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Laboratory Testing and Modeling for Structural Performance of Fully Permeable Pavements: Final Report

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LABORATORY TESTING AND MODELING FOR STRUCTURAL PERFORMANCE OF FULLY PERMEABLE PAVEMENTS: FINAL REPORT

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15. Abstract

This report presents a summary of the results of laboratory testing, computer performance modeling, and life-cycle cost analysis of fully permeable pavements. The use of these types of pavement is being considered as a potential best management practice for managing stormwater on California highways. The deliverables from this research are a **preliminary** design procedure and an **example** set of catalogue-type design tables that can be used to **design pilot and experimental** fully permeable pavement test sections in California. The results obtained from the analyses in this study indicate that fully permeable pavements could be a cost-effective stormwater best management practice alternative as a shoulder retrofit on highways, and for maintenance yards, parking lots, and other areas with slow moving truck traffic. However, these results need to be validated in controlled experimental test sections and pilot studies before wider-scale implementation is considered. It is recommended that accelerated pavement tests and pilot studies on in-service roadways be designed, using the procedure discussed in this report, and then constructed and monitored under traffic. The findings from these full-scale experiments should be used to identify situations where fully permeable pavements are an appropriate best management practice, validate and refine the design method, undertake detailed life-cycle cost and environmental life-cycle assessments, and to prepare guideline documentation for the design and construction of fully permeable pavements. **This document is not intended to be used as a guideline for the design, construction and maintenance of fully permeable pavements.**

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This document is not intended to be used as a guideline for the design, construction and maintenance of fully permeable pavements.

PROJECT OBJECTIVES

The objective of this project, titled "Laboratory Testing and Modeling for Structural Performance of Permeable Pavements under Heavy Traffic," is to develop preliminary designs for fully permeable pavements in California.

This objective will be met after completion of five tasks:

1. Evaluate the structural performance characteristics of all the materials potentially used in permeable pavement designs, namely porous asphalt, concrete, base, and subgrade materials.
2. Perform detailed performance modeling of these various designs based upon (1).
3. Develop recommended designs for subsequent accelerated pavement testing and field test sections on the UC Davis campus which are reasonably likely to perform satisfactorily, are constructible, and within reason, economical.
4. Based upon these designs, perform a preliminary life-cycle cost analysis (LCCA) and life-cycle analysis (LCA) of the various options.
5. Compile all the information gathered in this study into a comprehensive final report.

This research report summarizes all of the tasks.

The objectives did <u>not</u> include the preparation of guidelines for the design, construction and maintenance of fully permeable pavements, or any research into the influence of the design of fully permeable pavements on water quality.

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Chapter 1 Focus of the Report

The California Department of Transportation (Caltrans) initiated a laboratory and modeling investigation under Master Agreement 65A0108 to evaluate the structural performance of fully permeable pavements. This report summarizes all the work undertaken on the project and includes information from the following Technical Memoranda prepared at the end of specific tasks in this study, as well as from a research report prepared as part of a companion study on hydraulic modeling of fully permeable pavements:

- Summary of Laboratory Tests to Assess Mechanical Properties of Permeable Pavement Materials *(1)*.
- Summary of a Computer Modeling Study to Understand the Performance Properties of Fully Permeable Pavements *(2)*.
- A framework for Life-Cycle Cost Analyses and Environmental Life-Cycle Assessments for Fully Permeable Pavements *(3)*.
- Hydraulic Performance Evaluation of Fully Permeable Pavements under Heavy Load and Heavy Traffic *(4)*.

This report is organized as follows:

1. Introduction
2. Summary of existing information
3. Materials characterization
4. Structural design
5. Life-cycle considerations
6. Conclusions and recommendations
7. Appendices

The results included in this report complete all of the objectives for this project.

<u>NOTE</u>

This research report summarizes the laboratory testing and analysis completed to date by the University of California Pavement Research Center on fully permeable pavements. The preliminary design procedure and preliminary design tables should be used to design experimental test sections, which should be monitored to evaluate performance under typical highway loads and rainfall events. The results of this monitoring will be used to validate or modify the tables, and to make recommendations on implementation as a stormwater best management practice. <u>This document should not be considered as a guideline for the design, construction and maintenance of fully permeable pavements.</u>

Chapter 2 Introduction

2.1 Background

Fully permeable pavements are defined for the purposes of this study as those in which all layers are intended to be permeable and the pavement structure serves as a reservoir to store water during storm periods in order to minimize the adverse effects of stormwater runoff. The California Department of Transportation (Caltrans) is interested in investigating the viability and risks of fully permeable pavement designs as a potential stormwater management best management practice (BMP).

Since the late 1970s, a variety of fully permeable pavement projects have been constructed in a number of U.S. states for low traffic areas and light vehicles. Most of the information available in the literature is about successes, while few failures have been reported for these applications. Observations of several projects by the authors indicate that failures have occurred in localized areas due to clogging of the permeable surface, and to construction processes that have resulted in severe raveling (loss of particles from the surface) or cracking.

As noted, most applications of fully permeable pavements in North America have been for pavements that are not subjected to high-speed traffic or truck traffic, such as parking lots, which reflects road owner concerns about durability. Structural design methods have been empirical in nature, with little or no long-term monitoring data to support the empiricism. Purely empirical design methods require good comprehensive empirical data for all of the expected design conditions, which has limited the speed of technology development for fully permeable pavements because of the high cost of learning from inevitable failures. For this reason it is difficult for purely empirical design methods to consider different materials, climates, subgrades, and structural cross sections because of the need for a large factorial set of performance data that considers all of these design variable permutations. A review of design practice across the United States *(5)* shows the very limited scope of current applications for fully permeable pavements, even by the leading design firms specializing in this type of design. The limited scope of current applications is also reflected in the recently produced National Asphalt Pavement Association (NAPA) *(6)*, American Concrete Pavement Association *(7)*, and Interlocking Concrete Pavement Institute *(8)* manuals for design of porous asphalt, pervious concrete pavements, and permeable interlocking concrete pavements, respectively.

The mechanistic-empirical approach used in this project for the development of new fully permeable pavement designs will increase the speed of technology development. The mechanistic-empirical design development process consists of determining relevant material properties in the laboratory, and then using them in inexpensive and risk-free computer models to evaluate pavement performance, followed by empirical validation and calibration of failure mechanisms and performance of the most promising designs through accelerated pavement testing and field test sections.

There is limited published data on life-cycle cost analysis (LCCA) of fully permeable pavements that include actual costs and performance, and also little information regarding environmental life-cycle assessments (LCA) of fully permeable pavements. There have been several analyses of comparative initial costs for fully permeable pavements compared with conventional pavements, which indicate that the cost of constructing fully permeable pavements is greater than the cost of conventional pavements for residential streets; however some studies indicate that the total initial costs are similar or less because the fully permeable pavements do not require stormwater drainage systems. All of the studies in the literature are for slow-speed facilities with few trucks, and compare different fully permeable pavement systems with different conventional pavements for different applications (streets, parking lots, and other paved areas). None of the studies considered shoulder retrofit of a highway *(3)*.

2.2 Objectives

2.2.1 Fully Permeable Pavement Development Program Objectives

The study discussed in this report is part of a larger development program being undertaken by the University of California Pavement Research Center (UCPRC) for Caltrans with the objective of developing guidelines, and inputs for specification language, for the appropriate use of fully permeable pavements as a potential BMP for controlling stormwater runoff from highways, maintenance yards, rest stops, and other pavements that Caltrans owns and manages.

This objective will be met after completion of laboratory testing to characterize the mechanical and hydrological properties of fully permeable pavement materials, structural and hydrological performance modeling to develop initial designs, life-cycle cost analyses and environmental life-cycle assessment studies, and full-scale testing in the field and/or using accelerated pavement testing (using the Caltrans Heavy Vehicle Simulator [HVS]) to validate the structural and hydrological designs, or if necessary to calibrate them to match the observed field performance. This step-wise development process of first performing laboratory testing and computer modeling, followed by full-scale validation with the HVS and field test sections is the typical process being used for development of other pavement technologies for Caltrans. Caltrans pavement designers have been involved in the process of reviewing the results of this development process, and the planning for this current project. As with any other new pavement technology, there is no commitment by Caltrans to implement it until the development process has reached a point at which the uncertainties have been sufficiently addressed to reduce the risk of pilot section failure on the state highway network to an acceptable level.

