF	AB	3/6/96–9/18/96	4.0×10^5	1.91×10^6	81×10^6	6.5

[a] Estimated according to the Caltrans relationship for load equivalency:

$$ESALs = \left[\left(\frac{actual\ load}{18,000}\right)^{4.2}\right.$$

[b] Trafficked with HVS No. 2.

In Table 2, it should be noted that a considerable difference exists between the loading tolerated by the test sections versus the design level of 1×10^6 ESALs. To explain this difference, a number of factors must be considered. Recognized and emphasized at the outset is the unknown error that results from assuming that the Caltrans design estimate is dictated primarily by the prevention of premature fatigue cracking and not other distress modes. Historically this design strategy has been successful.

To investigate these differences, five different cases were analyzed for each test section to calculate a simulated response under traffic load. For Section 500RF, the cases are shown in Table 3.

The air-void contents for the mixes in the HVS test pavements differ from the assumed design (Case 1). Actual air-void contents for the test pavements are shown Table 4 and those values are listed in the case descriptions above for Section 500RF.

Table 3 Cases Analyzed for Section 500RF

Case	Description	Interface between lifts	Critical strain location
1	Design conditions with standard mix • 8 percent air-void content • 5 percent asphalt content	Full Friction	Bottom of lower lift
2	HVS conditions with standard mix • 8 percent air-void content • 5 percent asphalt content	Full Friction	Bottom of lower lift
3	HVS conditions with standard mix except for reduced air void content • 4.4 percent air-void content bottom lift • 7.8 percent air-void content top lift • 5 percent asphalt content	Full Friction	Bottom of lower lift
4	HVS conditions with HVS mix • 4.4 percent air-void content bottom lift • 7.8 percent air-void content top lift • 4.8 percent asphalt content	Full Friction	Bottom of lower lift
5	HVS conditions with HVS mix • 4.4 percent air-void content bottom lift • 7.8 percent air-void content top lift • 4.8 percent asphalt content	Frictionless	Bottom of upper lift

Table 4 Air-Void Contents of Mix in HVS Test Sections

Asphalt Concrete Lift	Air-void content			
	500RF	**501RF**	**502CT**	**503RF**
Upper	7.8	7.2	4.1	4.8
Lower	4.4	5.6	2.4	4.4

It was necessary to make a distinction between the assumed design conditions, and the as-built as-tested HVS conditions with respect to layer thicknesses and environmental influences. The difference between the two conditions was taken into account by assuming that the moduli of the various pavement layers for the design conditions were 80 percent of moduli values determined from elastic deflections measured under HVS loading. For the asphalt concrete, elastic moduli were based on stiffness measurements at 20°C. Moduli values for the ATPB and untreated materials were based on laboratory resilient modulus tests and results obtained by back-calculation procedures from falling weight deflectometer (FWD) tests.

The effect of reliability on estimates of design ESALs as well as the fundamental difference between design ESALs, whether from the Caltrans or UCB procedures, and HVS ESALs, whether measured under HVS loading or simulated using the UCB system, was addressed as follows. In computing HVS ESALs, variances of the several parameters (asphalt content, air-void content, asphalt concrete thickness, foundation support, and traffic) were assumed to be negligible. Computations using the UCB system for Case 1 conditions yielded the ESAL estimates shown in Table 5 (i.e., simulated HVS ESALs = 8.06×10^6 and ESALs for a reliability of 90 percent = 2.16×10^6) clearly demonstrate the influence of reliability on design ESALs. It is interesting that the fatigue analysis and design system estimated 2.16×10^6 design ESALs at 90-percent reliability, about twice the Caltrans design estimate of approximately 1×10^6 ESALs. Although not shown in Table 5, the fatigue analysis and design system estimated 0.98×10^6 ESALs at 98-percent reliability, very nearly the same as the Caltrans design estimate. As expected, the 8.06×10^6 simulated HVS ESALs is considerably greater than any of the design ESALs; for a design reliability level of 90 percent, the computed ratio of simulated HVS ESALs to UCB system design ESALs is approximately 3.7.

Table 5 **Comparisons of Measured and Estimated ESALs, All Test Sections**

	ESALs $\times 10^6$							
	Simulated HVS ESALs				**UCB System Design ESALs; Reliability = 90 percent**			
Case:	**500RF**	**501RF**	**502CT**	**503RF**	**500RF**	**501RF**	**502CT**	**503RF**
1	8.06	2.45	8.06	2.45	2.16	0.656	2.16	0.656
2	18.1	4.76	19.4	8.63	4.73	1.25	5.08	2.19
3	53.0	11.7	83.6	36.2	13.8	3.08	21.9	9.20
4	292	66.0	456	216	76.2	17.3	119	55.0
5	6.74	6.42	9.68	17.1	2.10	2.05	3.05	5.22
Actual	*112*	*59.0*	*117*	*81.0*				

Next, in order to demonstrate the significant difference between as-built and as-tested HVS conditions and assumed Caltrans design conditions, the simulated HVS ESALs estimate for Case 2 was compared with that for Case 1, Table 5. The ratio of HVS ESALs for HVS conditions to that for design conditions is approximately 2.2. The enhanced simulated performance for the HVS environment stems from a combination of favorable thickness differences and environmental effects, including both temperature and moisture.

To show the effect of the excellent mix compaction achieved in the construction of Section 500RF, particularly the lower lift, the simulated HVS ESALs estimate for Case 3 was compared with that for Case 2, Table 5. The significant effect of air-void content is illustrated by a ratio of approximately 2.9 in the HVS ESALs estimate for a 4.4-percent bottom lift and 7.8-percent top lift compared to that for an 8-percent mix in both lifts. This finding emphasizes the benefits of good construction practice and greater compaction levels than current Caltrans specifications typically require. An even larger improvement in simulated fatigue life than that shown here would have resulted result if the 4.4-percent air-void content had been achieved in both lifts. These findings corroborate similar findings from previous fatigue studies for a variety of typical Caltrans pavement structures.

To demonstrate the effect of the superior fatigue performance of the HVS mix compared to the standard mix, the simulated HVS ESALs estimate for Case 4 was compared with that for Case 3, Table 5. The ratio of simulated HVS ESALs for these two conditions is approximately 5.5. This large difference is not clearly attributable to any one particular component of the two mixes and is likely due to a combination of potential differences in components including aggregate type, asphalt, and aggregate gradation.

One such factor relates to the lack of bonding at the interface between upper and lower asphalt concrete lifts. CIRCLY enables analysis of two interface extremes: frictionless and full-friction. The interface condition of Section 500RF is probably somewhere between these two extremes. That is, the interface is rough (but unbonded) and the weight of the upper layer combined with vertical compressive stress beneath the load should allow some of the horizontal interface movement to be transmitted from one lift to the other. Even though partial friction conditions cannot be modeled with available techniques, the notable effect of interface condition can be demonstrated by comparing the HVS ESALs estimate for Case 5 with that for Case 4, both of which are shown Table 5.

The remarkably large difference in estimated performance between frictionless and full-friction conditions is due to two factors. The first factor is the nature of the friction condition at the interface between lifts. The second factor results from a shift in the critical strain (i.e., initial crack) location from the bottom of the lower lift for the full friction interface to the bottom of the upper lift for the frictionless interface. In the upper lift, the air-void content is much greater, and the number of load repetitions necessary to propagate cracks to the top surface are expected to be smaller because of the reduced thickness through which the cracks must propagate. The larger air-void content and reduced overlying thickness significantly decrease the simulated fatigue life.

Although this analysis is not definitive because the in-situ interface condition cannot be accurately modeled by CIRCLY, the estimate of 292×10^6 ESALs is reasonably comparable to HVS loading of 112×10^6 ESALs. The simulation results, which indicate that cracking would occur in the upper lift before it would occur in the lower lift for the frictionless interface condition, corroborate the cracking observed in cores from Section 500RF.

*N.B. 2-D and 3-D finite element simulations were also conducted on an idealization of structure 500RF.(*14*,*15*) These results also indicated that the cracks would be expected to initiate in the top layer.*

While not as well defined, the analyses also suggested that the cracking pattern of transverse cracks initially observed should, in fact, occur since the tensile strains in the longitudinal direction were larger than those in the transverse direction.

The analysis reported herein provides explanations and insights in reconciling the difference between the Caltrans design estimate of 1×10^6 ESALs and the HVS test measurement of 112×10^6 ESALs. In addition, it has highlighted factors such as mix, air-void content, and interface condition and yielded quantitative estimates of their impact on pavement performance.

Results of HVS tests on Section 501RF, 502CT, and 503RF, (summarized in Table 5) support the above discussion. Moreover, as seen in Table 5, the design thickness of AC for the undrained section appears inadequate at a reliability level of 90 percent (ESALs less than 1×10^6), reinforcing the discussion presented in Section 5.1 regarding the potential for fatigue cracking in Caltrans designed pavements for asphalt concrete on untreated aggregate base.

5.3 Asphalt Treated Permeable Base (ATPB) Study (*16*)

This study included:

- Evaluation of the performance of asphalt treated permeable base (ATPB) in asphalt concrete pavements including:
  1. a summary of Caltrans experience with ATPB and drainage systems, their development and implementation, and observations of field performance with respect to stripping and maintainability; and
  2. a summary of the characteristics and performance of ATPB materials and drainage systems used by two other highway agencies.
- Laboratory investigation of the stiffness and permanent deformation characteristics of ATPB mixes including the effects of soaking and repeated loading while saturated.
- Analyses of representative pavement structures to determine the effects of both as-compacted and soaked ATPB on performance; the purpose of this latter study being to extend the applicability of the HVS tests results from Sections 500 and 502 to representative in-service conditions.

From a survey among the Caltrans Districts, some problems have been reported with the use of ATPB. Stripping of asphalt from the aggregate has been observed in some ATPB materials. This phenomenon has also been reported by other agencies using similar materials. Maintenance of edge drains has been a problem for some Caltrans districts, particularly where the drains have been added as retrofits rather than as design features in new or reconstructed pavements. In addition, several districts have reported frequent clogging of their drainage systems. These observations stress the importance of examining ATPB in a soaked state.

While the extent to which an ATPB might remain saturated has not been extensively examined, results of an investigation of in-service pavements in Indiana suggests that the ATPB can remain saturated for a substantial period of time after a rain event.(*17*) These results indicate that it is important to study the response of saturated ATPB and that loading representative of moving traffic be applied to the material in this condition.

Results of pavement analyses using the laboratory-measured modulus values demonstrate that, in addition to any benefits provided by improved pavement drainage, inclusion of an ATPB layer can increase the structural capacity of AC pavements with respect to fatigue cracking and subgrade rutting. However, better structural capacity requires that the ATPB is resistant to stripping, loss of cohesion, and stiffness reduction from water damage. For these conditions, the Caltrans ATPB gravel factor (analogous to a gravel equivalent factor) can be increased to a value of the order of 2.0 from its current value of 1.4. If, on the other hand, water damage causes reduced stiffness, a gravel factor in the range 1.4 to 1.7 appears reasonable depending on the degree of water damage anticipated.

Current Caltrans mix design criteria leave ATPB layers susceptible to significant reduction in stiffness from the effects of water because of the low-specified asphalt content and lack of a water sensitivity evaluation. It is very likely that the performance of ATPB in the presence of water can be substantially improved through improved mix design, drainage design (e.g., use of soil filter or filter fabric), construction procedures, and maintenance practices.

This study also recommended that Caltrans reconsider its use of ATPB directly under the AC layer to intercept water entering through the pavement surface. Instead, by reducing the permeability of the AC through improved compaction and incorporating sufficient thickness to mitigate the potential for load associated cracking, the need for the ATPB in this location could be eliminated.

While the stiffness values of ATPB in both the dry and wet states appear larger than representative stiffness values for untreated granular bases, they are at least an order of magnitude less than the stiffness of conventional AC. Accordingly, improved pavement performance could, from a cost standpoint, be better achieved by proper mix design and thickness selection [e.g., use of the "rich bottom" concept (*3*)] and through improved construction practices, particularly AC compaction.

Based on the above results, a test program (Goal 5) to study the in-situ performance of ATPB in a wet state when subjected to the HVS loading was established. This added program included, for comparative purposes, a "wet" section of the pavement containing the untreated aggregate base as well. As shown in Figure 4, these sections have been designated 543RF and 544RF. Preliminary results of this study are reported in Section 5.7.

5.4 Three-Dimensional (3-D) Contact Stresses Between Tire and Pavement Surface Measured by Vehicle-Road Surface Pressure Transducer Array (VRSPTA) (*18*)

Slow moving wheel loads with free-rolling pneumatic bias/cross ply and radial tires were applied by the HVS to a pavement containing a 3-D stress sensor (VRSPTA) developed by the CSIR. A description of the VRSPTA is included in Reference (*18*). Six different tire types and several load/inflation pressure configurations were used in the test series, as presented in Table 6. The stresses measured simultaneously include: 1) vertical contact stress, σ_{zz}; 2) lateral (or transverse) shear stress, τ_{zy}; and 3) longitudinal shear stress, τ_{zx}. Figures 9a, b, and c illustrate the three components of stress measured for a new Goodyear Radial G159A 11R22.5 to be used

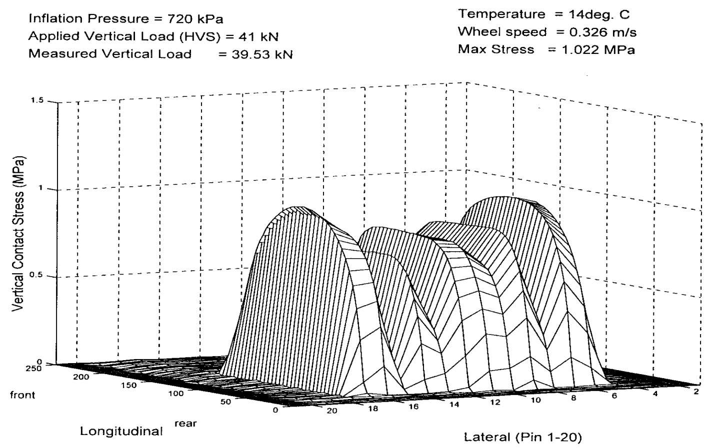
Table 6 Tires Tested in VRSPTA Study

Tire Type	Organization Using Tire	Tire Loads kN (lbs.$\times 10^3$)	Tire Pressures kPa (psi)	Tire Use
Goodyear Bias Ply, 10.00×20 (Used)	UCB-PRC	15–50 (3.37–11.2)	220–920 (32–133)	CAL/APT, HVS1 tests through May 1997
Goodyear Radial G159A, 11R22.5 (New)	UCB-PRC	15–50 (3.37–11.2)	220–920 (32–133)	CAL/APT, HVS1 tests beginning June 1997
Goodyear G286, Wide Base, 425/65 R22.5 (New)	UCB-PRC	20–100 (4.50–22.5)	500–1000 (73–145)	CAL/APT, HVS1 special tests after June 1997
BF Goodrich Aircraft Tire (Used)	UCB-PRC	20–100 (4.50–22.5)	1040 (151)	CAL/APT, HVS1 special tests
Goodyear Radial G159A 295/75 R22.5 (New and Used)[a]	NATC	15–35 (3.37–7.87)	420–820 (61–119)	Tires used on driverless trucks at WesTrack
Goodyear G178 Wide Base, 385/65 R22.5 (New)	NATC	30–50 (6.74–11.2)	500-1000 (73–145)	Typical off-road application tire

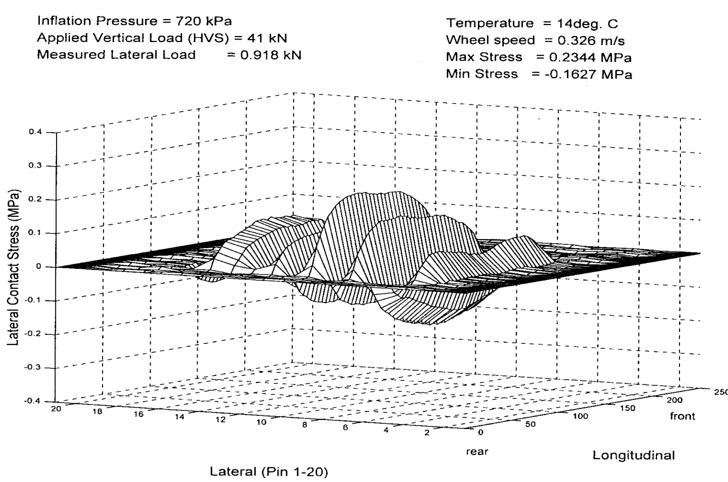
[a] New tires tested after 100 mile “run-in” at WesTrack; operating velocity of 40 mph

for the HVS tests which commenced in June, 1997, with a load of 41 kN (approx. 9,000 lb.) and a tire pressure of 720 kPa (approx. 105 psi).