Successful completion of this project will provide Caltrans with structural design procedures, performance estimates, life-cycle cost analyses, and an environmental life-cycle assessment framework to compare fully permeable pavement BMPs with existing approved BMPs.

2.2.2 Objectives of this Project

The goal of the project covered in this current task order (RTA249), entitled *Laboratory Testing and Modeling for Structural Performance of Permeable Pavements under Heavy Traffic* is to develop preliminary fully permeable pavement designs that can be tested in pilot studies under typical California traffic and environmental conditions *(9)*. This goal will be achieved on completion of the following tasks:

1. Review the latest literature.
2. Prepare and test specimens in the laboratory for the structural properties necessary for undertaking a mechanistic-empirical design of fully permeable pavement structures. Develop new testing methods if required to evaluate non-traditional materials. Include the materials testing properties in the Mechanistic-Empirical Pavement Design materials database developed by the University of California Pavement Research Center (UCPRC) for Caltrans.
3. Prepare additional specimens for hydraulic performance testing in the laboratory as part of the companion task order (RTA247, *Laboratory Testing and Modeling for Hydraulic Performance of Permeable Pavements under Heavy Traffic*).
4. Estimate pavement performance for prototype designs using the laboratory test results in pavement performance models.
5. Perform a preliminary life-cycle cost analysis and environmental life-cycle assessment of the various options.
6. Based on the results of the computer model analysis, develop detailed structural designs for HVS and field test sections that include pavement dimensions and material specifications.

This report summarizes the work undertaken in all of the tasks.

More detailed life-cycle cost analysis (LCCA) and life-cycle assessment (LCA) will need to be performed after construction, evaluation, and performance validation of accelerated pavement test sections and field test sections to provide more realistic initial cost information and improved maintenance and rehabilitation cost estimates.

2.3 Companion Hydraulic Design Study

A parallel study (RTA247) was undertaken in conjunction with the study discussed in this report to evaluate the hydraulic performance of fully permeable pavements *(4)*.

Hydraulic performance was assessed by determining the minimum required thickness of the aggregate base course to capture and retain stormwater during rainfall events. Performance was evaluated by simulation under varying hydrological, material, and geometric conditions. Hydraulic simulations were performed using the commercially available *HYDRUS* software, which uses unsaturated flow theory and a finite element analysis process. The simulations were performed for three representative rainfall regions in California using data from Eureka, Sacramento, and Riverside, and 24-hour rainfall intensity based on actual or mechanically generated rainfall. Critical aggregate depth was determined for two-, fifty- and one-hundred year storm recurrence duration.

Results obtained from the hydraulic simulations, which were used as inputs in developing the design procedure described in this report, can be summarized as follows *(4)*:

- The critical aggregate reservoir layer depth to capture all the runoff generated by typical rainfall events in California ranges from less than 3.0 ft (1.0 m) to about 10 ft (3.0 m).
- The minimum aggregate thickness in Eureka was about 50 percent higher than the minimum aggregate thickness required for the Sacramento and Riverside areas. Longer recurrence periods (50 and 100 years) required thicker aggregate bases (i.e., reservoir layers) compared with the two-year period. Simulations using natural rainfall required slightly thicker base layers compared to those where mechanically generated rainfall simulations were used. The use of actual data is therefore recommended to obtain a more conservative layer thickness estimation.
- Saturated soil hydraulic conductivity is the most sensitive factor when determining critical aggregate layer thickness. A soil permeability of less than 10^{-5} cm/sec was found to be impractical for the design of fully permeable pavements.
- In general, the required thickness of the aggregate base doubles with additional lanes (i.e., increasing a two-lane road to a four-lane road requires a doubling of the base layer thickness). The increase in aggregate thickness for Eureka was higher compared to Sacramento and Riverside.
- If the subgrade soil is still wet from earlier rainfall events and additional rainfall occurs, then the aggregate layer thickness needs to be increased by an additional 80 percent (compared to the dry condition). Alternatively, allowance needs to be made for two or three surface overflows on an annual basis.
- The critical layer thicknesses determined during 24-hour rainfall simulations were verified through annual storm event simulations. The results show that the critical aggregate thicknesses determined in the study are sufficient. A reduction in layer thickness would result in periodic overflows. These overflows will increase significantly when the subgrade soil hydraulic conductivity is less than 10^{-4} cm/sec.
- The simulation results showed that a significant reduction in the air-voids in the pavement surface layer (i.e., severe clogging) and consequent significant reduction in the surface pavement hydraulic conductivity would be needed before the pavement would be classified as impermeable (i.e., water flows over the permeable surfacing and off the edge of the road instead of through the road).

Chapter 3 Summary of Existing Information

A number of comprehensive literature reviews on fully permeable pavements, a generic term covering porous asphalt, pervious concrete, and permeable interlocking concrete pavement, have been undertaken on behalf of the California Department of Transportation Division of Environmental Analysis *(e.g., 10,11)*. Consequently, only relevant literature made available after these reports was reviewed, with a special focus on the design of fully permeable pavements as opposed to general case studies.

3.1 Manuals and Specifications

3.1.1 National Asphalt Paving Association (NAPA)

NAPA offers an Information Series document entitled *Porous Asphalt Pavements for Stormwater Management* to guide the design, construction and maintenance of porous asphalt pavements *(6)*. The guideline is primarily focused on parking lots and very low-volume community access roads and paths (e.g., golf courses and park trails, etc.) and does not cover higher traffic volume roads or shoulders on higher traffic volume roads. The design process is essentially based on empirical procedures developed from project experience.

Structural Design

The NAPA guide recommends a pavement structure with an open-graded HMA surface over an asphalt-treated permeable base (ATPB), over a permeable gravel subbase. An optional 25-mm thick choker course of small aggregate between the subbase and base can be considered to provide a level construction surface. Layer thickness design is based on the use of suggested layer coefficients (based on field observations of a limited number of experiments) for estimating the thickness of the various layers using the AASHTO Flexible Pavement Design Method. The guide also recommends different HMA thicknesses for different types of traffic, based on field observations, as follows:

- Parking lots with little or no truck traffic: 2.5 in. (60 mm)
- Residential streets with some trucks: 4.0 in. (100 mm)
- Heavy trucks: 6.0 in. (150 mm)

Other factors that need to be considered in the design include:

- Soil infiltration rates should be between 0.1 and 10 in./hr (2.5 mm/hr and 250 mm/hr).
- The subgrade/bottom of the excavation for the permeable structure should be flat to maximize the infiltration area.
- The maximum slope of the pavement surface should not exceed five percent.

- An overflow system should be included in the design to prevent water in the stone base course from rising into the pavement surface layer during extreme storm events.
- The stone recharge bed should be able to drain within 12 and 72 hours.

Materials

The NAPA guide provides recommendations for geotextile (used to prevent migration of fines from the subgrade into the base), open-graded aggregate base/subbase (also termed the stone recharge bed), and porous asphalt, covering both the surfacing and the ATPB:

- Geotextiles. For the geotextile filter fabric between the subgrade and the stone recharge bed, grab tensile strength (≥120 lb [55 kg]), Mullen burst strength (≥225 psi [1.5 MPa]), flow rate (≥95 gal/min/ft^2) [3,870 L/min/m^2]), and UV resistance limits (≥70 percent) are provided.
- Stone Recharge Bed. A coarse, single-sized grading is recommended for the stone recharge bed. AASHTO No.3 stone is preferred, but No.2 or No.1 stone are both permissible, provided that a minimum air-void content of 40 percent is obtained. A maximum of two percent passing the No.100 sieve is recommended to ensure that fines will not clog the voids. An optional 1.0 in. (25 mm) thick choker course (No.57 stone) can be used on top of the coarser recharge bed aggregate as a leveling course if required.
- Asphalt Treated Permeable Base. Use State DOT design.
- Asphalt Surfacing. Use State DOT design.

Construction

The NAPA guide provides general construction guidelines. Key points include:

- Subgrade soils should not be compacted.
- State DOT procedures and specifications should be followed.
- The completed road should not be trafficked in the first 24 hours.
- Care should be taken to ensure that sediment laden water does not flow over the pavement.

Maintenance

The NAPA guide provides general maintenance guidelines. Key points include:

- Pavements should be vacuum swept twice annually.
- High-pressure water cleaning should not be used to unclog the pavement.
- Sand should not be used for de-icing.
- Appropriate signage should be erected to ensure that inappropriate maintenance actions are not performed.

3.1.2 American Concrete Pavement Association (ACPA)

The ACPA guide *(7)* provides very general information on the design of fully permeable pavements. No specific information is provided on structural design, materials, construction, or maintenance.

3.1.3 Interlocking Concrete Pavement Institute (ICPI)

Permeable interlocking concrete pavements (i.e., permeable blocks or permeable gaps between blocks) were excluded from the scope of this project by Caltrans. However, design information is available. ICPI offers a guideline entitled *Permeable Interlocking Concrete Pavements* to guide the design, construction, and maintenance of these types of pavements *(8)*. The guideline is primarily focused on parking lots and very low-volume community access roads and does not cover higher traffic volume roads or shoulders on higher traffic volume roads. The design process is essentially based on empirical procedures developed from project experience.

Structural Design

The ICPI guide recommends a pavement structure with permeable concrete paving blocks, over a permeable gravel base and subbase. The design is essentially focused on stormwater infiltration rate rather than traffic loading requirements.

Materials

The ICPI guide provides recommendations for geotextile, used to prevent migration of fines from the subgrade into the base, open-graded aggregate base/subbase, and permeable paving blocks:

- Geotextiles. Similar recommendation to the NAPA guide.
- Aggregate Base/Subbase. A course, single-sized grading is recommended for the base and subbase. AASHTO No.2 stone is preferred for the subbase and No.57 stone for the base. Aggregates should have 90 percent fractured faces, a Los Angeles Abrasion value greater than 40, an effective porosity of 0.32, and a California Bearing Ratio of at least 80 percent. Open-graded stabilized layers can be included. A 50 mm (2.0 in.) No.8 base bedding layer on top of the base is required before the pavers are laid.
- Permeable Pavers. Select according to use.

Construction

The ICPI guide provides general construction guidelines and a checklist is provided. Key points include:

- Subgrade soils should not be compacted. If they are compacted to improve structural capacity, compaction should not exceed 95 percent of standard Proctor density, and additional drains should be provided to deal with overflows resulting from the reduced permeability.
- State DOT procedures and specifications should be followed.
- Care should be taken to ensure that sediment laden water does not flow over the pavement.

Maintenance

The ICPI guide provides general maintenance guidelines. Key points include:

- Pavements should be vacuum swept once annually.
- Localized repairs should be undertaken as necessary.

3.2 Relevant Literature

A review of recent published conference and journal proceedings revealed that no significant advances in the mechanistic design of fully permeable pavements had been made since the earlier literature reviews. The 2010 Transportation Research Board Annual Meeting Proceedings *(12)* included numerous papers pertaining to pervious concrete, porous asphalt, and fully permeable pavements. Many of the papers focused on the surface layer only, and most concentrated on the aggregate grading, asphalt binder/cement content, and reduction in permeability over time due to clogging. There were no papers on structural design of fully permeable pavements, and those papers covering fully permeable pavements referred to parking lots or very low volume traffic roads only. A number of case studies were also reviewed. However, all of these pertained to very low-volume traffic roads and parking lots.

3.3 Meetings with Industry and Caltrans

3.3.1 American Concrete Pavement Association (ACPA)

The authors held a number of discussions with Mr. Craig Hennings and Mr. David Akers from the ACPA and Mr. Guy Collignon, an experienced contractor in the Sacramento area regarding fully permeable pavement design criteria, concrete mix designs, and construction practices. Representatives from the Portland Cement Association (PCA) also attended the meetings. Also discussed was a draft specification from the National Ready Mixed Concrete Association (NRMCA).

3.3.2 National Asphalt Paving Association (NAPA)

The authors held a number of discussions with Mr. Kent Hansen from NAPA. Additional information supporting that provided in the NAPA guide was obtained.

3.3.3 Interlocking Concrete Pavement Institute (ICPI)

The authors held a number of discussions with Mr. David Smith from ICPI. Additional information supporting that provided in the ICPI guide was obtained.

3.3.4 Caltrans Maintenance

A meeting was held with Mr. Steve Price from Caltrans District 5 Maintenance to discuss realistic maintenance programs for fully permeable roadways and shoulders. Notes from the meeting include:

- Currently there is little or no funding dedicated specifically to shoulder maintenance on Caltrans highways. Typically, maintenance on dense-graded HMA shoulders includes one or two sweepings per year and an asphalt emulsion spray every five years.

- Although the mechanical brooms used by Caltrans have a vacuum action, very little fine and organic material is collected, and consequently the current equipment used will probably not significantly prevent the clogging of fully permeable pavements if they were installed.
- If a BMP is installed for stormwater management, the agency is obliged to keep it functioning and must be able to prove that it is functioning effectively and as designed. BMPs are subject to Environmental Protection Agency (EPA) audits. This requires a Caltrans staff commitment to verify performance.
- Shoulder backing and maintenance of embankments will need to meet specifications to ensure optimal performance of retrofitted fully permeable shoulders. The specifications may need to be modified/updated to meet the needs of the fully permeable pavement design, and thereafter more strictly enforced.

3.3.5 Asphalt Interlayer Association

A meeting was held with Mr. Ray Myers to discuss the selection of appropriate drainage and drainage barrier materials for use in fully permeable pavements. Recommendations for specific materials have been included in the proposed cross sections.

3.3.6 Contractors

Meetings were held with two other contractors (Granite and Teichert) to discuss constructability of fully permeable pavements for shoulder retrofit of highways. Teichert provided estimated example costs for the construction of a typical fully permeable structure described in the following chapters.

Chapter 4 Materials Characterization

4.1 Introduction

The approach used for development of detailed pavement designs in this study is referred to as "mechanistic-empirical" or "ME." Caltrans is in the process of implementing this approach as a replacement for the empirical R-value design method. The assumptions of R-value designs (levels of compaction, pavement structural layering, etc.) are also not appropriate for fully permeable pavements. The structural properties of interest include stiffness, strength, durability, fatigue performance, and rutting performance.

4.2 Experiment Plans

The proposed *(9)* and actual testing plans followed in the laboratory testing study are shown in Table 4.1 through Table 4.5. Differences between the proposed and actual test plans and justification for the inclusion/exclusion of tests and material types are discussed in the technical memorandum on laboratory testing *(1)*.

4.3 Summary of Materials Characterization

4.3.1 Subgrade Soils

Subgrade materials are generally the in situ soils below a pavement structure. On existing pavements, they are usually compacted as densely as possible to provide a platform for the overlying pavement layers and to provide added structural integrity to the pavement. However, on fully permeable pavements, compaction of the subgrade is generally restricted where possible to facilitate infiltration of water. This requires a thicker overlying pavement structure to compensate for the reduced subgrade strength. Testing of subgrade materials focused on the influence of different levels of compaction and different moisture contents on the stiffness of those materials.

Material Sampling

Clay subgrade material was sampled from an undisturbed area near the UCPRC research facility. The silt material was sampled from an undisturbed area near Stockton. The materials were considered representative of clay and silt materials in California. Sandy materials were not tested because they generally have adequate permeability and strength.

Table 4.1: Summary of Test Plan for Subgrade Materials and Permeable Gravel Base

Layer	Properties of Interest	Test Type	Materials	Compaction (%)	Saturation	Gradation	Moisture Content	Replicate	Total Tests[1]
Proposed Test Plan									
Subgrade	Stiffness	AASHTO-T307[2]	1 x Silt, 2 x Clays	80, 90	Saturated, Unsaturated	As excavated	OMC[4], OMC -2%	1	24
	Rutting resistance	TRLT[3]	1 x Silt, 2 x Clays	80, 90	Saturated, Unsaturated	As excavated	OMC, OMC -2%	1	24
Base	Stiffness	AASHTO-T307	1 x Crushed gravel 1 x Recycled concrete 1 x Recycled glass 1 x Recycled tire blend	n/a	Saturated, Unsaturated	3	n/a	1	24
Actual Test Plan									
Subgrade	Stiffness	AASHTO-T307	1 x Silt 1 x Clay	90, 95 80, 85, 90, 95	Saturated Unsaturated	As excavated	OMC, OMC -2%, OMC +3% OMC, OMC -2%, OMC + 3%, +8%	1	44
	Rutting resistance	TRLT	1 x Silt 1 x Clay	80, 90	Saturated Unsaturated	As excavated	OMC, OMC -2%, OMC +3% OMC, OMC -2%, OMC + 3%, +8%	1	28
Base	Stiffness Permeability	AASHTO-T307	3 x Crushed gravel	n/a	Saturated Unsaturated	As supplied	n/a	2	12

[1] Total tests = Compaction x Saturation x Gradations x Moisture Contents x Materials x Test Variables.
[2] Triaxial Stiffness Test. [3] Triaxial Repeated Load Test.
[4] Optimum moisture content.