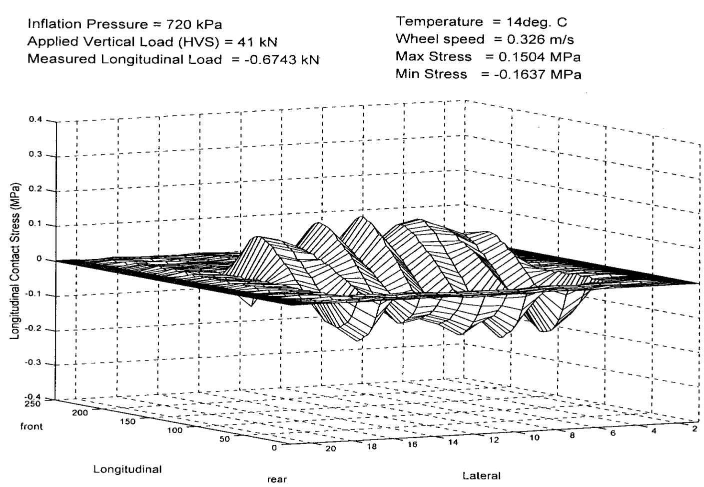
The HVS test program associated with Goal 1 (discussed in Section 5.2) was performed using a dual bias ply tire. The decision was made to change to radial tires for successive programs because they are used on a greater number of trucks in California. To compare results, it was considered important to include the tire data in the database obtained for the Goal 1 study to insure compatibility of test data between the initial and successive programs and proper interpretation of their results. The VRSPTA study provided detailed measurement of the surface contact stresses in order to model stress distributions in the asphalt concrete, both for permanent deformation (rutting) estimation (*19*) and for evaluation of fatigue cracking in the AC layer (*14,*



a. Vertical contact stress.



b. Lateral contact stress.



c. Longitudinal contact stress.

Figure 9. Stress distributions, Goodyear radial tire 11R22.5; inflation pressure = 720 kPa (105 psi); vertical load = 41 kN (9000 lb.).

15). For example, in the case of fatigue cracking, the initial cracks were observed to occur in the transverse direction. Results of 3-D finite element analyses performed using a representative stress distribution based on the VRSPTA generally support the observations, as reported in Section 5.2.(*15*)

In the permanent deformation analyses, the 3-D finite element simulations indicated that the deformation experienced in the AC layer depends strongly on the layer's resistance to shape distortion and only to a small degree on resistance to volume change.(*19*) In addition, the simulations indicated that the majority of the deformation in the AC layer occurs in the 75 mm (3 in.) immediately below the tire-pavement contact area. This finding is corroborated by field observations in the HVS rutting studies, in the WesTrack accelerated pavement test (*20*), and by observations of mixes in existing pavements [e.g., Reference (*21*)].

Results of the VRSPTA measurements are currently being used to define appropriate conditions for permanent deformation assessment in the constant-height repeated load shear test through finite simulations. In addition, the contact stress distributions have been incorporated in a new multi-layer elastic analysis, termed LEAP, for the analysis and design of AC pavements.(*22*) Discussion of this program is included in Section 5.18.2.

5.5 Mix Permanent Deformation Studies (Goal 4) (*23–25*)

In the period May to September 1997, HVS testing was performed with various wheel and tire types on the AC surface of Sections 500–503 as well as on the overlays of these sections (Goal 4). Table 7 provides a summary of the tires used and of the 10 tests conducted. For all of the tests, the HVS load carriage was operated in the channelized mode, i.e., without wander, and loading was applied in only one direction.[5] By operating the HVS in this mode, the resulting data can be utilized to validate analytical-based models that predict permanent deformation in the field from mechanical properties of mixes measured in the laboratory. In addition, it provides the opportunity to evaluate SHRP developed technology for mix design to mitigate permanent deformation, e.g., use of the simple shear test (*26*).

Figure 10 illustrates the development of rut depth with load applications for all of the tests conducted. Table 8 provides a summary of the repetitions to rut depths of 6.3 and 12.5 mm (0.25 to 0.5 in.) for the 10 tests. It will be noted that, in this instance, the dual wheels with bias-ply and radial-ply tires produce approximately the same amount of rutting.[6] The wide-base single tire results in about a 25 percent increase in rutting over the dual configuration, and the aircraft wheel causes significantly more rutting than the other tires for these conditions. The data also demonstrate the significant influence of pavement temperature on the development of permanent deformation, i.e., comparison of the test results for the wide-base single tire at 40ºC and 50ºC (104°F and 122°F) (Section 512RF versus 507RF).(*23*)

Results of laboratory tests on the DGAC and the ARHM-GG mixes indicate that the Stabilometer "S" value does not properly reflect the rutting performance of the ARHM-GG

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[5] When the HVS operates in the unidirectional mode, the HVS wheel travels the 8-m long section loaded in one direction. It rolls up a short ramp at the end of the section and is locked in a position in which the wheel is not in contact with the pavement. The wheel is then pulled back to the beginning of the section where it is placed in contact with the pavement for the next cycle.

[6] The dual bias-ply tires operate at a somewhat lower tire pressure than the dual radial tires [620 kPa (90 psi) vs. 720 kPa (105 psi)]

Table 7 Experiment Matrix for CAL/APT HVS No. 1 Tests for Rutting of the Original and Overlay Mixes

Section	Mix type	Wheel type	Loading condition	Speed (Standard Deviation)	Temp C @ 50 mm
504RF	Original DGAC (137 mm)	wide base single	40 kN, 110 psi	7.69 km/h (0.35)	50
505RF	Overlay DGAC (75 mm)	bias-ply dual	40 kN, 90 psi	7.74 km/h (0.54)	50
506RF	Overlay DGAC (75 mm)	radial dual	40 kN, 105 psi	6.94 km/h (0.25)	50
507RF	Overlay DGAC (75 mm)	wide base single	40 kN, 110 psi	7.69 km/h (0.35)	50
508RF	Overlay ARHM-GG thick (60 mm)	wide base single	40 kN, 110 psi	[a]	50
509RF	Overlay ARHM-GG thick (60 mm)	radial dual	40 kN, 105 psi	[a]	50
510RF	Overlay ARHM-GG thin (37 mm)	radial dual	40 kN, 105 psi	[a]	50
511RF	Overlay ARHM-GG thin (37 mm)	wide base single	40 kN, 110 psi	[a]	50
512RF	Overlay DGAC (75 mm)	wide base single	40 kN, 110 psi	[a]	40
513RF	Overlay DGAC (75 mm)	aircraft wheel	100 kN, 150 psi	[a]	50

- **Bias-ply dual:** 10.00×20 in., tread 6 plies nylon cord, sidewalls 6 plies nylon cord, maximum dual load 6,300 lbs. at 90 psi cold
- **Radial-ply dual:** 11R22.5, tread 6 plies steel cord, sidewalls 1 plies steel cord, maximum dual load 5,750 lbs. at 105 psi cold
- **Wide base single:** 425/65R22.5, tread 5 plies steel cord, sidewalls 1 ply steel cord, maximum load 10,500 lbs. at 110 psi cold
- **Aircraft wheel:** 46×15, reinforced tread, tubeless, 44,800 lbs. at rated pressure

[a] The wheel speeds were relatively constant for the three wheel types so they were not measured in subsequent tests.

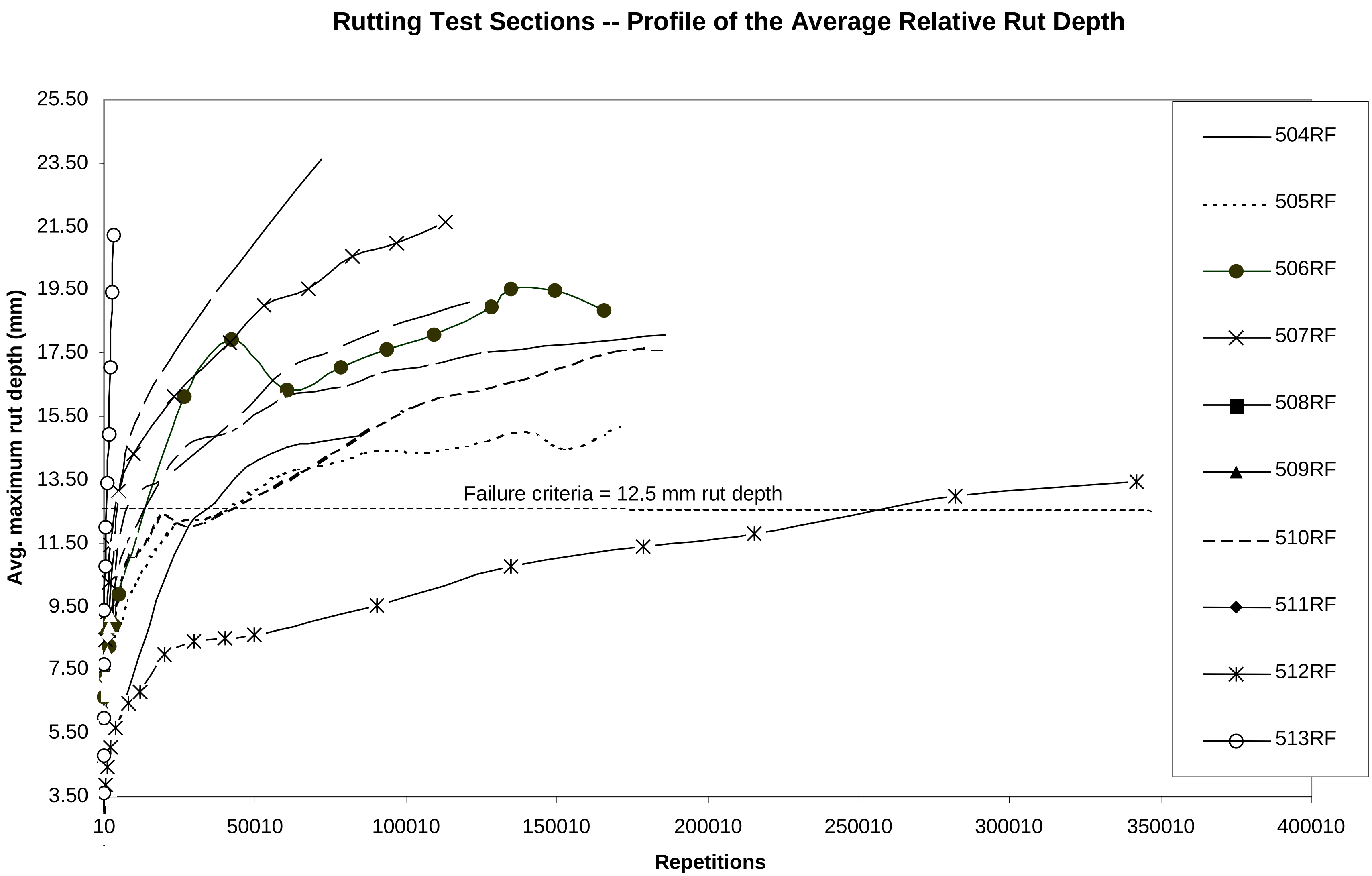

Figure 10. Plot of average maximum rut depth versus load repetitions for all test sections.

Table 8 Load Repetitions to 6.25-mm and 12.5-mm Average Maximum Rut Depth

Section	Tire Type	Overlay Type	Average Temperature at 50 mm (°C)	Reps to 6.25-mm Rut	Standard Deviation at 6.25 mm (mm)	Reps to 12.5-mm Rut	Standard Deviation at 12.5 mm (mm)
505RF	dual bias-ply	DGAC	50	756		14,500	2.1
506RF	dual radial	DGAC	50	120		7,000	2.3
507RF	wide-base single	DGAC	49	90	2.5	910	2.4
512RF	wide-base single	DGAC	41	3,530	0.9	127,600	1.5
513RF	aircraft	DGAC	48	30	1.7	420	3.8
508RF	wide-base single	ARHM-GG 62mm	51	375	0.6	4,150	1.5
509RF	dual radial	ARHM-GG 62mm	52	160	0.4	6,850	0.9
511RF	wide-base single	ARHM-GG 38mm	50	110	0.8	2,220	1.6
510RF	dual radial	ARHM-GG 38mm	51	310	1.0	15,800	1.4

relative to the DGAC ("S" for ARHM-GG = 23 versus "S" for DGAC = 43).(*23*) Results of the RSST-CH tests on a limited number of specimens prepared by rolling wheel compaction on both mixes suggest that this test may be a suitable procedure for mix design for mixes containing crumb rubber modified binders.(*25*) This conclusion is supported by the results of other investigations as well, e.g., References (*27*, *28*).

While the test results have validated the 2 to 1 equivalency of ARHM-GG relative to DGAC thickness it must be emphasized that this is applicable only for the fatigue and reflection cracking modes of distress. Because of the layer stiffness of the ARHM-GG compared to the DGAC over a range in temperatures, if ARHM-GG is used for overlays in relatively thin structural pavement sections at the 2 to 1 equivalency, surface rutting contributed by the underlying materials will, in all likelihood, be larger than if conventional DGAC is used.(*23*)

Results of the study suggest that Caltrans should monitor usage of the wide-base single tire on the pavement system. Extensive use of this type of tire could result in an increase in the rutting mode of distress in asphalt pavements.

It should be noted that these tests were completed in a total of about 14 days of loading. The results provide an indication of the usefulness of the HVS test to quickly examine rutting conditions and therefore serve as a valuable validation technique for evaluation of improved mix analysis and design methods used to evaluate this mode of distress, as well as a rapid means for evaluating the influences of new tire types and configurations on the rutting performance of asphalt pavements.

5.6 Accelerated HVS Loading Tests on Overlaid Pavements (Goal 3) (*29*)

The primary objective of this investigation was to evaluate the performance of two rehabilitation overlay strategies currently used by Caltrans:

1. conventional dense-graded asphalt concrete (DGAC); and
2. asphalt rubber hot mix gap-graded (ARHM-GG).

The overlays were placed, as described in Section 4, on the first four sections which had been loaded to failure (fatigue cracking) with the HVS (Figure 4).

Thicknesses for the DGAC overlays were selected according to the current Caltrans procedure, a deflection-based overlay design methodology.(*30*) Table 9 contains a summary of the thicknesses of the four overlay sections and their location in relation to the existing test sections. Trafficking was applied to all sections at a temperature of about 20ºC, the same as the tests on the original sections.

Table 9 Overlay Test Sections

Overlay Test Section	Material	Thickness mm (in.)	Underlying Test Section
514RF	DGAC	75 (3.0)[a]	500RF (Drained)
515RF	ARHM-GG	37 (1.5)	502CT (Drained)
517RF	DGAC	75 (3.0)	501RF (Undrained)
518RF	ARHM-GG	37 (1.5)	503RF (Undrained)

[a] Includes 15 mm (0.6 in.) to level up the existing rutted pavement

Current Caltrans practice for overlays is to design the thickness of the DGAC to provide a service life of 10 years. The thickness of the ARHM-GG overlay is taken as one-half the corresponding thickness of the DGAC. HVS tests by the CSIR on pavements in South Africa completed as a part of the Phase I portion of the CAL/APT program indicated that this approach appeared to be reasonable. However, it was considered important to verify this using local materials and standard construction practices in California. Statistical analyses of the results shown in Table 10 reinforce the Caltrans practice of the use of a 2-to-1 equivalency for ARHM-GG relative to DGAC in overlay applications. As stated in Section 5.5, however, this overlay equivalency is applicable to sections where the contributions of the untreated materials in the pavement section to surface rutting are minimal, that is, pavement sections for which there is adequate cover over the untreated layers.

Table 10 Results of CAL/APT HVS Tests on Overlays

Overlay Test Section	Load Applications, HVS$\times 10^6$				ESALs$\times 10^6$
	40 kN	80 kN	100 kN	Total	
514RF	0.17	0.14	1.35	1.67	66.0
515RF	0.13	0.022	2.06	2.41	101
517RF	0.15	0.18	2.02	2.35	98.1
518RF	0.12	0.11	1.41	1.63	68.0

5.7 HVS Loading on Drained and Undrained Pavements Under Saturated Base Conditions (Goal 5) (*31*)[7]

Two test sections, 543RF and 544RF (Figure 4), have been subjected to HVS loading under "wet" base conditions. As shown in Figure 4, Section 543RF includes ATPB (drained) while Section 544RF includes AB (undrained). Both sections were untrafficked at the time of this study.

Water was introduced into the pavement to simulate approximate surface infiltration rates that would occur for a badly cracked asphalt concrete layer along the northwest coast of California during a wet month. While the AC surface course in each of the test sections was initially uncracked, it was assumed that water would infiltrate from adjacent lanes. This permitted the evaluation of the performance of the drained and undrained structures and potential benefits of the drained pavement from the uncracked to the cracked condition.

HVS testing of Section 543RF was completed in March 2000 with approximately 1.2 million load repetitions applied to the pavement (38.5 million ESALs). Average maximum surface rutting at this time had reached 22 mm (0.9 in.).

Cores taken from the trafficked area indicated that the ATPB had stripped, whereas cores from the untrafficked portions of the pavement indicated that the ATPB was still in good condition at these locations. Percolation tests in the cored areas indicated a significant reduction of the permeability of the ATPB in the trafficked areas. When the section was later trenched, visual inspection showed that fines from the untreated AB intruded into the stripped ATPB in the trafficked portion, accounting for the measured reduction in permeability.

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[7] Report summarizing results of this investigation are in preparation at the date of this report. The test program is described in *Test Plan for CAL/APT Goal 5,* Pavement Research Center, Institute of Transportation Studies, University of California, Berkeley, November 1999.(*31*)

Testing of Section 544RF was completed in June 2000 after approximately 1 million load repetitions (38.5 million ESALs). Average maximum surface rutting was somewhat less [14.5 mm versus 22 mm (0.6 in. versus 0.9 in.)]. Fatigue cracking was, however, more extensive than obtained in the drained section at the same number of load repetitions. Deflections obtained from the MDDs indicated a significant increase in elastic deflection in the AB after the introduction of water; this likely would account for the increased fatigue cracking.

Results of the study confirm, for the ATPB section, the conclusions reached from the laboratory test for the ATPB program reported earlier.