Table 4.2: Summary of Test Plan for Permeable Concrete Subbase

Layer	Properties of Interest	Test Type	Materials	Air-voids (%)	Gradations	Test Variables	Total Tests[1]
Proposed Test Plan							
Surface	Compressive strength	ASTM C-39[2]	1 x Recycled concrete	20 25	3	3 replicates	18
	Fatigue resistance	ASTM C-78[3]	1 x Recycled concrete	20 25	3	3 replicates	18
	Flexural strength	ASTM C-78[4]	1 x Recycled concrete	20 25	3	3 replicates	18
Actual Test Plan							
Subbase	Compressive strength	ASTM C-39	1 x Crushed Gravel	n/a[5]	6	3 replicates	18

[1] Total tests = Materials x Air-Voids x Gradations x Test Variables.
[2] Compressive Strength Test. [3] Flexural Controlled-Deformation Fatigue Test. [4] Flexural Beam Test.
[5] Air-void content is dependent on gradation.

Table 4.3: Summary of Test Plan for Permeable Asphalt Wearing Course

Layer	Properties of Interest	Test Type	Materials	Mixes	Air-voids (%)	Gradations	Test Variables	Total Tests
Proposed Test Plan								
Asphalt Wearing Course	Stiffness	AASHTO T-321[1]	1 x Crushed aggregate	1 x HMA-O 1 x R-HMA-O	15 20	2	3 x temperatures 1 x strain level 1 x replicates	24
	Fatigue resistance	AASHTO T-321[2]	1 x Crushed aggregate	1 x HMA-O 1 x R-HMA-O	15 20	2	1 x temperatures 2 x strain level 2 x replicates	32
	Rutting resistance Moisture sensitivity	AASHTO T-324[3]	1 x Crushed aggregate	1 x HMA-O 1 x R-HMA-O	15 20	2	1 x temperatures 2 x strain level 2 x replicates	48
Actual Test Plan								
Asphalt Wearing Course	Permeability	ASTM PS 129	3 x Crushed aggregate	17[4]	n/a[5]	n/a[5]	3 x replicates	51
	Flexural Stiffness	AASHTO T-321[1]	3 x Crushed aggregate	17	n/a	n/a	3 x temperatures 1 x strain level 2 x replicates	102
	Fatigue resistance	AASHTO T-321[2]	4 x Crushed aggregate	4	n/a	n/a	1 x temperature 2 x strain levels 3 x replicates	24
	Rutting resistance	AASHTO T-320[6]	3 x Crushed aggregate	17	n/a	n/a	1 x temperatures 1 x stress level 3 x replicates	51
	Moisture sensitivity	AASHTO T-324[3]	3 x Crushed aggregate	17	n/a	n/a	3 x replicates	51
	Raveling resistance	ASTM D7064[7]	3 x Crushed aggregate	17	n/a	n/a	3 x conditions 3 x replicates	153

1 Flexural Frequency Sweep Test.
2 Flexural Controlled-Deformation Fatigue Test.
3 Hamburg Wheel Track Test.
4 Includes a range of aggregate sizes, sources, binder types, and fillers.
5 Air-voids dependent on gradation.
6 Repeated simple shear test.
7 Standard Practice for Open-Graded Friction Course (OGFC) Mix Design (Cantabro Test).

Table 4.4: Summary of Test Plan for Permeable Concrete Wearing Course

Layer	Properties of Interest	Test Type	Materials	Air-voids (%)	Gradations	Cement Content	Test Variables	Total Tests
Proposed Test Plan								
PCC Wearing Course	Compressive strength	ASTM C-39	1 x Crushed aggregate	15 20	3	1	3 replicates	18
	Fatigue resistance	ASTM C-78	1 x Crushed aggregate	15 20	3	1	3 replicates	18
	Flexural strength	ASTM C-78	1 x Crushed aggregate	15 20	3	1	3 replicates	18
	Coefficient of thermal expansion	AASHTO T-336	2 x Crushed aggregate	15 20	3	1	2 replicates	24
Actual Test Plan								
PCC Wearing Course	**Phase 1**							
	Permeability	ASTM PS 129	1 x Crushed aggregate	n/a[1]	6	1	3 replicates	18
	Compressive strength		1 x Crushed aggregate	n/a	6	1	5 replicates	30
	Phase 2							
	Permeability	ASTM PS 129	1 x Crushed aggregate	n/a	3	1	3 replicates	9
	Compressive strength	ASTM C-39	1 x Crushed aggregate	n/a	3	1	3 replicates	9
	Split tensile strength	ASTM T-198	1 x Crushed aggregate	n/a	3	1	5 replicates	15
	Flexural strength	ASTM C-78	1 x Crushed aggregate	n/a	3	1	3 replicates	15
	Fatigue resistance	ASTM C-78	1 x Crushed aggregate	n/a	3	1	3 replicates	9
	Phase 3							
	Permeability	ASTM PS 129	3 x Crushed aggregate	n/a	3	2	3 replicates	9
	Compressive strength	ASTM C-78	3 x Crushed aggregate	n/a	3	2	3 replicates	9
	Split tensile strength	ASTM T-198	3 x Crushed aggregate	n/a	3	2	5 replicates	9
	Coefficient of thermal expansion	AASHTO T-336	2 x Crushed aggregate	n/a	3		2 replicates	24

[1] Air-void content is dependent on gradation.

Table 4.5: Summary of Test Plan for Precast/Cast In-Place Concrete Wearing Course

Layer	Properties of Interest	Test Type	Materials	Hole Types	Hole Configurations	Gradations	Test Variables	Total Tests[1]
Proposed Test Plan								
PCC Wearing Course	Fatigue resistance	ASTM C-78[2]	1 x Crushed aggregate	2	4	1	3 replicates	24
	Flexural strength	ASTM C-78[3]	1 x Crushed aggregate	2	10	1	2 replicates	40
Actual Test Plan								
PCC Wearing Course	Permeability	ASTM PS 129	1 x Crushed aggregate	1	1	1	3 replicates	3
	Fatigue resistance	ASTM C-78	1 x Crushed aggregate	1	1	1	3 replicates	3
	Flexural strength	ASTM C-78	1 x Crushed aggregate	1	1	1	2 replicates	2

1 Total tests = Hole Types x Hole Configurations x Gradations x Test Variables.
2 Flexural Controlled-Deformation Fatigue Test.
3 Flexural Beam Test.

Test Results: Grading Analysis

The grading analysis was carried out following AASHTO Test Method T-11. The results for the two soils are shown in Figure 4.1. The gradings are typical for these soil types and were considered to provide a good representation of subgrade soils in the Central Valley of California. They should be representative of other areas of the state as well, and provide an adequate variation to understand behavior in terms of fully permeable pavements.

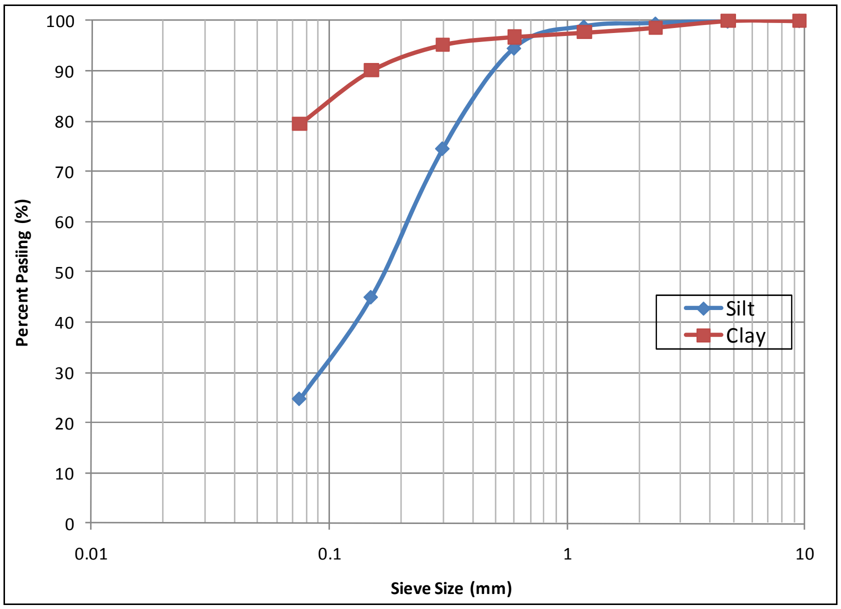


Figure 4.1: Subgrade materials grading analysis

Test Results: Atterberg Limits

The Atterberg limits were determined following AASHTO Test Methods T-89 and T-90. The Atterberg limits for the two soils and their soil classification based on the grading analysis and Atterberg limits are summarized in Table 4.6. The difference between the two soil types was considered sufficient for distinguishing performance trends. Although clays with much higher plasticity indices are common in California, the testing of these clays was not considered necessary as they would typically not be considered suitable for supporting fully permeable pavement structures.

Table 4.6: Subgrade Soil Atterberg Limits and Classification

	Atterberg Limits		
Soil Type	**Liquid Limit**	**Plastic Limit**	**Plasticity Index**
Silt Clay	Soil pat slips 30.9	Non-plastic 18.5	0 12.4
Soil Type	**Classification**		
	USCS[1]	**AASHTO[2]**	
Silt Clay	ML CL	A-2-4 A-6	

[1] USCS – Unified Soil Classification System
[2] AASHTO – American Association of State Highway and Transport Officials

Test Results: Density-Moisture Relationships

The maximum dry density and optimum moisture content of each material were determined using AASHTO Test Method T-99 (Method A) and Caltrans Test Method CT-216. Results are summarized in Table 4.7. The results show that the densities obtained using the Caltrans method were approximately five percent higher than those determined using the AASHTO method. The optimum moisture contents of the silt material were the same for both test methods, but were significantly different for the clay material (Caltrans method was four percent lower). The differences were attributed to the different compaction energies and amount of shearing in the two methods. The AASHTO densities and optimum moisture content were selected for all further work as this provided a more conservative representation of field conditions.

Table 4.7: Optimum Moisture content and Maximum Density of Silt and Clay

Soil Type	Wet Density[1] (kg/m^3)		Dry Density[1] (kg/m^3)		Optimum Moisture Content (%)	
	AASHTO	**Caltrans**	**AASHTO**	**Caltrans**	**AASHTO**	**Caltrans**
Silt	2,070	2,150	1,850	1,920	12	12
Clay	2,100	2,170	1,800	1,910	17	14

[1] Densities rounded to nearest 10 kg/m^3

Test Results: Permeability

Permeability of the silt and clay materials for a range of compaction levels was determined using AASHTO Test Method T-215 (constant head method). The relationship between permeability and soil compaction for the silt and clay is summarized in Figure 4.2. Permeability on both materials was poor and decreased with increasing compaction, as expected. The clay material was more consistent than the silt, which was attributed to the finer gradation. The reduction in permeability with increasing compaction was not as significant for the silt as it was for the clay. The permeability of the clay decreased from 10^{-2} cm/s (natural, uncompacted in situ soil) to 10^{-5}cm/s (100 percent of laboratory determined maximum dry density) over the range of compactions tested.

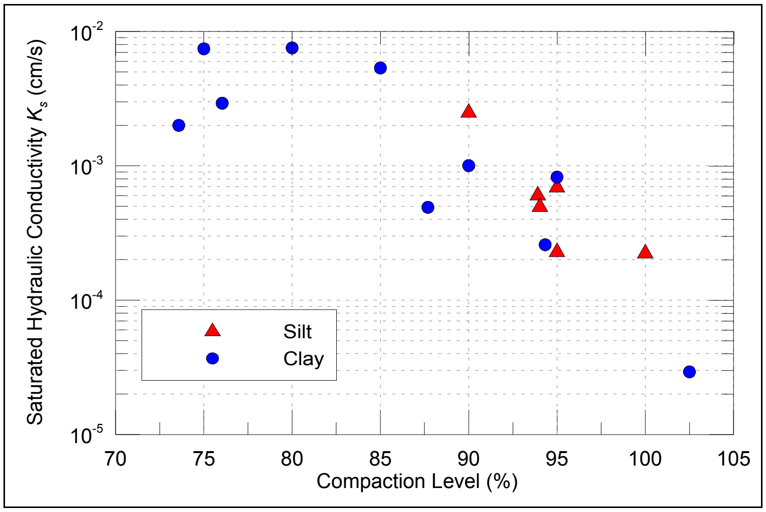


Figure 4.2: Saturated hydraulic conductivity vs. compaction level of silt and clay.

(Note permeability determined using AASHTO T-215 [constant head])

Test Results: Resilient Modulus

The resilient modulus of each material was assessed using AASHTO Test Method T-307, using the testing sequence summarized in Table 4.8. Specimens were prepared using the moisture content and density determined earlier in the study as a baseline, with additional specimens prepared with different density and moisture content combinations. Specimens for determining the resilient modulus of the silt material were prepared as follows:

- Two different density combinations:
  - 90 and 95 percent of the previously determined AASHTO density. Densities below 90 percent were not considered for tests on the silt material as it is unlikely that such a low density would be found on a highway given the natural compaction of the soil and additional compaction through unavoidable movements of the construction equipment.
- Three different optimum moisture content (OMC) combinations:
  - OMC, OMC – 2 percent, and OMC + 3 percent. Testing in the saturated condition was not undertaken due to difficulties in preparing specimens (specimens “failed” before testing started) and the knowledge gained from testing at the three selected moisture contents, which indicated that the soils would have little or no bearing capacity at higher moisture contents.

Specimens for determining the resilient modulus of the clay material were prepared as follows:

- Four different density combinations:
  - 80, 85, 90, and 95 percent of the previously determined AASHTO density. Densities below 90 percent were considered for tests on the clay materials. Although it is unlikely that such a low density would be found on a highway given the natural compaction of the soil and additional compaction through unavoidable movements of the construction equipment, possible worst case conditions representing high rainfall events, or prolonged rainfall, at the lower densities were assessed.

- Four different moisture content combinations:
  - OMC, OMC – 2 percent, OMC + 3 percent, OMC + 5 percent. Testing under saturated conditions was not undertaken for the same reasons as those provided for the silt material.

Table 4.8: Testing Sequence for Resilient Modulus of Subgrade Soil

Sequence No.	Confining Pressure, σ_3		Max. Dev. Stress, σ_d		No. of Load Applications
	kPa	psi	kPa	psi	
0	42	6	28	4	500
1	42	6	14	2	100
2			28	4	
3			42	6	
4			56	8	
5			70	10	
6	28	4	14	2	100
7			28	4	
8			42	6	
9			56	8	
10			70	10	
11	14	2	14	2	100
12			28	4	
13			42	6	
14			56	8	
15			70	10	

The results of the resilient modulus testing are summarized in Table 4.9 and Table 4.10 and in Figure 4.3 through Figure 4.9 and are consistent with results presented in the literature *(13,14)*. It should be noted that preparing and handling stable specimens at the lower densities and higher moisture contents proved difficult and therefore the full range of moisture contents are only shown for the 90 percent compaction level (i.e., most likely field compaction) for the clay material. Figure 4.3 shows that the resilient modulus of the silt material increased with an increase in confining pressure and decreased with an increase in moisture content, as expected. The relationship between resilient modulus and deviator stress showed similar trends, but was less significant. The specimen with the highest compaction and lowest moisture content had the highest resilient modulus, and the specimen with the lowest compaction and highest moisture content had the lowest resilient moisture content, as expected. The influence of moisture content was more significant than that of compaction level and small changes in moisture are likely to have a significant influence on the strength and stiffness of subgrade materials. It should be noted that under field conditions, saturated soils under pavements still have some strength due to natural confinement of the surrounding soil and compacted layers above.