5.8 Comparison of Caltrans, AASHTO, and Mechanistic-Empirical Pavement Design Methods (*32*)

This study included:

1. comparison of thicknesses determined by the Caltrans and AASHTO procedures for a range in traffic conditions and subgrade strengths;
2. determination of the effects of different drainage conditions on pavement thicknesses according to the AASHTO procedure together with comparison of these thicknesses with those obtained by the Caltrans method for the same traffic and subgrade conditions;
3. determination of the performance of pavements designed by the Caltrans procedure with equal gravel equivalents but with different thicknesses of asphalt concrete and comparison with performance estimated by the mechanistic-empirical procedure described in Section 5.1.

The analyses indicate that, for the same inputs, the AASHTO and Caltrans pavement thickness design procedures do not produce the same pavement thicknesses. This conclusion is based on currently used conversions of subgrade material response characteristics since the two procedures utilize different measures of subgrade response (which are sensitive to conversion from one type of laboratory test to another)—Caltrans uses the R-value and AASHTO uses the resilient modulus, M_R.

Generally, the pavement structures designed according to the Caltrans procedure are thicker than those resulting from the AASHTO procedure, as presented in Figure 11.

The AASHTO procedure includes provision for different drainage conditions. While the thickness of the AC remains constant, thicknesses of base and subbase can change substantially depending on anticipated drainage conditions. On the other hand, the Caltrans procedure assumes that pavement designs without special drainage provisions are adequate and that their inclusion make Caltrans pavement designs conservative, but the extent of this conservatism is not known.

Having validated the mechanistic-empirical design system with results of the first four HVS tests, the system was applied to two design options obtained from the Caltrans design procedure (*33*): one is termed *lowest (initial construction) cost* in the computer program and the other *thinnest AC layer allowed*. Both provide the same gravel equivalent for a given TI and subgrade R-value. The lowest cost pavements, which have thicker AC layers, exhibited larger fatigue lives than those with the thinnest AC layer, the difference increasing with increase in traffic, Table 11.

In terms of reliability, the lowest cost pavements are adequate at a 90-percent reliability level for all ranges of traffic and subgrade stiffnesses equal to or greater than about 84 MPa (12,000 psi). For stiffnesses less than 84 MPa, these pavements are not adequate at the 90-

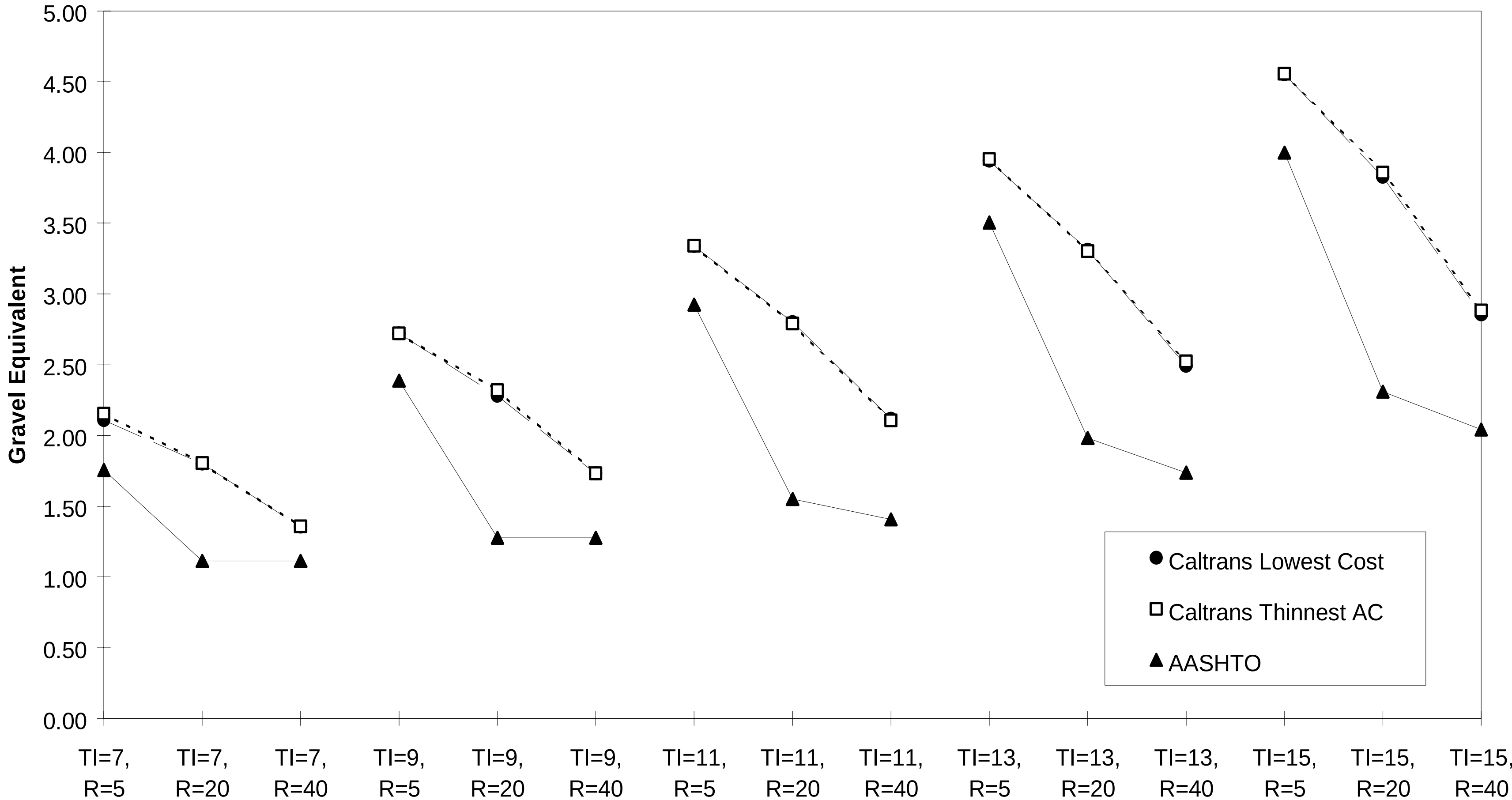


Figure 11. Gravel equivalents (GE) for pavements designed by Caltrans and AASHTO procedures.

Table 11 Ratio of Predicted Fatigue to Design ESALs, 90 Percent Reliability Level

ESALs	Subgrade Stiffness (MPa)	Caltrans Lowest Cost	Caltrans Thinnest AC
120,000	27	0.97	0.44
	84	0.85	0.54
	161	1.32	0.77
1,000,000	27	0.29	0.29
	84	1.38	0.37
	161	2.17	0.53
5,400,000	27	0.64	0.17
	84	2.18	0.20
	161	2.25	0.28
22,000,000	27	0.59	0.09
	84	1.27	0.11
	161	2.87	0.14
73,160,000	27	0.81	0.07
	84	1.70	0.09
	161	3.72	0.11

percent reliability level. All Caltrans designs with the thinnest AC layer allowed were not adequate at the 90-percent reliability level.

The results obtained in this study indicate that the structural contribution of the asphalt concrete (AC) to fatigue cracking resistance for thicker AC layers is larger than indicated by the Caltrans gravel equivalent factors, suggesting that the gravel factors for asphalt concrete should be re-evaluated.

All of the above analyses were made using a conventional mix containing a California Valley asphalt. Improved performance was obtained using a California Coastal asphalt. This improved performance did not, however, change the above conclusions regarding fatigue response.

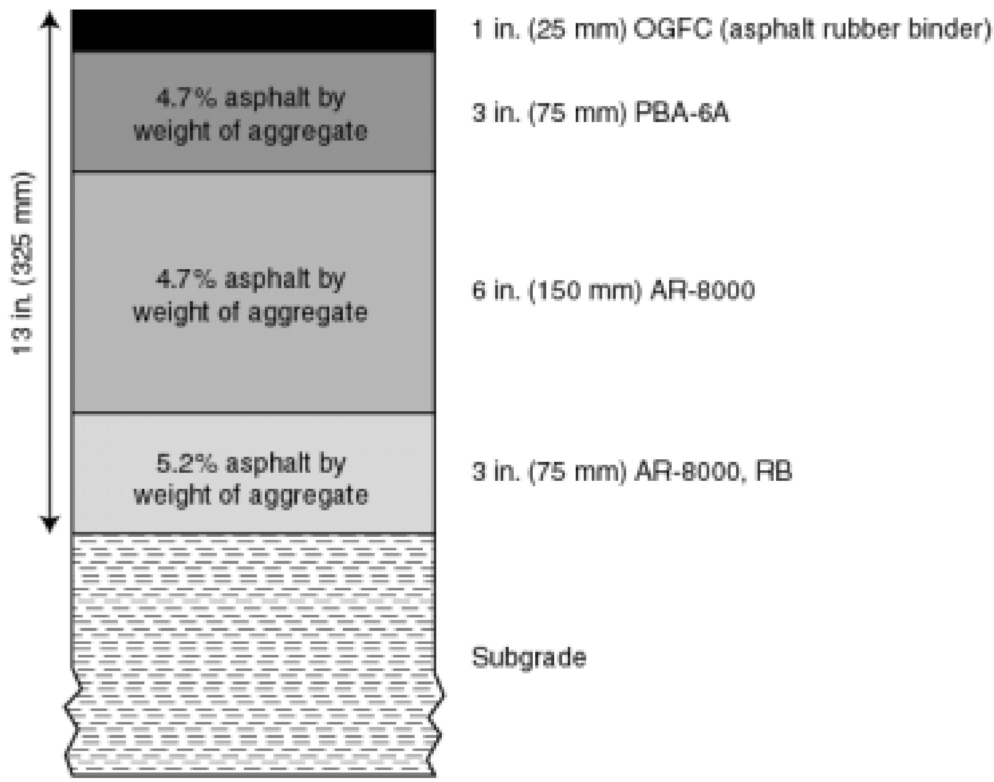
5.9 Mix and Structural Pavement Designs for Long Life Pavement Reconstruction (LLPR) — Interstate 710, Long Beach, California (*34, 35*)

This activity involved working with a joint Caltrans and Industry subcommittee of the Caltrans LLPRS Committee. The objective was to prepare suitable mix designs and structural pavement designs for a section of the I-710 Freeway adjacent to the Port of Long Beach California. The structural sections consisted of a full-depth asphalt section to be placed under the overcrossings as replacements for the existing portland cement concrete (PCC) pavement and an asphalt overlay for the cracked and seated PCC pavement.

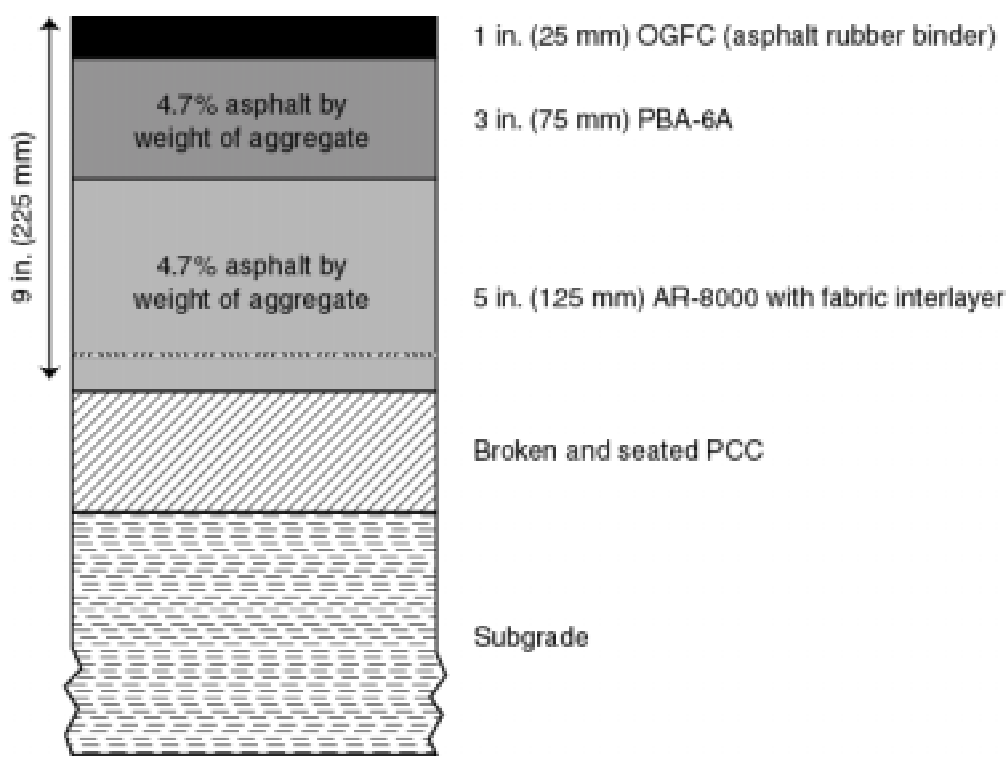
Strategic Highway Research Program (SHRP) developed rutting and fatigue tests as well as the California Stabilometer test were used for mix design and to provide information for mechanistic-empirical structural section designs to accommodate estimated traffic of 200 million ESALs for a 30-year period.

The recommended designs for both the replacement and overlay sections are shown in Figure 12. Included in the figure are mix composition data as well as structural section thicknesses. The procedures used were originally developed during SHRP and improved during the CAL/APT program using, in the case of fatigue, the results of the studies described in Sections 5.1 and 5.2.

N.B. At the date of this writing, HVS testing is underway on an overlay on Test Section 516 CT at the Richmond Field Station. The overlay consists of 75 mm (3 in.) of the PBA-6A mix overlaying 75 mm (3 in.) of the AR-8000 mix and the PCC pavement. The two mixes are representative of those used in the Long Beach area. They contain aggregate shipped to the Bay Area and locally available binders for mixing at a local central batch plant and placed by a local paving contractor at the RFS test site.



a. Replacement section.



b. Overlay section.

Figure 12. Proposed designs for Interstate 710 rehabilitation.

5.10 Pay Factor Determinations (*36, 37*)

With Caltrans instituting a QC/QA system for asphalt concrete construction and establishing penalties/bonuses (pay factors) related to the quality of construction, results from the CAL/APT program coupled with earlier SHRP-developed and recent WesTrack information on mix performance (*37*) provide a rational and feasible method for establishing these penalties and bonuses.

The approach that has been adopted focuses principally on economic impacts to a highway agency (in this case, Caltrans). It assumes that an appropriate penalty for inferior construction should be the added cost to the agency. It also assumes that the bonus for superior construction should be no greater than the added savings to the agency.

For new construction, these agency costs/savings are associated primarily with subsequent pavement rehabilitation. Inferior construction hastens future rehabilitation and may increase the cost of rehabilitation as well. As a result, inferior construction increases the present worth of future rehabilitation costs. Superior construction, on the other hand, reduces the present worth of these costs largely by deferring the future rehabilitation. The difference in present worths of rehabilitation costs, as constructed versus as specified and as expected, provides a rational basis for setting the level of penalty/bonus for inferior/superior construction quality.

To compute the differential worth of future rehabilitation requires two different types of models:

1. a performance model or models for determining the effect of construction quality on expected pavement performance; and
2. a cost model for translating these effects into rehabilitation dollars.

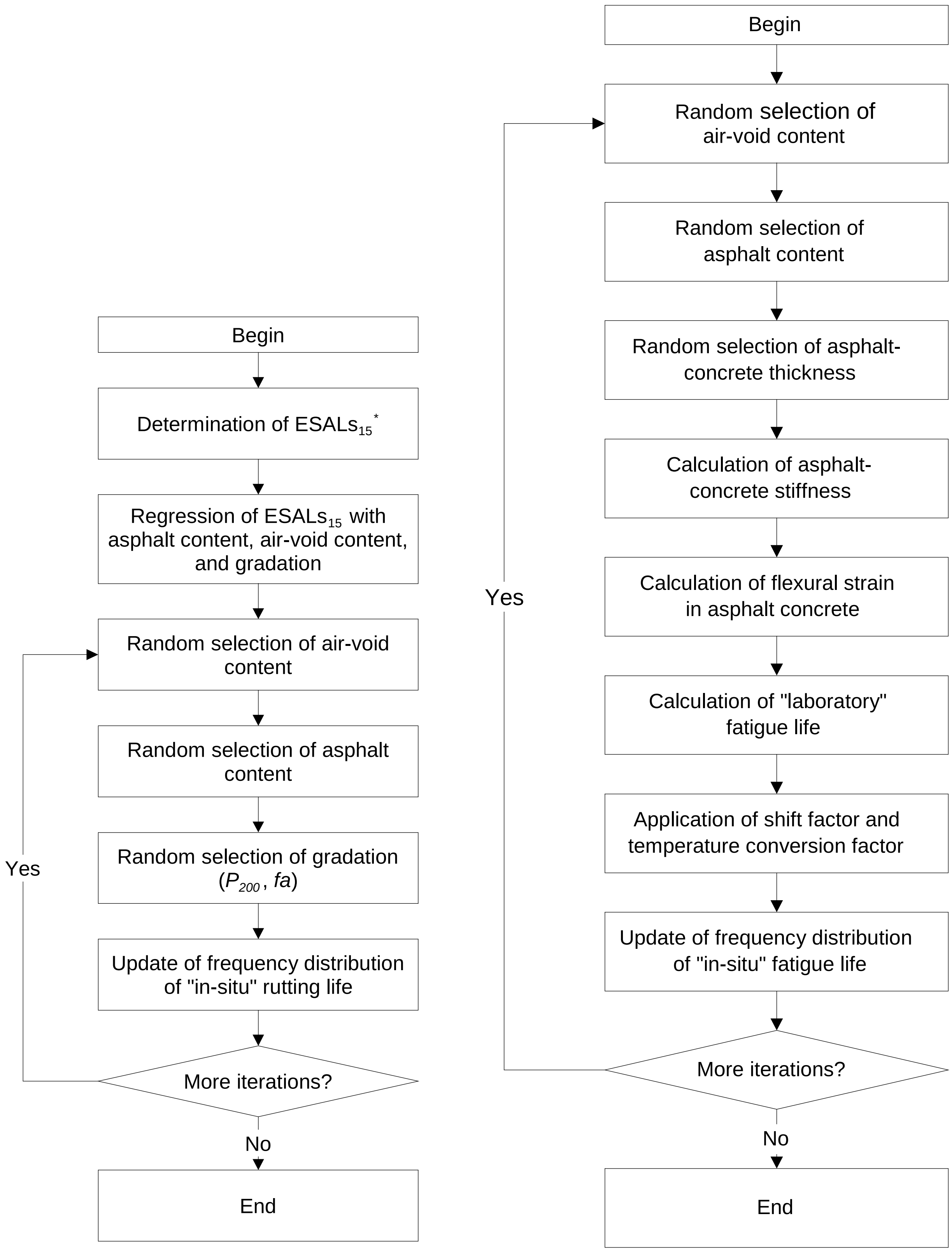
Two performance models have been used: one for rutting and the other for fatigue cracking. The rutting model utilizes the results of the WesTrack experiment (*37*) while the cracking model follows the framework described in detail in Reference (*36*). Monte Carlo simulations are used to obtain distributions of pavements lives. Figure 13 outlines the performance simulations using both models.