Table 4.9: Silt Subgrade: Results of Resilient Modulus Testing

Conf. Pressure (kPa)	Dev. Stress (kPa)	Resilient Modulus (MPa)					
		90% Compaction			95% Compaction		
		MC=10%	MC=12%	MC=15%	MC=10%	MC=12%	MC=15%
14	13	66	57	41	88	71	53
	26	60	52	38	80	65	50
	39	64	56	40	85	70	52
	52	64	53	NR	89	72	54
	65	56	NR	NR	86	66	53
28	13	92	81	56	120	98	66
	26	82	73	50	110	90	60
	39	84	75	52	111	92	63
	52	86	77	53	115	95	64
	65	86	77	54	118	97	65
42	13	116	108	72	148	123	91
	26	111	101	67	142	120	87
	39	110	99	66	142	119	85
	52	106	95	65	140	118	83
	65	105	94	65	139	117	81

MC = Moisture Content NR = No result

Table 4.10: Clay Subgrade: Results of Resilient Modulus Testing

Conf. Pressure (kPa)	Dev. Stress (kPa)	Resilient Modulus (MPa)									
		80% Compaction		85% Compaction		90% Compaction				95% Compaction	
		MC=15%	MC=17%	MC=15%	MC=17%	MC=15%	MC=17%	MC=20%	MC=25%	MC=15%	MC=17%
14	13	105	87	130	103	179	118	101	NR	201	140
	26	87	73	114	88	161	101	87	NR	185	117
	39	79	63	104	78	151	90	78	NR	175	105
	52	71	56	97	70	142	82	73	NR	167	95
	65	66	51	91	65	135	76	68	NR	160	88
28	13	110	95	141	113	192	125	107	NR	215	146
	26	94	77	122	95	171	107	89	NR	194	126
	39	83	66	111	82	157	94	81	NR	183	110
	52	75	58	102	73	147	85	74	NR	172	98
	65	70	53	95	67	139	79	71	NR	164	91
42	13	112	93	141	108	190	128	107	19	217	149
	26	97	79	125	91	171	111	97	13	198	128
	39	85	67	113	81	158	98	89	10	185	112
	52	77	59	103	73	148	87	80	10	173	101
	65	71	53	96	67	139	80	73	NR	163	92

MC = Moisture Content NR = No result

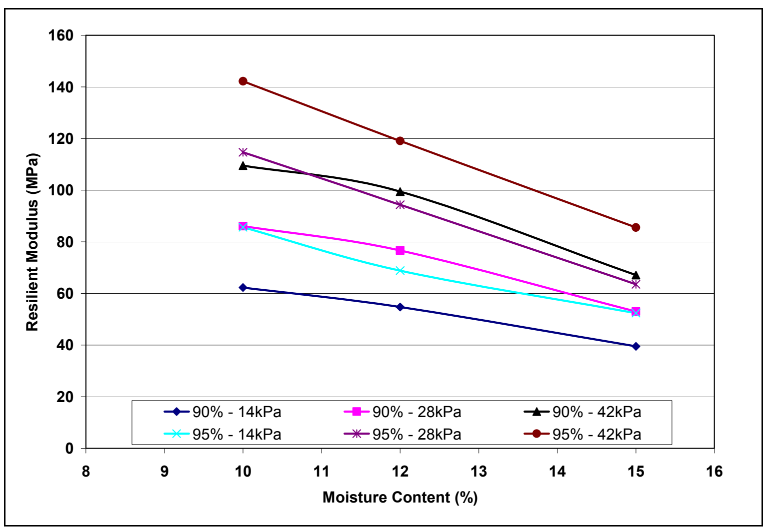


Figure 4.3: Silt: Resilient modulus vs. compaction moisture content for different confining pressure.

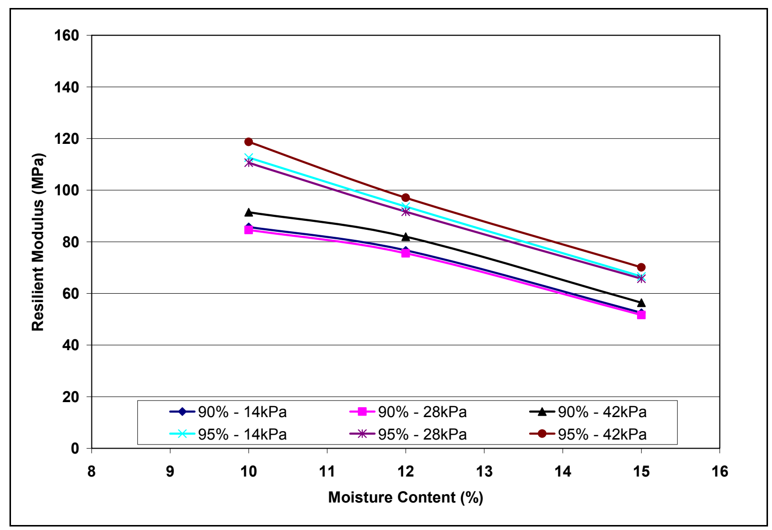


Figure 4.4: Silt: Resilient modulus vs. compaction moisture content for different deviator stresses.

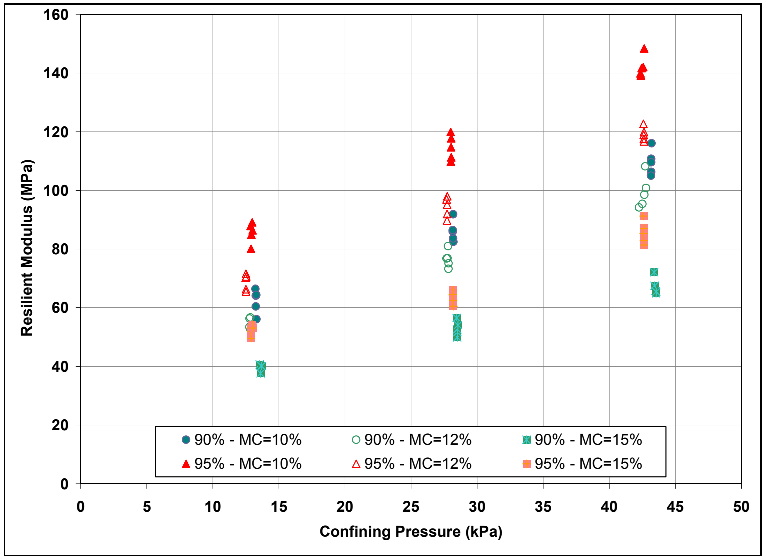


Figure 4.5: Silt: Resilient modulus vs. confining pressure.

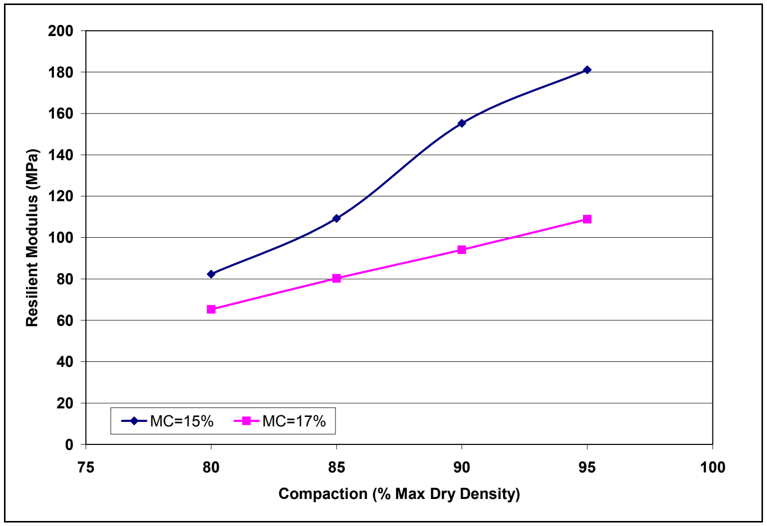


Figure 4.6: Clay: Resilient modulus vs. compaction.

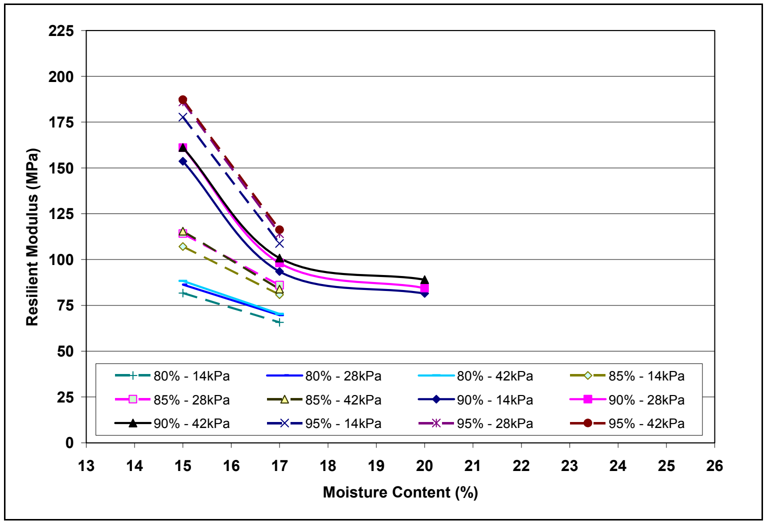


Figure 4.7: Clay: Resilient modulus vs. compaction moisture content for different confining pressure.