As shown in Figure 13, central to the process is the random selection of asphalt concrete (AC) construction quantities including asphalt content (P_{Wasp}), air-void content (V_{air}), aggregate gradation parameters [percent passing No. 200 sieve (P_{200}) and the amount of aggregate between the No. 8 and No. 200 sieves (*fa*)] for rutting, and AC thickness for fatigue.

The random selections assume normally distributed random variables with known or assumed means and variances. Estimates of these variances were obtained from a combination of literature review, moduli backcalculations of FWD measurements, and data obtained as a part of WesTrack (*37*). Summary results are presented in Table 12. This table includes both materials and construction components and components resulting from sampling and testing. The latter components must be removed from the variance estimates to isolate materials and construction effects. The percentages of variance attributed to materials and construction are shown in Table 12 as well. Reference (*37*) describes the basis for obtaining these values.

The cost model considers only the time to the next rehabilitation activity; i.e., it ignores future rehabilitation measures beyond the first cycle. It requires an estimate of future rehabilitation cost; it considers annual inflation of rehabilitation costs, traffic growth, expected years of the constructed life of the asphalt concrete, and a discount rate representing the time value of money.

The performance models yield the 10^{th} percentile in-situ lives for ruts (15 mm in depth) and fatigue cracking (10 percent in wheel paths) for both expected or on-target construction quality as well as off-target construction quality. The relative performance, *RP*, the performance



a. Rutting **b. Fatigue Cracking**

***ESALs to a rut depth of 15 mm**

Figure 13. Outlines of performance simulations for rutting and fatigue cracking.

Table 12 Construction Targets

Variable	Mean	Total standard deviation (including sampling and testing)	Percent of variance attributed to materials and construction
Asphalt content (%)	5.0	0.3	40
Air-void content (%)	7.0	1.5	60
Mineral filler (%)	5.5	0.9	75
Fine aggregate (%)	30.0	3.0	85
Asphalt-concrete thickness (in.)	4 pavement structures	$0.15 \times$ AC thickness$^{0.69}$	75

Table 13 Levels and Ranges for Variables Evaluated

Variable	Mean		As-constructed standard deviation	
	Levels	Range	Levels	Range
Asphalt content	21	4.0 to 6.0	9	0.114 to 0.266
Air-void content	21	5.00 to 9.75	9	0.684 to 1.596
Mineral filler	21	3.0 to 8.0	9	0.4674 to 1.0906
Fine aggregate	21	24.0 to 36.0	9	1.6596 to 3.8724
Thickness	21 for each of 4 pavement sections	-1.0 to 1.0	9	4.8% to 11.2%

input to the cost model, is computed as follows:

$$RP = \frac{\textit{off-target ESALs}}{\textit{on-target ESALs}}$$

The first step in the cost model is to determine the off-target pavement life in years, *OTY* (off-target years), that results from the simulated performance differential. Assuming that traffic grows geometrically, the off-target pavement life is computed as follows:

$$OTY = \frac{\ln\left(1 + RP\left[(1+g)^{TY} - 1\right.\right)}{\ln(1+g)}$$

in which g is the annual rate of traffic growth expressed as a decimal and *TY* (target years) is the number of years of pavement life resulting from on-target construction activity.

The cost model assesses the present worth of moving the first rehabilitation cycle from its on-target position, *TY*, to its off-target position, *OTY*. The net present worth, expressed as a percentage of the rehabilitation costs (in current-year dollars) is computed as follows:

$$\Delta PW = C\left(\frac{(1+r)^{OTY}}{(1+d)^{OTY}-1} - \frac{(1+r)^{TY}}{(1+d)^{TY}-1}\right)\left(\frac{(1+d)^{OTY}-1}{(1+d)^{OTY}}\right)$$

in which ΔPW is the percentage change in the present worth of the cost of the first rehabilitation cycle, r is the annual rate of construction-cost inflation expressed as a decimal, and d is the annual discount rate expressed as a decimal. Applying this percentage to the expected rehabilitation cost yields the agency cost increment due to off-target construction.

With this approach, pay factors were developed to consider the effects of asphalt content (pf_{ac}), air void content (pf_{av}), AC thickness (pf_t), percent passing No. 200 sieve (pf_{mf}) and the fine aggregate amount (pf_{fa}).

The process involves determination of ΔPW for each of the construction variables individually for rutting and fatigue. Table 14 illustrates the effect of asphalt content on ΔPW (in percent) for rutting for the range in parameters shown in Tables 12 and 13. The computations are based in the following list parameters:

1. 2 percent annual rate of inflation in resurfacing/rehabilitation cost (r);
2. 2.5 percent annual rate of traffic growth (g);
3. 5 percent discount rate (d);
4. 20-year expected pavement life (TY); and
5. Rutting failure results in resurfacing which costs 20 percent of the cost of new pavement construction in current-year dollars.

Table 14 Effect of Off-Target Asphalt Content on Future Agency Resurfacing Cost Based on Rutting Model (Change Expressed as a Percentage of New Pavement Construction Cost)

As-Constructed Average Asphalt Content (Percent)	As-Constructed Standard Deviation of Asphalt Content (Multiple of 0.19 percent)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
4.0	-13.9	-13.9	-13.8	-13.8	-13.7	-13.6	-13.5	-13.4	-13.3
4.5	-10.0	-9.9	-9.6	-9.5	-9.2	-9.0	-8.7	-8.5	-8.1
5.0	-1.6	-1.2	-0.9	-0.4	0.0	0.5	0.9	1.5	2.0
5.5	9.8	10.2	10.6	10.9	11.4	11.8	12.2	12.6	13.1
6.0	17.4	17.6	17.8	18.0	18.2	18.3	18.5	18.6	18.7

Table 15 illustrates the effect of air void content on fatigue using the same cost parameters but assuming that fatigue failure results in rehabilitation which costs 50 percent of the cost of new pavement construction in current-year dollars. Negative ΔPW values indicate savings to the agency while positive values indicate increased agency costs.

Table 15 Effect of Off-Target Air-Void Content on Future Agency Rehabilitation Cost Based on Fatigue Model (Change Expressed as a Percentage of New Pavement Construction Cost)

As-Constructed Air-Void Content (Percent)	As-Constructed Standard Deviation of Air-Void Content (Multiple of 1.2 Percent%)								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.2**	**1.3**	**1.4**	**1.6**
5.00	-20.4	-19.9	-19.3	-18.7	-18.1	-17.4	-16.7	-15.9	-15.1
6.00	-12.9	-12.2	-11.5	-10.8	-10.0	-9.2	-8.4	-7.5	-6.6
6.9	-4.4	-3.6	-2.8	-2.0	-1.2	-0.3	0.5	1.5	2.4
7.85	4.5	5.3	6.0	6.8	7.6	8.4	9.3	10.2	11.1
9.0	15.0	15.6	16.3	16.9	17.6	18.3	19.0	19.7	20.4
9.75	20.4	20.9	21.4	21.9	22.5	23.0	23.5	24.1	24.6

Table 16 contains the results of combining the computations for rutting and fatigue cracking for asphalt content for results most favorable to the agency. It will be noted that agency costs are increased for deviations in asphalt content both above and below the target value.

Table 16 Effect of Off-Target Asphalt Content on Future Agency Resurfacing/Rehabilitation Costs (Change Expressed as a Percentage of New Pavement Construction Cost)

As-Constructed Average Asphalt Content (Percent)	**As-Constructed Standard Deviation of Asphalt Content (Multiple of 0.19 Percent)**								
	0.6	**0.7**	**0.8**	**0.9**	**1.0**	**1.1**	**1.2**	**1.3**	**1.4**
4.0	3.2	3.2	3.2	3.2	3.3	3.3	3.3	3.3	3.3
4.5	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
5.0	0.0	0.0	0.0	0.0	0.0	0.5	0.9	1.5	2.0
5.5	9.8	10.2	10.6	10.9	11.4	11.8	12.2	12.6	13.1
6.0	17.4	17.6	17.8	18.0	18.2	18.3	18.5	18.6	18.7

With information like that shown in Table 16, pay factor tables were then established for each of the construction variables. Tables 17, 18, and 19 show the pay factors for asphalt content, air-void content, and AC thickness, respectively.

Combined pay factors can be computed by the following equation:

$$Combined\ \ pay\ \ factor = (1+pf_{ac})(1+pf_{av})(1+pv_{mf})(1+pf_{fa})(1+pf_{t})-1$$

in which all pay factors are expressed as decimals. Reference (36) describes the basis for this simplified expression for combining pay factors.

As an example, consider the combined pay factor for the following mix parameters

Mix Parameter	Value Relative to Target	Standard Deviation (percent)
asphalt content	+ 0.2 %	0.3
air-void content	+2.0 %*	1.5
AC thickness	-0.6 in.	9.0

* target value = 7.0 percent

The resulting combined pay factor is:

$$Combined\ \ pf\ = (1-0.05)(1-0.19)(1-0.13) = 0.67,\ \ or\ 67\ percent$$

This approach provides a rational basis for defining reasonable pay factors which are based on estimates of pavement performance using mechanistic-empirical pavement analyses and supported by HVS tests and other test track performance.

Table 17 Contractor Pay Factors for Asphalt Content (Percentage of Future Resurfacing/Rehabilitation Cost in Current-Year Dollars)

Difference Between As-Measured Average Asphalt Content and Design Asphalt Content (Percent)	As-Measured Standard Deviation of Asphalt Content (Percent)		
	Below 0.255	0.255 to 0.345	Above 0.345
-1.10 to -0.91	-3	-3	-3
-0.90 to 0.71	-3	-3	-3
-0.70 to -0.51	-2	-2	-2
-0.50 to -0.31	-1	-1	-1
-0.30 to -0.11	-1	-1	-1
-0.10 to 0.09	0	0	-1
0.10 to 0.29	-3	-5	-6
0.30 to 0.49	-8	-9	-11
0.50 to 0.69	-12	-13	-14
0.70 to 0.89	-15	-16	-17
0.90 to 1.09	-18	-18	-19

Table 18 Contractor Pay Factors for Air-Void Content (Percentage of Future Resurfacing/Rehabilitation Cost in Current-Year Dollars)

As-Measured Average Air-Void Content (Percent)	As-measured standard deviation of air-void content (%)		
	Below 1.32	1.32 to 1.78	Above 1.78
4.8–5.7	5	5	4
5.15–5.7	4	3	3
5.75–6.20	3	2	2
6.25–6.65	2	1	1
6.70–7.05	1	0	-1
7.1–7.55	-1	-3	-6
7.6–8.05	-5	-8	-10
8.1–8.55	-10	-12	-14
8.6–8.95	-14	-16	-18
9.0–9.45	-17	-19	-21
9.5–10.0	-21	-22	-24

Table 19 Contractor Pay Factors for Asphalt Concrete Thickness (Percentage of Future Resurfacing/Rehabilitation Cost in Current-Year Dollars)

Difference between As-Measured Average AC Thickness and Design Thickness (in.)	As-measured standard deviation of AC thickness (%)		
	Below 7.85	**7.85 to 10.62**	**Above 10.62**
-1.10 to -0.89	-18	-21	-23
-0.90 to -0.69	-15	-17	-20
-0.70 to -0.49	-11	-13	-16
-0.50 to -0.29	-6	-9	-12
-0.30 to -0.09	-2	-5	-8
-0.10 to 0.09	3	0	-3
0.10 to 0.29	7	5	2
0.30 to 0.49	11	9	6
0.50 to 0.69	15	13	10
0.70 to 0.89	19	17	15
0.90 to 1.09	24	21	19

5.11 Effects of Binder Loss Stiffness (SHRP PG Binder Specification Requirement) on Fatigue Performance of Pavements (*38*)

This study evaluated the influence of binder loss stiffness ($G^*\sin\delta$), the parameter included in the SHRP binder specification to control fatigue response on pavement performance. Results from two studies were included, namely: 1) those performed during the SHRP research program, which evaluated the fatigue response of mixes containing eight asphalts and two aggregates and the simulated performance in representative pavement structures;(*39*) and 2) a detailed study of the effects of binder loss stiffness on the simulated fatigue performance of 18 different pavement sections designed according to the Caltrans procedures and evaluated in three different temperature environments in California.(*3*) (*N.B. These are the same pavement sections used for the analyses reported in the fatigue study and described earlier in Section 5.1*).

Results of both investigations indicated that the loss stiffness of the binder is not by itself a sufficient indicator of the fatigue performance of asphalt concrete in pavement structures.

Moreover, these studies have highlighted the basic difference between the current binder specification (which sets a maximum limit on loss modulus) and field performance simulations, which suggest that larger moduli are beneficial for most pavement structures. Figure 14 illustrates this point for the 18 pavement sections designed by the Caltrans procedure.

This study emphasized that the binder alone does not determine fatigue response in the pavement structure. Mix characteristics as well as the pavement structure itself and the environment within which it is located have a significant role in determining pavement performance.

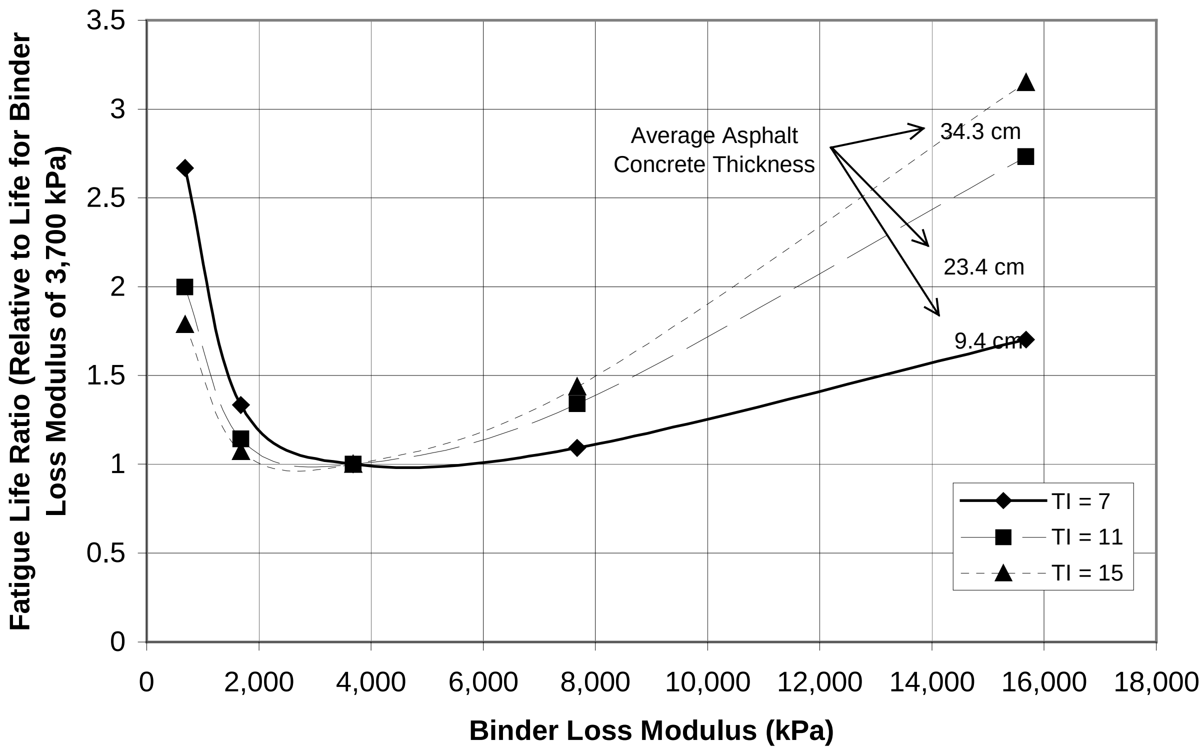


Figure 14. Relationship between average fatigue life ratio and binder loss modulus for 18 hypothetical pavement structures.

5.12 Accelerated Loading of Full Scale Concrete Pavements at the RFS and on State Route 14 Palmdale, CA (*40–43*)

This section describes the results obtained to date for the accelerated test program associated with CAL/APT Goal LLPRS-Rigid Phase III.(*40*) The program was initiated in January 1998 as described in Section 2. Included is a summary of the results obtained from the HVS test on Section 516CT at the Richmond Field Station during the period March–May 1998 and the results to date from the HVS tests on the test sections on State Route 14 near Palmdale, California.

5.12.1 RFS Test Section (516 CT) Results.

Test section 516CT was constructed at the RFS in late December 1997. The purpose of its construction was to gain experience with the installation of instrumentation and data acquisition under HVS loading planned for the extensive accelerated test program at Palmdale prior to the construction of the Palmdale test sections.

Figure 5 illustrates the layout and cross-section of the RFS test with instrumentation including thermocouples and static and dynamic strain gages. Testing began in March 1998 and lasted for a 2-month period during which about 440,000 repetitions of a 60-kN (13.5-kip) load were applied along the edge of the pavement.[8] Failure of the concrete was obtained in the form of a corner crack due to loss of support from pumping in the base/subgrade layer.

Performance of the test section relative to the expected life according to Caltrans' design methodology is shown in Figure 15. The figure indicates that the Caltrans design is conservative. The thickness of the concrete slab was 228 mm (9.0 in.) [versus 200 mm (8.0 in.)

[8] One 60-kN load application at the edge of the pavement corresponds to 113 ESALs according to the AASHTO definition (*45*).

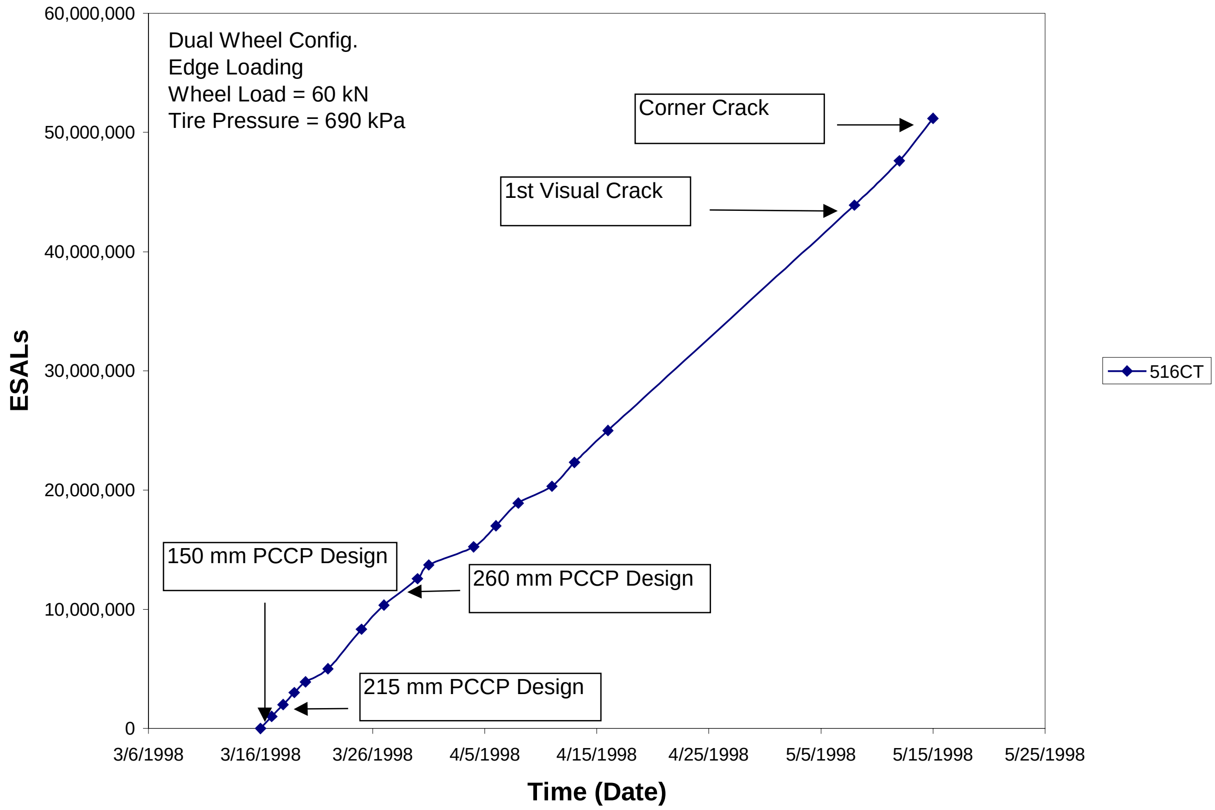


Figure 15. ESALs versus time, Test Section 516 CT.

planned] and the strength of the concrete was approximately 55 percent higher than the minimum strength required by Caltrans for opening concrete pavements to traffic.

The failure experienced with this section under heavy loading stressed the importance of using a non-erodable base and load transfer devices (dowels) at the transverse joints.

In addition to providing useful performance information, the overall experience gained from this test assisted the research team in avoiding time consuming and costly instrumentation and data acquisition problems in the Palmdale sections, the major reason for which it was constructed.

5.12.2 Palmdale (SR14) Test Section Results

Figure 6 contains a summary of the layout of test pavements, construction of which was completed in June 1998. The FSHCC was hand-placed between forms using ready-mix trucks and a dry mix batch plant. Instrumentation is described in Reference (*42*).

The primary purpose of the sections on the South Tangent, three thicknesses of FSHCC ranging from 100 mm (4 in.) to 200 mm (8 in.), was to provide data to define the fatigue resistance of the FSHCC under repeated stressing relative to conventional PCC. The sections on the North Tangent have been designed to provide information on the performance of concrete pavements with dowels at the transverse joints, tied concrete shoulders, and widened traffic lanes, i.e., 4.3-m (14-ft.) as compared to the conventional 3.7-m (12-ft.) width. Table 20 provides a summary of the test sections planned for investigation.

HVS testing started on the South Tangent sections on 15 July 1998. For these sections loading was applied bi-directionally along the edge of the slabs. Temperature in the majority of slabs was maintained at 20° ± 5°C (68° ± 9°F) to ensure a temperature gradient of approximately zero. Table 20 provides a summary of the test program. At the date of this report all of the tests have been completed on the South Tangent sections (1A–D, 3A–D, 5A–D) and on one-half of the North Tangent sections (7A–D, 9A, 9C). For each test section, failure was defined when there was a visual crack on the surface of the main slab. Test locations have failed with longitudinal, transverse, or corner cracks.

A typical deflection versus HVS repetitions relationship is shown in Figure 16 for Section 3-B. Measured deflections can be rationalized by looking at the development of cracking in Figure 16. In this figure, the sequence of cracking is designated by the letters a, b, and c. Deflections at the joint are much more sensitive to slab cracking than at the edge for this test section. Figure 17 shows the change in dynamic strain at the mid-slab edge versus HVS repetitions for Section 3-B. The strain output of the gages appears to be stable until the cracking approaches the vicinity of the gage.

To evaluate the fatigue resistance of the FSHCC pavement in Palmdale relative to fatigue data for PCC, bending stresses in the slab were backcalculated from measured edge deflections. These backcalculated stresses were then divided by the 90-day flexural strength of the concrete to determine the applied stress ratio in the slab during HVS testing. The applied stress ratio versus HVS repetitions to failure for all nine test locations were then plotted. Figure 18 shows the results of the HVS fatigue tests on FSHCC pavements relative to the Portland Cement Association (PCA) fatigue curve (*46*), beam fatigue curve based on 50 percent probability of fatigue failure,(*47*) PCC slab fatigue curve taken from laboratory tests,(*48*) and field fatigue curve by Vesic (*49*) based on the AASHO Road Test. This preliminary field fatigue curve for FSHCC pavements is similar to the fatigue resistance of PCC slabs in the laboratory.

Current testing on the North Tangent is focused on the performance of the different pavement design features, as described in Table 20.

Shortly after construction, many of the slabs in the test sections cracked under environmental loading before any traffic loading was applied. Environmental loading resulted in transverse cracking through the middle of the slab. Results of the investigation of the failure of these FSHCC slabs using field measurements, laboratory testing to define shrinkage and thermal properties, and finite element analysis, are included in Section 5.14.

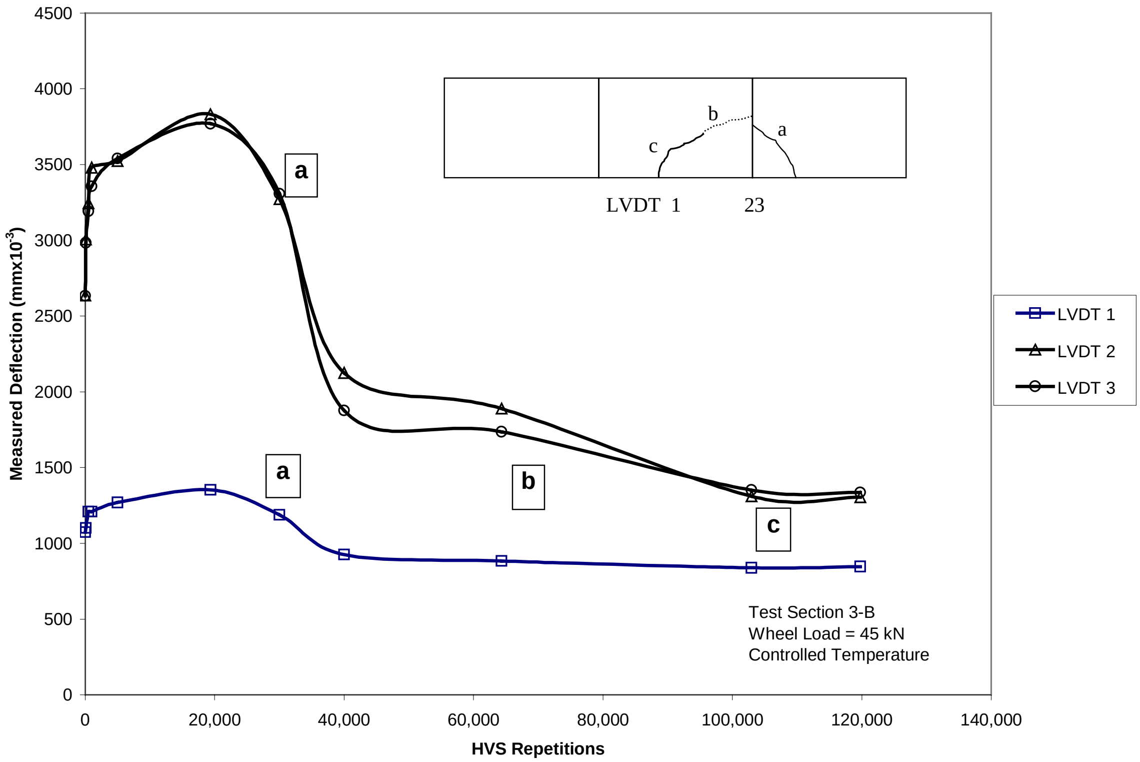


Figure 16. Measured deflections at slab edge and joint for HVS Test Section 3-B.

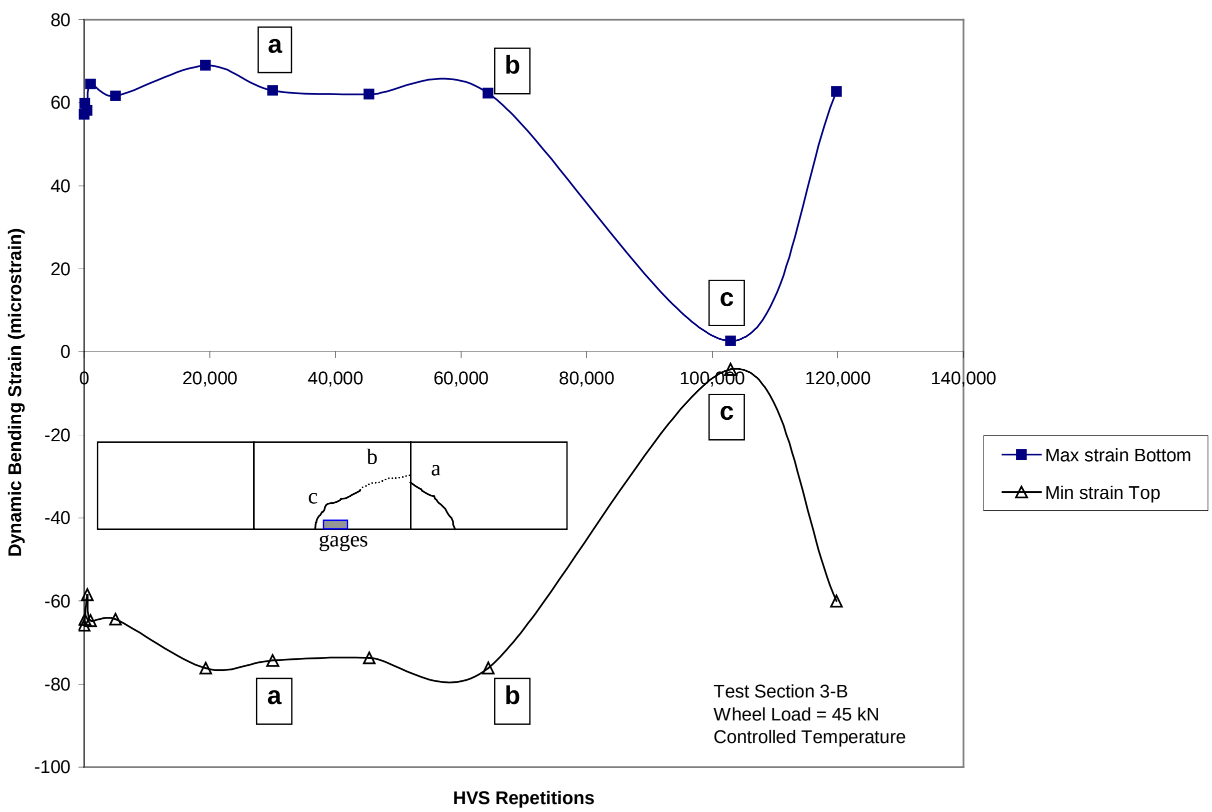


Figure 17. Measured bending strains at the slab edge for Test Section 3-B.

Table 20 Test Sections and Test Parameters

Study	Temporary Test Number	Concrete Thickness (mm)	Base Type	Design Features[a]	Wheel Load (kN)	Wheel Load Direction	Water Condition/ Temperature Conditions[b]
Develop FSHCC Fatigue Curve	1A	100	AB	none	25	bi	dry/C
	1B	100	AB	none	35	bi	dry/C
	1C	100	AB	none	30	bi	dry/C
	1D	100	AB	none	20	bi	dry/C
	3A	150	AB	none	80	bi	dry/C
	3B	150	AB	none	60	bi	dry/C
	3C	150	AB	none	60	bi	dry/A
	3-D	150	AB	none	40	bi	dry/C
	5A	200	AB	none	100	bi	dry/C
	5B	200	AB	none	90	bi	dry/C
	5C	200	AB	none	90	bi	dry/C
	5D	200	AB	none	80	bi	dry/C
Evaluation of Design Features	7A	200	CTB	none	60	bi	dry/C
	7B	200	CTB	none	60	uni	wet/C
	7C	200	CTB	none	80	bi	dry/A
	7D	200	CTB	none	80	uni	wet/A
	9A	200	CTB	D/T	60	bi	dry/C
	9B	200	CTB	D/T	60	uni	wet/C
	9C	200	CTB	D/T	80	bi	dry/A
	9D	200	CTB	D/T	80	uni	wet/A
	11A	200	CTB	D/W	60	bi	dry/C
	11B	200	CTB	D/W	60	uni	wet/C
	11C	200	CTB	D/W	80	bi	dry/A
	11D	200	CTB	D/W	80	uni	wet/A

[a]design feature notes: D = dowels
T = tied concrete shoulder
W = widened lane

[b]temperature conditions: A= ambient
C = controlled at ~20°C

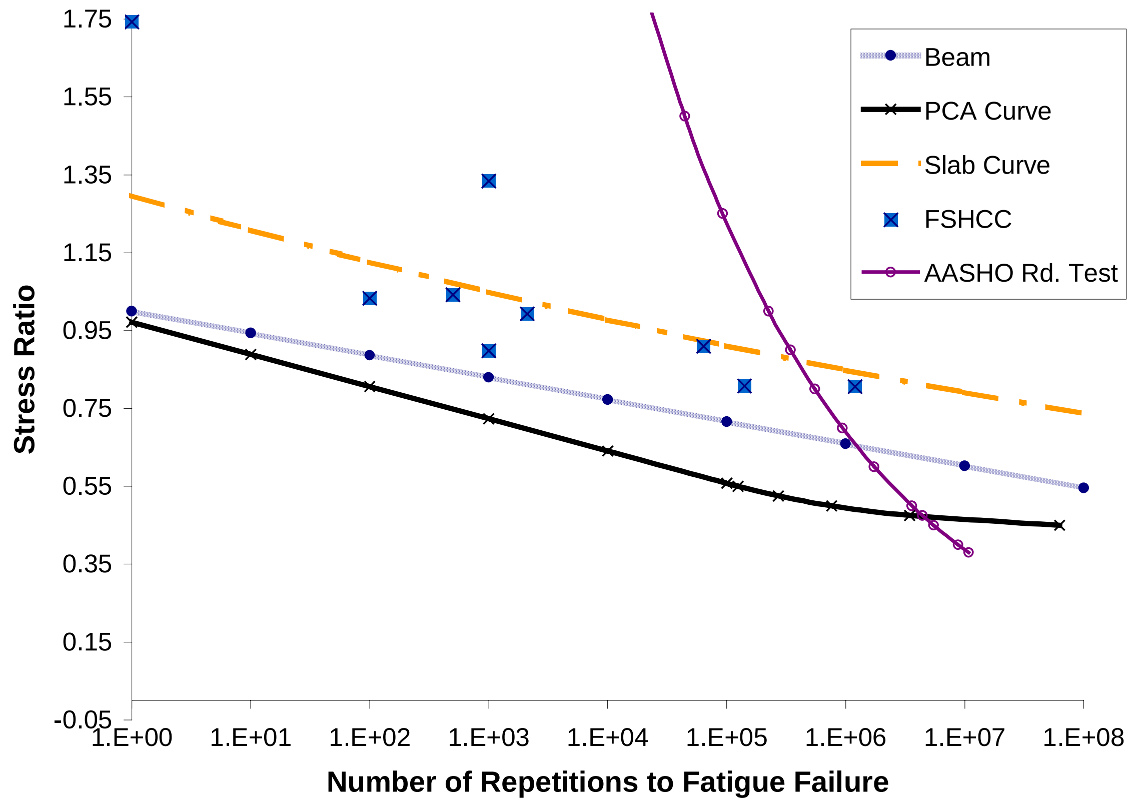


Figure 18. Comparison of FSHCC and PCC fatigue resistance.