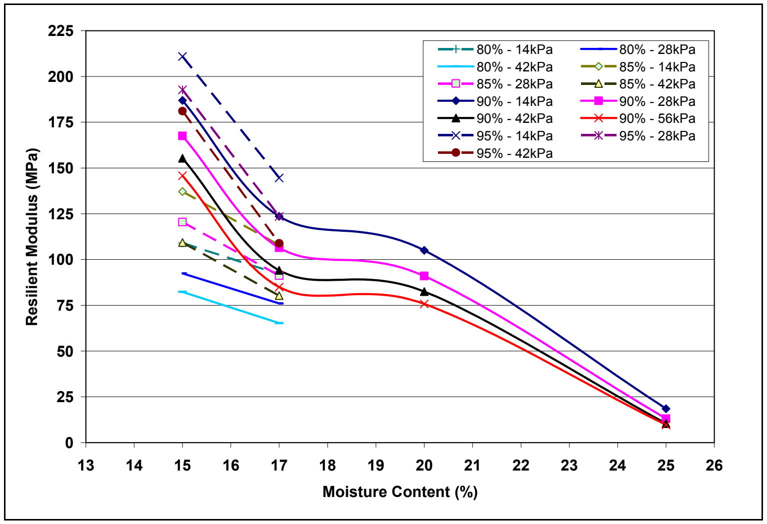


Figure 4.8: Clay: Resilient modulus vs. compaction moisture content for different deviator stresses.

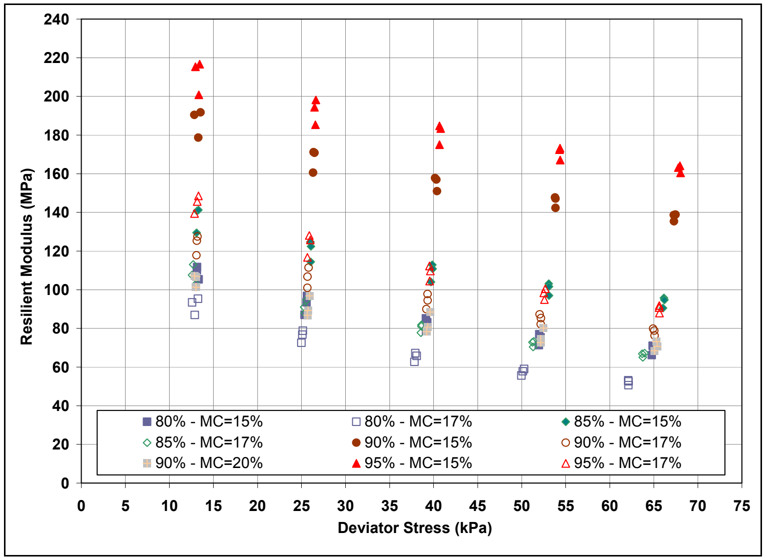


Figure 4.9: Clay: Resilient modulus vs. deviator stress.

Test Results: Permanent Deformation

Repeated load permanent deformation test specimens were prepared using the moisture contents and densities determined earlier in the study. The permanent deformation of each specimen was assessed using the testing sequence summarized in Table 4.11. Lower loads were used on the high moisture content specimens to limit very early failures.

Table 4.11: Testing Sequence of Permanent Deformation for Subgrade Soil

Moisture Content	Sequence No.	Confining Pressure, σ_3		Max. Deviator Stress, σ_d		No. of Load Applications
		kPa	psi	kPa	psi	
Silt						
10%, 12%	1	14	2	28	4	1,000
	2			42	6	2,000
	3			56	8	3,000
	4			70	10	5,000
	5			84	12	9,000
Total						**20,000**
15%	1	14	2	14	2	1,000
	2			28	4	1,000
	3			42	6	2,000
	4			56	8	3,000
	5			70	10	5,000
	6			84	12	9,000
Total						**21,000**
Clay						
15%, 17%	1	14	2	42	6	1,000
	2			70	10	2,000
	3			98	14	3,000
	4			126	18	5,000
	5			154	22	9,000
Total						**20,000**
20%, 25%	1	14	2	21	3	1,000
	2			42	6	1,000
	3			70	10	2,000
	4			98	14	3,000
	5			154	22	5,000
	6			154	22	9,000
Total						**21,000**

The results of the repeated load permanent deformation tests on the silt and clay materials are shown in Figure 4.10 and Figure 4.11 respectively and show that both materials will add very little strength (permanent deformation resistance) to a pavement structure, with performance negatively influenced with increasing moisture content.

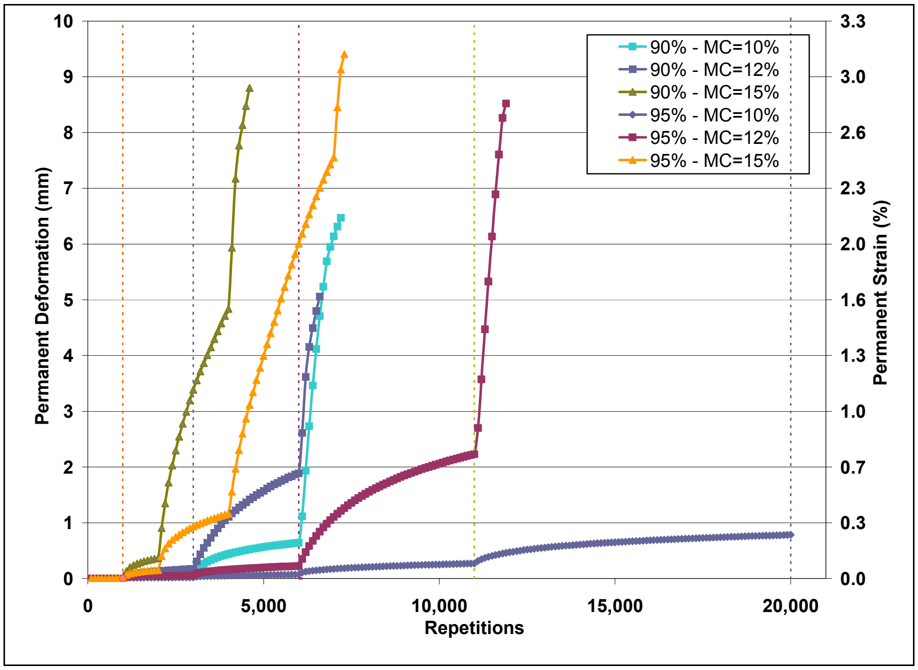


Figure 4.10: Silt: Permanent deformation using confining pressure of 14 kPa.

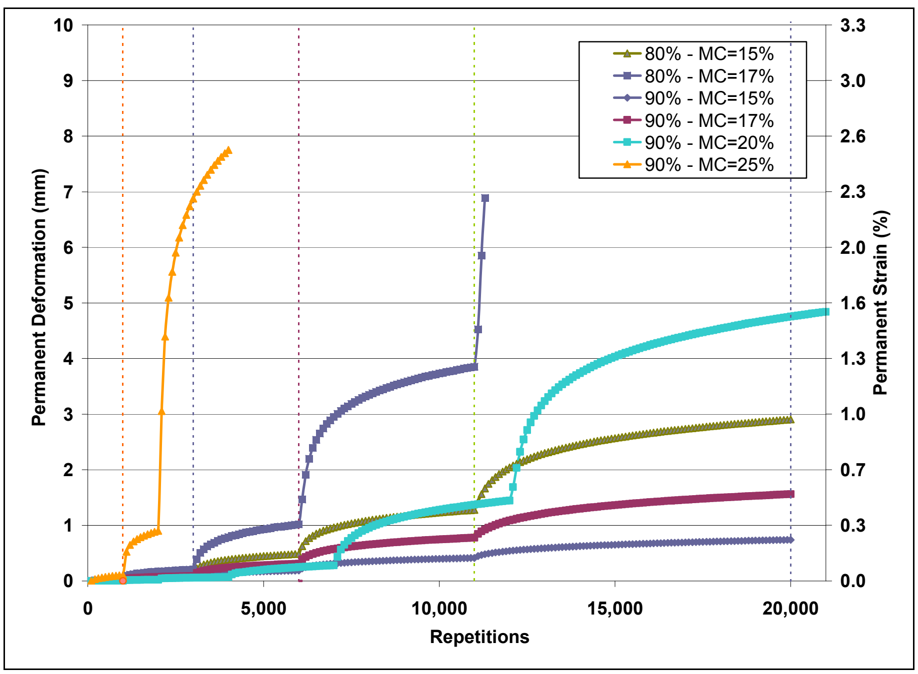


Figure 4.11: Clay: Permanent deformation using confining pressure of 14 kPa.