5.13 Long-Term Durability of Concrete Mixes Used in LLPR Program (*50–52*)

In order to obtain high early strengths considered necessary for the use of concrete in the LLPR program, new cementitious materials are being evaluated by Caltrans. For the anticipated 30-plus year design life, it is essential that the materials selected exhibit long-term durability. Most of the cements under consideration have not been used extensively for pavement construction in the U.S. Thus, it was considered extremely important to characterize the long-term durability of each material.

Deleterious reactions that could impact long-term performance of cementitious materials include sulfate attack, alkali-aggregate reaction, corrosion of reinforcing steel and dowels, and freeze-thaw action. Thus far, studies have been directed to sulfate attack and alkali-aggregate reaction, also referred to as alkali-silica reaction (ASR).

5.13.1 Sulfate Resistance of Hydraulic Cements (*51*)

In order to assess the susceptibility of cements considered for use in the LLPR program, an accelerated test program was undertaken. In the accelerated test method utilized, changes in cement paste strengths after periods of sulfate exposure relative to the strength after seven days hydration were used to assess the sulfate resistance of five cements submitted by four different manufacturers, three standard portland cement types, and one portland cement/pozzolan blend. The cements were classified into three categories: portland cements and blends (PC), calcium aluminate cements and blends (CA), and calcium sulfoaluminate cements (CSA). After 28 and 63 days of exposure to a 4-percent Na_2SO_4 solution maintained at 7.2 pH, performance of the nine cements and blends tested can be described by the following order:

At 28 days,

CA3 = CSA2 = Type I/II > Type V = Type III > CA1 > PC4 > CA2 > CSA1

while at 63 days,

CA3 = Type I/II = CSA2 > Type III = Type V > PC4 > CA2 > CA1 > CSA1

The laboratory testing has shown that several cementitious products may be susceptible to sulfate attack (CA1, CA2, CSA1). Oxide analyses of the portland cements show that Type I/II, Type III, and Type V had similar tricalcium aluminate contents (< 5 percent). The accelerated sulfate testing results indicated that all three cement types were sulfate resistant, as is expected from the chemical oxide analysis. One calcium aluminate (CA3) and one calcium sulfoaluminate cement type (CSA2) demonstrated excellent sulfate resistance.

Due to the lack of evidence of sulfate attack on California highway pavements, it can be assumed that the existing cement being utilized by Caltrans (Type I/II) is sulfate resistant. Accordingly, sulfate resistance of this cement has been considered the baseline for evaluation of the other cements tested in the study.

Based on these tests it was recommended that Caltrans adopt and enforce the sulfate resistance guidelines for 100 percent portland cement concretes, as defined by ACI Building Code 318/318-95 (Section 4.3 sulfate exposures, p. 37–38).(*53*)

If a contractor proposes to use a different type of cementitious material not covered by the ACI Building Code 318/318-37, evidence should be provided that the material in question is sulfate-resistant. The proposed cementitious material should have similar performance to ASTM Type I/II cement in the accelerated sulfate resistance test described in this report. Any proposed cementitious material should have less than 25 percent loss of strength at 28 days and 63 days of sulfate exposure relative to the 7-day strength of the material following the procedure described in Reference (*53*).

5.13.2 Alkali-Silica Reaction (ASR) Susceptibility (*52*)

It has been demonstrated that certain types of aggregates can cause deleterious expansion through an alkali-silica reaction (ASR). To insure the long-term durability of new concrete pavements, the susceptibility of cements and aggregates to ASR requires evaluation. In this investigation, the accelerated test for ASR was one in which length changes in mortar bars of the cement and aggregate were measured to indicate reactivity potential (ASTM C 1260).

Initially, four aggregates were evaluated for reactivity: granite, mylonite, phyllonite, and ultramylonite. The granite was selected to represent a mildly reactive material while the phyllonite was considered highly reactive. Four cements from four manufacturers were evaluated: Type I/II portland cement (I/II), Type III portland cement (III), calcium sulfoaluminate cement (CSA), and calcium aluminate cement (CA).

After 16 and 32 days from the time of casting, the order of expansion of cements containing granitic (mildly reactive) aggregate is:

$$CA \ll CSA < I/II < III$$

For cements containing phyllonitic (highly reactive) aggregate, the order for expansion at 16 days is:

$$CA \ll CSA < I/II < III$$

while at 32 days the order became:

$$CA \ll I/II < III < CSA$$

Based on the data from the tests, one cement (CA) was clearly highly resistant to ASR. The other three cements failed the test when using highly reactive aggregate based on the upper expansion limit of 0.20 percent for tests performed 16 days after casting according to ASTM C 1260. Even when using mildly reactive aggregate, both Types I/II and III cements fall into the ambiguous range, while CSA bars expanded less than 0.10 percent. However, due to large uncertainties inherent in the accelerated test, it is very difficult to rank the order of performance for these three cements. This test only shows that these three cements did not perform as well as CA cement.

A modified accelerated test based on ASTM C 1260 was explored. This test changed the chemical composition of the chemical bath to contain a 3-to-1 ratio of potassium to sodium as found in concrete pore solution. This test showed that mortar bars of the same cement and aggregate compositions expanded less when using the modified chemical bath. This illustrates the possibility that ASTM C 1260 may overestimate the expansion potential of aggregates.

5.14 Shrinkage and Environmental Effects on the Performance of FSHCC Pavements at Palmdale, CA (*54–56*)

The purpose of this study was to investigate the influence of the shrinkage and thermal properties of the FSHCC used at Palmdale together with the measured temperature data at the site on slab performance.

Many of the longer slabs cracked under environmental influences before any traffic load was applied to them. Cores drilled through the cracks indicated that cracking initiated at the top of the slabs and propagated downwards. Concrete shrinkage and thermal strain data from field instrumentation was recorded and analyzed along with laboratory test data to determine the cause of the cracking. Finite element analysis using the measured strains and temperatures predicted high tensile stresses at the top of the test section slabs as a result of the differential drying shrinkage between the top and base of the slab and the non-linear nature of the negative temperature gradients through the slab.(*54, 55*) Laboratory free shrinkage tests on the test section cement indicated significantly higher shrinkage than ordinary Type II portland cement.

Based on the analysis, it is recommended that the use of high shrinkage hydraulic cements in rigid pavement construction should be discouraged as these can result in high differential shrinkage gradients and premature cracking. Laboratory tests indicated that fast setting hydraulic cements do not necessarily have high shrinkage and some can have significantly lower shrinkage than typical Type II cements. Shorter slab lengths (< 4.5 m) will reduce tensile stresses and thereby reduce the chance of premature failure in the event that high shrinkage cement is used. Stiff bases such as lean concrete, will increase the stresses in pavements because of friction between the base and slab. Bases that are flexible under long-term loading and stiff under short-term traffic loading (for example asphalt concrete bases) are preferred.

A special study was also conducted of the edge curling in both the plain-jointed slabs and those containing dowels and tie-bars.(*56*) The addition of the dowels and tie-bars between the slabs produced a significant reduction in edge curling, with little impact on horizontal expansion and contraction movements.

5.15 Evaluation of Proposed LLPR Strategies for Rigid Pavements; Design and Constructability Considerations (*57, 58*)

As a part of the LLPR-Rigid Program, investigation of design and construction issues are underway. Reference (*57*) presents the results of a recent condition survey of existing concrete pavements which are candidates for the LLPR-Rigid Program, evaluation of existing concrete pavement design methods,[9] and a series of design recommendations that have the potential to contribute to at least 30 years of good performance.

Recommendations to Caltrans, based on the material contained in Reference (58) are as follows:

- Faulting is the most prevalent distress that occurs in Caltrans rigid pavements. Transverse cracking due to axle loading and temperature curling, corner cracking, and longitudinal cracking are also present in the network. Each distress must be specifically addressed in the pavement designs.
- Axle loads and the number of trucks in the design lanes will undoubtedly increase over the next 30 years. Designs that may have worked in the past may not work in the future, and designs that did not provide adequate performance in the past will

[9] Methods included, in addition to the Caltrans procedure (*33*): Portland Cement Association (PCA) thickness design guide (*60*); American Concrete Paving Assoc. (ACPA) version of the 1993 AASHTO Guide (*61*); and the Illinois Department of Transportation (IDOT) procedure (*62*).

deteriorate even more quickly under the increased loading. This traffic and loading growth must be accounted for in the pavement designs. The efficacy of evaluating truck traffic in terms of ESALs, as opposed to evaluating distress mechanisms in terms of axle load spectra, merits further investigation.

- The performance of the LLPR proposed pavement structures will depend in large part on the climate and the slab lengths of the adjoining lanes. Rigid pavements in the Desert and Valley climates, with their large day to night temperature changes, will deteriorate more quickly than pavements in the milder coastal climates due to environmentally induced cracking. Pavements with transverse joint spacing greater than 15 ft. (4.57 m) will also experience more rapid cracking than pavements with joint spacing less than 15 ft. (4.57 m), all other variables being equal. Pavement structural designs must be considered on a project by project basis, rather than applying a uniform structure across a variety of climates and joint spacings, as well as base, subgrade, and drainage conditions.
- With respect to constructability and structural performance, alternative base types should be considered. For example, the use of very stiff bases may lead to earlier cracking because of temperature curling, especially for pavements with long slab lengths and large concrete coefficients of thermal expansion in the Valley and Desert climates. At the same time, bases should be as non-erodable as possible in order to minimize loss of support to the slab, which contributes to faulting and corner cracking. The effectiveness of retaining the existing CTB warrants further study. Of primary concern is its condition, especially stiffness and strength. New asphalt concrete bases with relatively high asphalt contents may provide the desired

properties of being non-erodable, yet exhibit low stiffnesses under loading times of several hours.

- The most important concrete properties from a pavement structural performance perspective are flexural strength and coefficient of thermal expansion. Long term durability is also important, as noted above. Large flexural strengths (650 to 800 psi [4.44 to 5.52 MPa]), and small coefficients of thermal expansion (3×10^{-6} to 5×10^{-6} in./in./ºF) are needed to minimize slab thicknesses. Development of materials meeting these requirements is essential if the desired design life of 30 or more years is to be obtained.
- It is apparent from the design methods that the use of dowels is necessary to address faulting. The use of tied concrete shoulders or widened truck lanes is needed to address fatigue cracking and loss of support to the slab, which contributes to faulting and corner cracking. These features should be implemented in the LLPR-Rigid strategies based on these preliminary investigations performed using existing design methods.
- Although not exactly in agreement, the PCA and Illinois DOT methods indicate the 8- and 9-inch (203- and 229-mm) concrete slabs may provide adequate design lives, provided that all of the other factors included in these recommendations are addressed. At this time, it can be assumed that 8- or 9-in. (203- or 229-mm) thicknesses will be adequate for some projects. At the same time, methods for constructing somewhat thicker slab thicknesses, probably ranging from 10 to 12 inches (254 to 305 mm), should be considered for projects with combinations of the

heaviest truck traffic, Valley and Desert climates, and slab lengths greater than 15 ft. (4.57 m).

5.16 Constructability Analyses for Long Life Concrete Pavement Rehabilitation Strategies (*63, 64*)

One of the main objectives of the Caltrans LLPR Program is to have a construction productivity of approximately 6 lane-kilometers within a 55-hour construction window. This productivity objective must be compatible with the necessity to provide 30-plus years of pavement service life and to minimize pavement maintenance. The purpose of this study has been to perform a constructability analysis for the Caltrans LLPR-Rigid project, focusing on the optimization of maximum production capability within a 55-hour weekend closure. The analyses explored the effect of the following parameters on the construction productivity of rigid pavements in California: pavement design profile, paving material, curing time, number and capacity of resources, number of lanes to pave, type of construction scheduling, and alternative lane closure strategies. The typical construction processes for concrete pavement rehabilitation were modeled with input from a contractor's association, Caltrans, and academia.

Typical Critical Path Method (CPM) schedules for each design profile (i.e., 203-, 254-, and 305-mm slabs), together with lead-lag relationships between activities involved in the rehabilitation were generated from the information gathered. Sensitivity analyses were conducted to find which parameters constrain the production capability of the rehabilitation. The constructability analysis was performed using spreadsheet software designed to interactively link all factors involved in the rehabilitation processes, permitting easy visual comparison between the available options as the user adjusts parameter values.

The constructability analyses indicated that the current proposed strategy to rebuild 6 lane-kilometers with 55 hours of weekend closure has very low probability of success (less than 15 percent of the options investigated) even when use of fast-setting hydraulic cement concrete was considered. The analyses showed that concrete curing time was not the most critical activity for the production capability of the rehabilitation. Rather, material delivery resources, especially dump trucks for demolition (removal) and end dump trucks for concrete supply, were the major constraint limiting the production capability of the rehabilitation. The design profiles of the pavement structures [i.e., different thicknesses of the concrete slab (203, 254, or 305 mm)] also proved to be a major element influencing the production capability. Increasing the concrete slab thickness from 203 to 305 mm, as may be required structurally on some projects, reduced the productivity by about 50 percent.

The constructability analysis verified that different working methods (concurrent or sequential), experimentally designed for the analysis affected the construction productivity. A concurrent working method, in which demolition and paving activities are allowed to proceed simultaneously, was more productive than a sequential working method in which paving could only commence after demolition is complete. The number of lanes to be paved simultaneously (i.e., single or double lane), impacted the production capability. Double lane paving was more productive at a cost of closing one additional traffic lane. Changing the concrete curing time from 4 to 12 hours reduced the productivity by less than 20 percent.

With respect to the time to completion, the concurrent working method with double lane paving was the most efficient strategy for all pavement thicknesses and curing times compared to alternative strategies. However, this finding excludes the effect of the construction on the traveling public. An inconvenience factor was developed to measure the length of time each construction strategy would close a facility (lane-weekends blocked). It was determined that for thick pavements (254 and 305 mm), the sequential working method with double lane paving was the least intrusive to the road user. When comparing various construction windows, such as continuous closure with one, two, or three shifts operation per day and 55 hour weekend closure, it was found the continuous closure with two or three shifts operation was both the most productivity strategy and provided the least inconvenience to the public.

Construction productivity data obtained from the demolition and paving operation on a section of I-10 (Pomona, CA) was used to validate the model.(*64*) The average results from the analysis were in agreement with the actual project productivity.

5.17 Cal Cool – A Computer Program for Determining Pavement Temperatures During AC Placement (*65*)

The objective of this work has been to provide a solution to the pavement heat transfer problem by means of a computer program (Cal Cool) that can be used to determine pavement temperature profiles throughout the duration of the paving operation. Use of the program can provide an optimal compaction timeframe that minimizes construction delays and improves construction efficiency, e.g. in the Caltrans LLPR program.

Cal Cool was adapted from the Pave Cool program developed in Minnesota.(*66*) The program permits a maximum of nine pavement lifts and considers cloud cover; ambient temperature; wind speed; lift thickness; existing base material type, thermal properties, and temperature; and hot mix material type and thermal properties. Figure 19 illustrates the main window inputs; Figure 20 schematically illustrates results of temperature versus time for a two-lift paving process.

The model is currently being calibrated on a series of multiple lift paving projects.

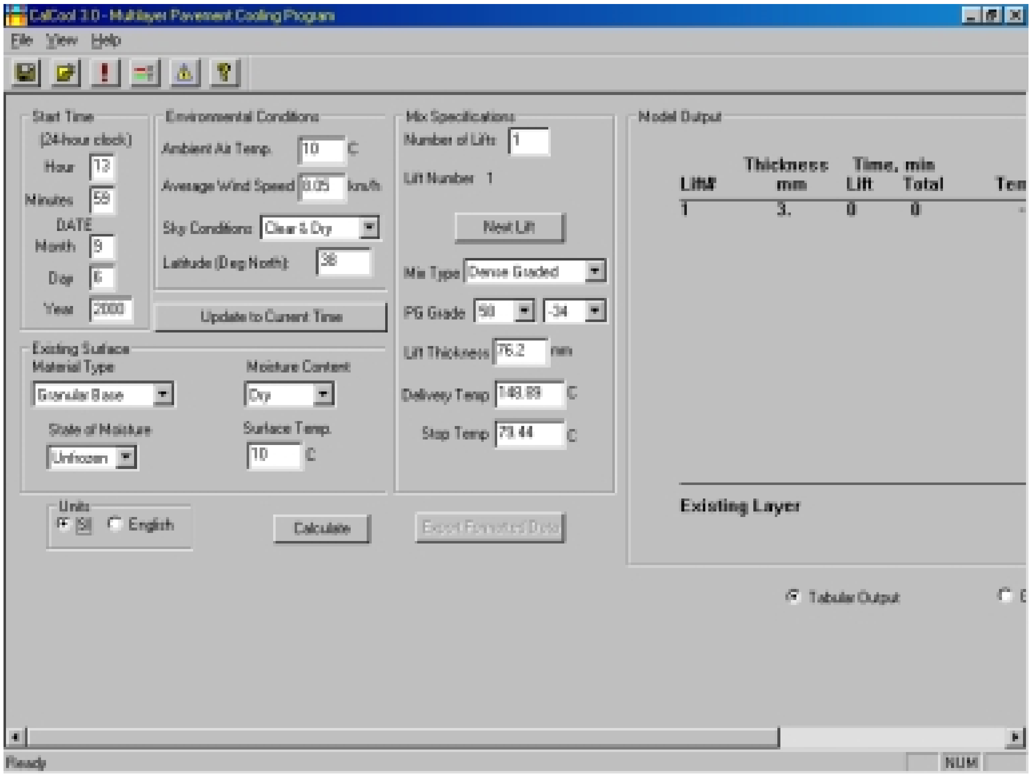


Figure 19. CalCool main window inputs.

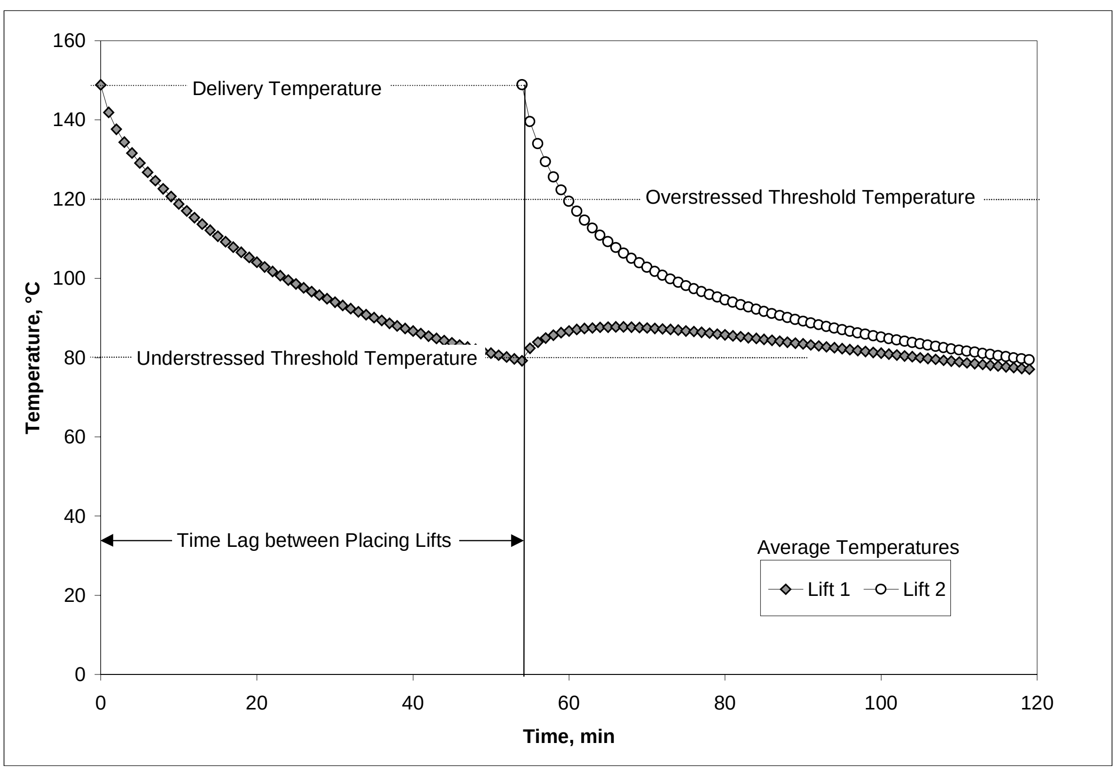


Figure 20. Temperature versus time for two-lift paving process.

5.18 Mechanistic-Empirical Pavement Design and Rehabilitation and Performance-Based Asphalt Mix Design and Analysis (*22, 67–71*)

There have been a number of activities associated with the development of a mechanistic-empirical pavement design and rehabilitation methodology for Caltrans.(*22, 28, 67, 70–71*) This methodology will eventually include procedures for design of both new and rehabilitated asphalt (flexible) and concrete (rigid) pavements. In addition, analytical and laboratory studies are underway directed to the development of an improved procedure for the design of asphalt/binder aggregate mixes.(*69*) Brief summaries of these developments are included in the following five subsections.

5.18.1 Climate Regions for Mechanistic-Empirical Pavement Design in California and Expected Effects on Performance (*67*)

The purpose of this study has been to identify environmental regions in California that are sufficiently different both in terms of temperatures and moisture regimes to require these differences to be considered in material selection, and in structural pavement and rehabilitation design.

Seven climate regions have been identified based on rainfall and air temperature data. The Integrated Climate Model (ICM) has been used to determine pavement temperatures from the air temperature data.(*72*) With the pavement temperature and rainfall data, their effects on distress mechanisms in flexible, rigid and composite (AC overlays on concrete) pavements were evaluated. Recommendations have been made for incorporation of these factors where they have a large impact on design.

For asphalt pavements, environmental considerations should be included for asphalt concrete mix design for rutting, asphalt binder selection for rutting and thermal cracking, thickness design for fatigue cracking and subgrade rutting, and drainage requirements and the need for drainage features. A simplified map for selection of performance graded (PG) binder grades has been developed, and it is recommended that Caltrans implement portions of the PG specification (*73*), as shown in Figure 21. For composite pavements, these design considerations, as well as the effects of reflection cracking are applicable.

For rigid pavements, several factors have an effect on the design of the pavement:

- environmental factors are critical for concrete mix design for shrinkage and strength
- cement selection is critical for shrinkage, strength, and coefficient of thermal expansion
- maximum slab length is critical for cracking caused by thermal stresses
- slab thickness is critical for fatigue
- base type selection is critical for mitigation of erosion, drainage requirements, and the need for drainage features.

5.18.2 Multilayer Elastic Analysis Computer Program (LEAP) (*22,68*)

A multilayer elastic analysis program (LEAP) has been developed for the PRC by Symplectic Engineering, Inc.(*22*) The main features of this program include:

- a simple user interface,
- interactive and batch mode capabilities,
- interfaces between layers with full and partial friction,
- normal and tangential load applications on multiple loaded areas, and
- the ability to analyze a large number of layers (limited only by the amount of computer memory).

This program will be incorporated into the mechanistic-empirical asphalt (flexible) pavement design and analysis system. The program has been written in Java language; accordingly, it can run on any computer that runs the Java VM including Windows 95, 98, 2000, and NT, various Unix systems, BeOS, and Macintosh.

A software package entitled SIM (stress in motion) has been developed using the results of the tire pressure studies conducted with the VRSPTA.(*68*) The SIM software can be used as an input to the LEAP program for AC pavement design, or as an input to finite element analysis programs such as FEAP (*74*) for AC rutting evaluations. The advantage of this process is that the actual complex stress patterns of the tires can be used for evaluation of the pavement in the vicinity of the tire contact and will be most useful in evaluating AC rutting and surface cracking distress modes.

5.18.3 Constitutive Relation to Represent Permanent Deformation Characteristics of Asphalt/Binder-Aggregate Mixes (*69*)

A constitutive relation intended for use in analysis of the rutting characteristics of AC mixes at elevated temperatures is under development for the PRC by Symplectic Engineering, Inc. The proposed model consists of two components that act in parallel: *viscoelastic* and *elastoplastic*.

Briefly, the main features of the model are:

1. It is developed within the framework of finite deformations. This choice has been made because large rotations are observed near the edges of ruts, and relatively large strains (10 percent) are measured in the upper part of thick AC pavements.
2. It includes volumetric-deviatoric coupling that is introduced through the elastoplastic component of the model. This volumetric-deviatoric coupling is incorporated in both

the elastic and plastic parts of the rate-independent elastoplastic component of the model.

3. The elastoplastic model includes the Bauschinger effect, which laboratory tests suggest is quite strong for AC mixes at elevated temperatures. This feature is achieved by allowing the yield surface to move so that it does not contain the origin. As a result, plastic flow can occur during unloading. Also, plastic flow is not necessarily normal to the yield surface, a feature that is believed to be important for the modeling of granular media.

Special laboratory tests, such as creep and relaxation tests, are being performed on AC mixes to provide input for the model development.

The analytical model and associated laboratory testing will provide a methodology to predict the development of rutting in AC mixes under repeated truck trafficking using actual tire pressure distributions like those measured with the VRSPTA and input to an analysis program using the SIM software.

This study is a continuation of an effort initially funded by the FHWA, the results of which have been reported in Reference (*75*) and summarized in Reference (*28*).

5.18.4 Load Transfer at Joints in Rigid Pavements (*70*)

Symplectic Engineering, Inc., under contract with the PRC, conducted a brief analytical study of load transfer at joints in concrete pavements. A number of two- and three-dimensional finite element simulations of pavement structures were conducted. It was concluded that the method of load transfer calculation should be adjusted, and a recommendation for a field test to evaluate the calculated response was made. To date, the recommendation has not been implemented.

5.18.5 Back-Calculations to Define the Elastic Properties of Pavement Components (*71*)

Symplectic Engineering, Inc., under contract with the PRC, developed a procedure to back-calculate the elastic properties of the different layers in pavements, taking advantage of the dynamic nature of the Falling Weight Deflectometer (FWD), the equipment used by the PRC for non-destructive pavement evaluation.

The proposed method employs a two step approach. First a mutation algorithm is used to obtain the value of a prescribed cost function below a specified value. Second, a Newton iteration, together with a line search algorithm, are used to find the minimum of the cost function. A number of examples included in the report demonstrate that the approach can be used to back-calculate the properties for pavements with as many as six layers (current methods are typically constrained to three or four layers due in part to problems encountered in backcalculation with field data as noted below). An additional advantage of the proposed method is that it avoids the need to assume the values of the Poisson’s ratios, which, as is shown in the report, may introduce a significant error into the back-calculated Young’s moduli.

The proposed approach does have several drawbacks. First, it is quite expensive. Second, problems were encountered during back-calculations of field data. These problems may be due in part to the load applied during the back-calculations, which for the example in the report was taken from measured data and includes a period in which the falling weight pulls on the pavement (physically not possible). Also, it should be noted that the quality of the back-calculation is sensitive to some of the parameters employed in the cost function. Based on this initial investigation, it was recommended that a different approach be used for the forward calculation because the finite element methodology used in the study proved to be too time consuming.

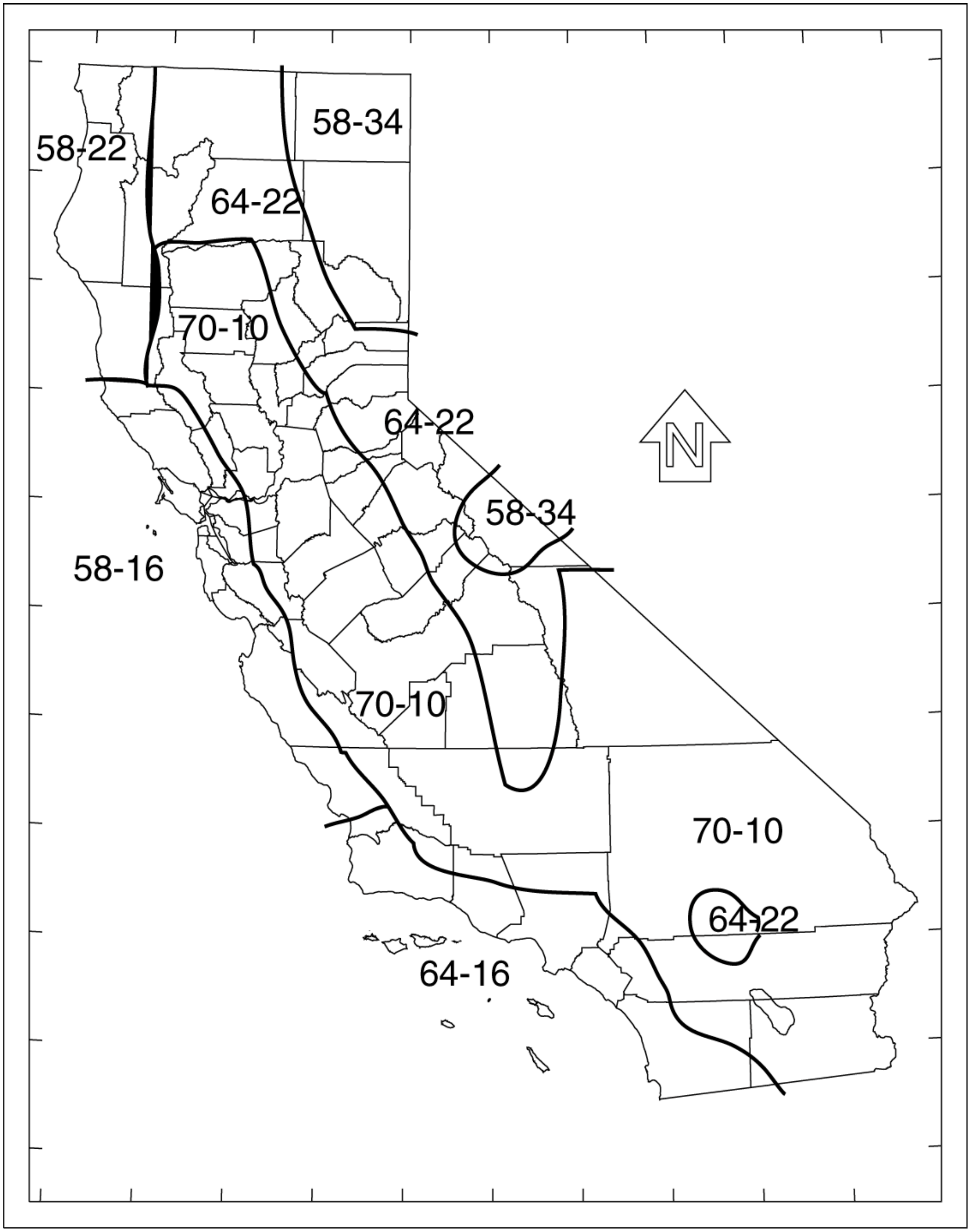


Figure 21. Recommended PG binder regions for California.

In light of other higher priority requirements, the decision has been made to delay further study in this area.

5.19 Performance Characteristics of Compacted Untreated Granular Materials (Goal 5) (*76, 31*)

A comprehensive investigation of the behavior of untreated aggregate base (AB) and subbase (ASB) materials has been initiated as a part of the Goal 5 study. This study includes laboratory tests on granular materials used in the Goal 1 and 3, as well as in the Goal 5 studies. Triaxial testing to define the stiffness (modulus) and strength characteristics and testing to measure permeability have recently been initiated.

The data resulting from these studies will not only permit mechanistic-empirical analyses of the pavement sections being tested in the Goal 5 study, but also provide stiffness and strength data for the mechanistic-empirical pavement design and rehabilitation methodologies under development for Caltrans.

Included in this study is an assessment of the influence of water content and dry density on the performance of untreated base and subbase materials. A considerable amount of research on this subject has already been completed in South Africa. Accordingly, since the behavior of unbound aggregates in South Africa and California should be similar, data from the South African HVS database and associated laboratory projects have been utilized to illustrate the effects of dry density and degree of saturation on the stiffness, strength, and permanent deformation response of unbound materials already evaluated.

Results of this evaluation indicate that the dry density and degree of saturation have a significant influence on the stiffness, strength, and permanent deformation of untreated granular materials. Stiffness, strength, and permanent deformation resistance of these materials were shown to increase as the dry density is increased and as the degree of saturation is reduced.

As a result of this study, the recommendations for California specifications are as follows:

- The influence of density and water content on the bearing strength of the material should be incorporated in the specification. Strength requirements for the different pavement layers (e.g., AB and ASB) should be stated at specific dry density and water content levels.
- The method for determining the reference density for compaction control should be changed from the current wet density requirement to one based on dry density. Moreover, the compaction effort for the test should be increased to that associated with the Modified AASHTO Test, T-180.

Relative to permeability testing, a technique to measure the permeability of compacted specimens without disturbing the compacted sample has been developed. Permeability will be measured using a falling head permeameter for a range in dry densities and water contents. Results of these tests will be compared with the results of field percolation tests conducted near HVS Test Sections 517RF and 543RF.(*31*)

5.20 Nondestructive Monitoring of Water Contents in Untreated Base, Subbase, and Subgrade of Pavement Structures by Ground Penetrating Radar (GPR) (*77*)

Ground Penetrating Radar (GPR) methods have the potential to provide high-resolution, non-destructive, water content estimates in pavement structures. Such information can be of considerable assistance in the interpretation of non-destructive pavement stiffness and strength measurements for use in pavement rehabilitation design. This study is directed to developing a reliable procedure to measure in-situ water contents of the untreated portions of pavement structural sections (base, subbase, and subgrade).

The first phase, a pilot study to determine the feasibility of the approach, was successfully completed at the PRC. The second phase is now underway to evaluate the water contents in the untreated base, subbase, and subgrade of sections 543RF and 544RF, which have been subjected to water infiltration and traffic loading over a period of several months.

Preliminary analysis of the GPR data indicates that water content fluctuates with depth, lateral location, and time. These preliminary results suggest that GPR techniques may provide an efficient and reasonably accurate method for obtaining non-invasive water content estimates.

5.21 Studies Related to Caltrans Pavement Management System (PMS) (*78, 79*)

A series of studies of the Caltrans Pavement Management System have been conducted by the PRC staff in order to develop pavement performance models for the various types of pavements used in the California State Highway System. This information will eventually be used to assist in the development of mechanistic-empirical methods for the design of both new and rehabilitated pavement structures.

As an initial activity, a memorandum was prepared that recommended changes to the *Caltrans Pavement Survey Manual*.(*78*) The objective of these changes is to develop pavement data, which if incorporated into the PMS, will enhance its utility for performance model development.

The second activity was the development of a prioritized list of test sections for inclusion in the Caltrans condition survey network.(*79*) This list was assembled to insure that performance data from the test sections could be utilized effectively in new design and rehabilitation practices.

The third activity, which is currently underway, is the "mining" of the Caltrans PMS database. The purpose is to extract environmental performance indicators for the various climatic regions in California, and to extract section and reflection cracking data for PCC pavements that have been overlaid with asphalt concrete.

Results of this project will provide a single database containing pavement design and condition information for the highway network subdivided into approximately 250,000 sections.

5.22 Pavement Research Center Database Development (*80*)

A database is under development for the CAL/APT program and has been named the *CAL/APT Database.* This database consists of the following:

1. PRC Lab Database
2. HVS Asphalt Database
3. HVS PCC Database
4. Caltrans Database.

Figure 22 illustrates the framework for the database.

The database has been designed as a relational data model in normalized form using Microsoft Access. Oracle is being used as the relational database management system.

5.23 Assessment of Economic Benefits from Implementation of Findings from CAL/APT Program (*81*)

The objective of this study was to evaluate the potential economic benefits if Caltrans were to implement three changes in flexible pavement technology resulting from CAL/APT program results. The recommended changes are:

1. Increase compaction requirements for asphalt concrete.

2. Require the use of tack coats to improve bonding between AC lifts in all construction projects.
3. Include a "rich bottom' layer in thick AC structures.

A full cost model, developed in the report, was used to calculate the direct cost savings to Caltrans with the use of the new pavement technologies. The new pavement technologies were represented as increasing the life of the roadway and the time between necessary maintenance and rehabilitation actions. This study showed that an increase in the period between overlays by 15 percent results in savings of $6,933 per two-lane-km equivalent. Applying this saving to the roadway system for the state of California yields potential statewide savings of over $56 million.

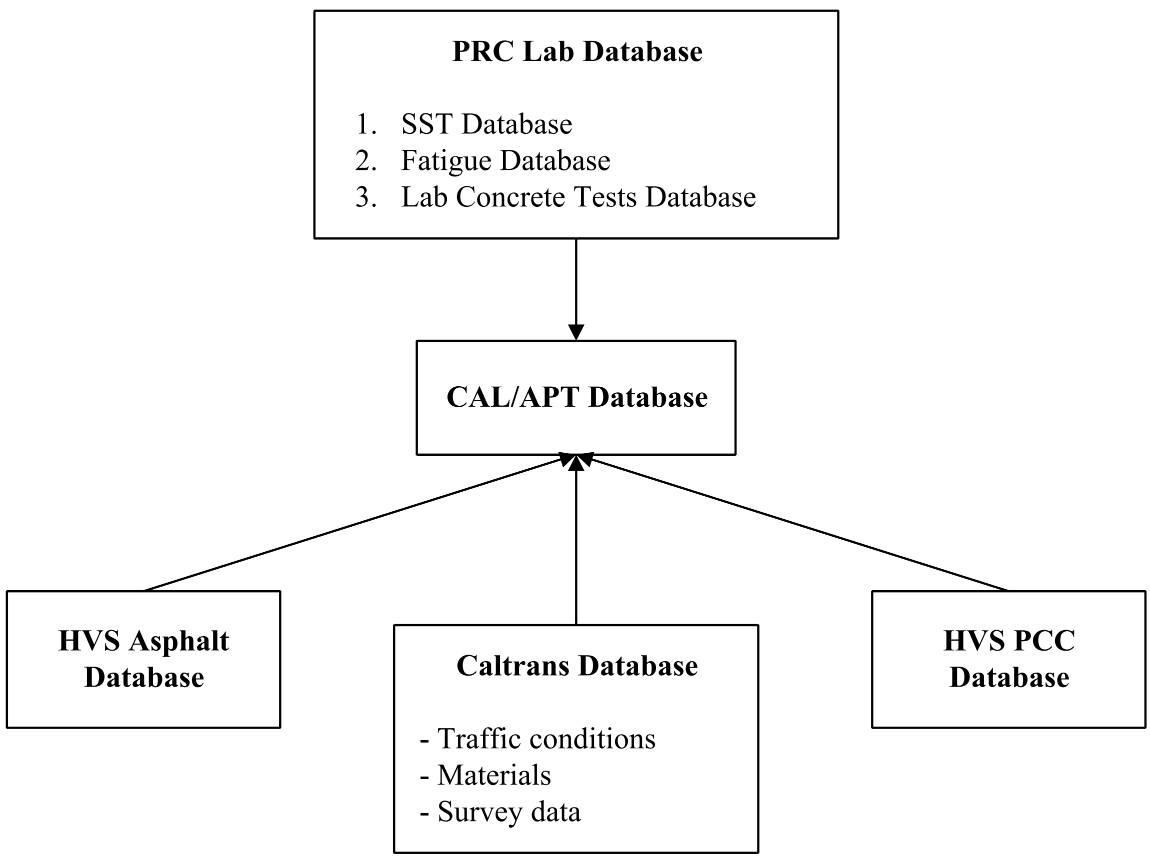


Figure 22. General structure of the *CAL/APT Database.*

If the period between overlays is extended by 5 years, the statewide savings is more than $244 million, a net present value of more than $163 million.

In addition to these direct savings, user cost savings and safety cost savings will be realized. Because maintenance and rehabilitation actions will be required less frequently, and therefore, fewer shutdowns, closures, and roadway capacity reductions will be required, user costs and safety costs will be reduced. These savings were calculated for a representative project on I-5 near Sacramento. For this example, this study shows that the time cost savings would be $1,335,600, or 54 percent of the total benefits. Benefits to safety improvements amounted to $658,627, approximately 20 percent of the total benefits. The direct cost savings to Caltrans on this project amounted to $468,480, or 19 percent of the total.

The increase in pavement life and reduction in frequency of required rehabilitation has led to a benefit of approximately $2.5 million for this representative project. This benefit is realized at relatively little cost. The use of the new pavement technology is primarily focused on method or technique of application rather than new, additional, or more costly materials. New pavement technologies may result in a small initial increase in labor costs while contractors become familiar with the techniques, however, at some point the techniques would be commonplace and have little or no impact on man-hours of labor required on a given contract.

Overall, the potential for cost savings using these new pavement technologies appears to be quite large. In the representative project, they were 19 percent of total benefits. If applied statewide, and using the factor of proportionality of 19 percent, the total savings potential may be in the neighborhood of $587 million (1998 dollars). More research to explore any additional costs and how benefits may vary among types of projects, pavement age, and project location is required.

6.0 IMPLEMENTATION OF RESULTS OF CAL/APT PROGRAM, PHASE II

When the results presented in Section 5 are viewed collectively, the investigations which have been completed to date, if implemented, have the potential to significantly improve pavement performance.

In the asphalt (flexible) pavement area, the mix design and analysis system originally developed as part of the Strategic Highway Research Program (SHRP) has been extended to efficiently treat in-situ temperatures, calibrated to the Caltrans asphalt concrete pavement design system, extended to incorporate construction variability, and used to interpret the results of the first four HVS tests completed at the Richmond Field Station.

With increased confidence resulting from the successful interpretation of the HVS test results, use of this system provides the basis for recommendations to Caltrans on a number of important issues:

- AC pavement and mix design and analysis
- Design and use of asphalt treated permeable bases
- Materials for overlays on existing AC pavements
- Construction practices and pay factors for QC/QA specification.

Similarly, in the concrete (rigid) pavement area, results of both the laboratory and HVS test programs provide the basis for recommendations in the following areas:

- Design considerations for concrete pavements including the use of dowels, widened truck lanes, joint spacing, and the use of non-erodable bases with low stiffness under long-time loading.
- Concrete mix design considerations including: control of cement shrinkage in hydraulic cements, use of higher flexural strengths than currently specified, control of

sulfate resistance, and the development of an improved accelerated sulfate resistance (ASR) test.

In the pavement construction area, two computer programs have been developed which should prove useful in the LLPR program as well as for other construction projects. These are:

- Constructability analysis for both concrete and AC pavement construction
- Temperature profile determinations throughout the paving operation for multi-lift AC construction.

6.1 Asphalt Concrete Pavement Design and Rehabilitation

Results indicate that the total pavement thicknesses developed by the current Caltrans pavement design procedure are generally adequate to preclude the incidence of rutting caused by permanent deformations occurring in the subgrade and untreated aggregate pavement layers. On the other hand, recommended thicknesses of the asphalt concrete layers (particularly for weaker subgrades and higher traffic levels) may lead to premature fatigue cracking. Utilization of the mix design and analysis systems developed during the CAL/APT program should reduce this propensity for fatigue cracking and generally improve pavement performance. Innovative pavement designs could extend fatigue lives substantially beyond conventional designs.

The mix design and analysis system permits the more effective utilization of materials, e.g., the use of the “rich bottom” concept, as well as insuring the effective use of new materials such as modified binders. Such designs could extend fatigue lives substantially. Innovations in design and related improvements in construction quality will contribute significantly to the development of asphalt concrete alternatives to be used in the Caltrans long life pavement rehabilitation strategies (LLPRS) program. This has been demonstrated by the application of the methodology to both mix and structural pavement design for the AC pavements to be used on the I-710 freeway in Long Beach, CA.

The results of the overlay study support the current Caltrans practice of the 2 to1 thickness equivalences, of ARHM-GG to DGAC for overlays on fatigue-cracked asphalt pavements. This must be carefully applied, however, to insure that rutting at the pavement surface from deformations in the untreated pavement components does not control performance.

6.2 Design and Use of Asphalt Treated Permeable Base

From the HVS tests on the pavement sections containing ATPB, laboratory tests on representative ATPB mixes, and associated analyses and surveys of the field performance of ATPB including the experience of district personnel with maintenance of pavement drainage systems, the general use of ATPB directly under the dense-graded asphalt concrete layer in the pavement section warrants reconsideration.

Improved compaction in the asphalt concrete layer will reduce its permeability. Improved compaction and increased asphalt concrete layer thickness, following the mix design and analysis system described herein, will substantially delay crack initiation and propagation in the asphalt concrete layer. Reducing the permeability and cracking potential of the asphalt concrete will thus reduce the necessity for ATPB in this location—*potentially the use of ATPB could even be eliminated*. It is likely that the resistance to cracking and reduction in permeability will also be improved by the use of a “rich bottom” layer of asphalt concrete. Despite the steps to reduce the propensity for surface water to enter the pavement, it must be recognized that drainage layers may still be required to help remove seepage entering the pavement structure through the subgrade.

If ATPB is used directly beneath the asphalt concrete, then improvements should be made to the material to enhance its performance in the presence of water. Increasing binder content, use of modified binders such as asphalt rubber, and the use of an additive such as lime or an anti-stripping agent are alternatives which should be considered. Associated with the changed mix design is the necessity for incorporation of properly designed geotextile filters adjacent to the ATPB layer in the pavement structure to prevent the ATPB from clogging. Results of the Goal 5 tests reinforce these recommendations.

Finally, to insure continued effectiveness of the ATPB, effective maintenance practices for the clearing of edge and transverse drains should be established.

Following these and other performance enhancing recommendations would justify raising the gravel factor for ATPB from its current value of 1.4 to a value as high as 2.

6.3 Construction Practices—AC Pavements

Both the fatigue analyses and the fatigue performance of the asphalt concrete in the HVS tests emphasize the importance of proper compaction of these layers in the pavements structure. Accordingly, compaction requirements should be established to insure that in-place constructed mix air-void contents do not exceed 8 percent.

While the use of relative compaction requirements based on the laboratory density is satisfactory, a reduction in asphalt content from that selected in the laboratory could lead to an air-void content higher than 8 percent, even though the relative compaction requirements were met. Accordingly, the change from a relative compaction requirement to a maximum air-void requirement based on ASTM D2041 (“Rice” specific gravity) is strongly recommended.

In the construction (using the Caltrans method specification) of the ARHM-GG for the overlay study, relatively low compaction levels were obtained. The current specification (method specification) should be replaced by the compaction requirement stated above.

A weak bond was observed between the first two asphalt concrete lifts in the HVS test sections. In all cases, this lack of bond was found to significantly degrade pavement performance. While the extent to which weak bonding may be prevalent in California pavements is unknown, the fact that the HVS test pavements were constructed according to standard Caltrans procedures suggests that a weak bond may contribute to performance problems for in-service pavements under heavy traffic. Effects from weak bonding may become more evident in the pavement network as axle weights and freight traffic increase in the future. If additional investigations confirm such problems, recommended use of a tack coat will result in significant improvements in pavement performance and, hence, reduction in life-cycle cost.

With Caltrans moving toward using QC/QA procedures in pavement construction, CAL/APT data can provide the basis for a rational procedure for the development of pay factors. Using the calibrated mix analysis and design system, pay factors based on fatigue analysis—including the effects of degree of mix compaction (as represented by relative compaction), asphalt content, and asphalt concrete thickness—have already been developed.

These pay factors have been combined with those developed from rutting analyses for the WesTrack test road. This blending of the results from both projects provides an example of the synergistic effects that can result from the CAL/APT group being involved in other related projects.

The pay factor study also stresses the importance of proper compaction to insure improved fatigue and rutting performance. In addition, the study has highlighted the importance of thickness control for the asphalt concrete layer. Implementation of a bonus/penalty system based on this study as a part of a QC/QA program has the potential to significantly improve asphalt concrete pavement performance.

6.4 Concrete Pavement Design Considerations

Results of analytical studies, supported by the results of HVS tests at the RFS and in Palmdale, stress the importance of the use of dowels and non-erodable bases for heavily trafficked jointed concrete pavements. Results from the Palmdale site also demonstrate the effectiveness of dowels in restricting curling movements along transverse joints from daily temperature changes. Tie bars produce similar results for longitudinal joints.

In order to minimize slab thicknesses for concrete sections, greater than current required flexural strengths along with small coefficients of thermal expansion should be used.

6.5 Concrete Mix Design Considerations

Some hydraulic cements considered for use in the LLPR program may be susceptible to sulfate attack. Accordingly, it is recommended that Caltrans enforce sulfate resistance guidelines for PCC and that contractors produce evidence that any HCC being considered for a project is sulfate resistant.

Test data developed thus far suggest that an improved test should be developed for ASR since this could be a problem with some aggregates and could impact pavement performance in the LLPR program.

High shrinkage hydraulic cement led to top-down premature cracking in longer slabs at Palmdale. If this type of material is used, shorter slab lengths will be required.

6.6 Construction Management

Two computer programs have been developed to assist in pavement construction: 1) a program for constructability analysis for both concrete and AC pavements; and 2) Cal Cool for pavement temperature profile determinations during multi-lift AC construction.

The constructability has provided guidelines for improved productivity in various alternatives under consideration for the LLPR-Rigid Program. For example, it suggests that the current proposed strategy to rebuild 6 lane-kilometers with 55 hours of weekend closure has a very low probability of success. On the other hand, the program has been of value in guiding the construction activities associated with the rehabilitation of a section of I-10 in Pomona, CA.

Thus, it is recommended that this program be used to assist in scheduling LLPR program paving activities. It is expected that the program for AC pavement will be completed in the near future.

6.7 Other Considerations

Results of the tire pressure studies together with the evaluation of the performance of the test sections under channelized traffic conditions at elevated temperatures have the potential to improve mix design and analysis with respect to permanent deformation response. Results of the CAL/APT program coupled with earlier SHRP and current SHRP related studies should also prove most useful in this regard. The approach used for the mix designs for the I-710 project provides an example of the approach.

7.0 SUMMARY

The information presented in this report emphasizes the important role of accelerated pavement testing in providing a key element in the development of improved pavement technology. In the 6-year period since its inception, the CAL/APT program has focused on a number of problems of importance to Caltrans. A series of recommendations have been developed from the program, which has involved analytical studies, a laboratory test program, and HVS loading of full-scale (real) pavements both at the RFS and at the Palmdale test sections.

The full scale testing with the HVS has, for asphalt pavements, clearly demonstrated the importance of proper construction particularly the importance of AC compaction and the use of tack coats between layers. It has lent strong support to recommendations for the use of improved analysis and design procedures to improve field performance.

The concrete pavement test program was quickly implemented in response to needs associated with the LLPR Program. The laboratory test program has developed important data on the durability, thermal, and shrinkage characteristics of HCC. Both the analytical studies and field HVS tests have demonstrated the importance of the use of dowels for heavy duty pavements.

The constructability analyses and the Cal Cool program should prove to be useful in the LLPR program. Both programs provide information to assist in effective scheduling of construction activities and equipment and in proper placement of both AC and concrete courses.

Finally, the project to date has demonstrated the efficacy of government, industry, and academia working together to provide solutions to critical pavement problems. Moreover, it demonstrates the benefits of international cooperation in which technology is transferred among the participants to the benefit of the involved organizations.

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