Summary of Test Results on Subgrade Soils

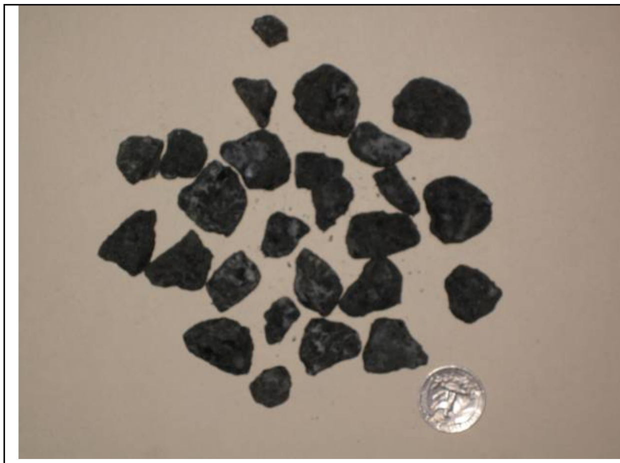
The results of tests on two different subgrade soils common in the Central Valley of California indicate that both soil types will add very little support to a pavement structure, and that the stiffness and the associated strength of the materials will decrease significantly as the moisture content increases. Any fully permeable pavement structure on these materials will need to compensate for this poor bearing capacity with thicker base and surfacing layers. Testing was not undertaken in the saturated condition given the already poor performance recorded at compaction moisture contents, and the difficulty in preparing specimens for testing (i.e., specimens "failed" before the test could be started). It should be noted that under field conditions, saturated soils under pavements still have some strength due to natural confinement of the surrounding soil and compacted layers above. Since testing under saturated conditions was not feasible, a worst case soil strength under saturated conditions was used for modeling the performance of fully permeable pavements (Chapter 5) and for developing the structural design procedures discussed in Chapter 6.

4.3.2 Base Course Materials

The base course separates the wearing course and subgrade materials and provides much of the bearing capacity in any pavement. On existing non-permeable pavements, base courses typically have a very dense grading and are usually compacted as densely as possible to provide a platform for the overlying wearing course layers and to provide the maximum possible structural integrity to the pavement. However, on fully permeable pavements, an open-graded base course is used to maximize water storage. This influences the degree of compaction and resultant strength that can be achieved. The base course will therefore typically need to be thicker to compensate for the lower strengths and stiffnesses associated with the less dense grading. Testing of base course materials focused on the stiffness of those materials.

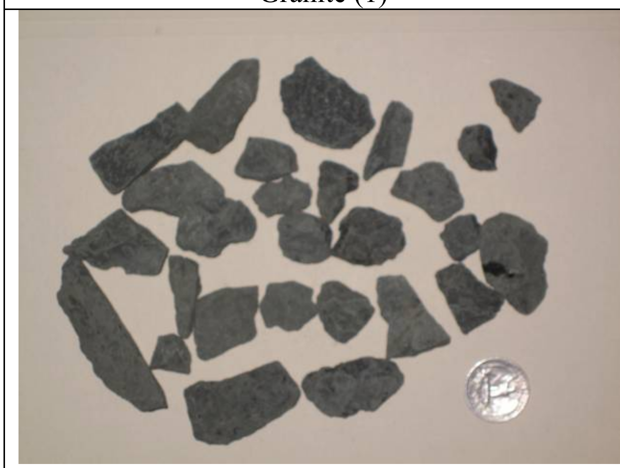
Material Sampling

Four different commercially available aggregate samples of different geological origin (granite [two gradings], basalt, and alluvial) were sourced from three different suppliers in northern California. These materials were considered to be representative of sources in the Central Valley and coastal regions of the state. Photographs of the various aggregates are shown in Figure 4.12. The basalt and granite materials were sourced from a hard-rock quarry and were angular in shape. The basalt particles were predominantly flaky compared to the granite, which was predominantly blocky in shape. The alluvial material consisted of primarily smooth, rounded particles, although most had at least one crushed face.



Granite (1)

Granite (2)



Basalt

Alluvial

Figure 4.12: Photographs of aggregates indicating size distribution and shape.

<u>Test Results: Grading Analysis</u>

The grading analysis was carried out following AASHTO Test Methods T-11 and T-27. The results for the four materials are shown in Figure 4.13. The results are compared with those discussed in the NAPA manual *(6)* and the work done at the University of Illinois *(15,16)* in Figure 4.14.

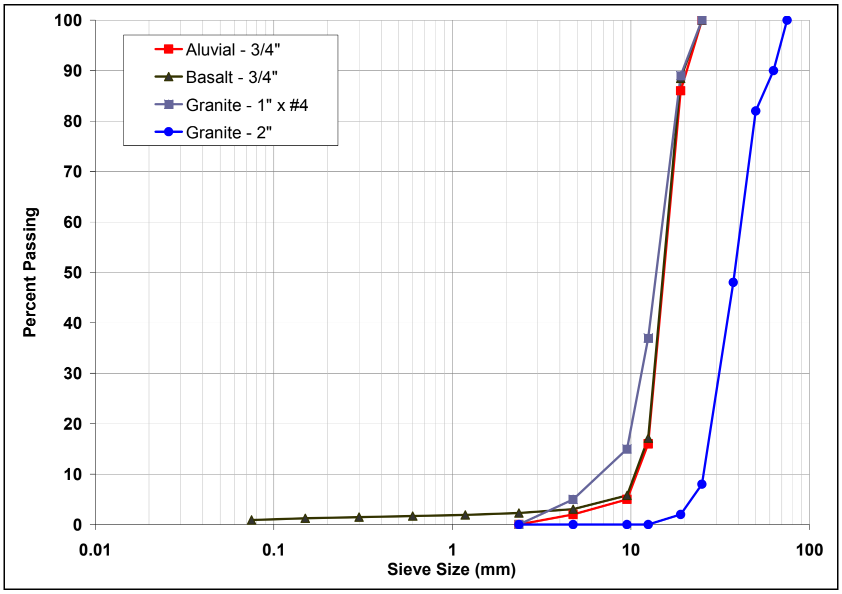


Figure 4.13: Grading analysis base course materials.

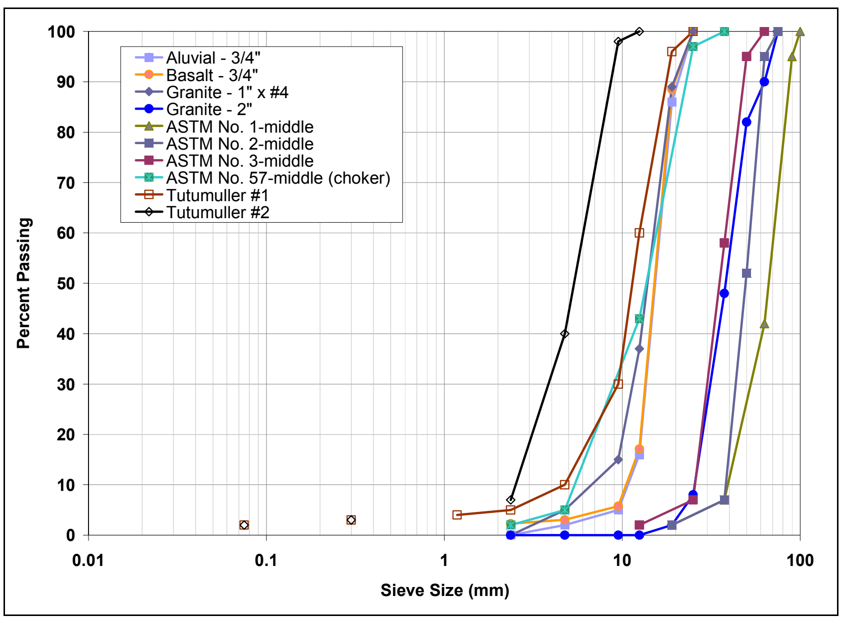


Figure 4.14: Grading analysis comparison with NAPA manual materials *(6)*.

The results show that the alluvial and basalt materials had a similar grading with no significant variation in particle sizes. The finer granite material (1 in. x #4) had a larger range of particle sizes. The coarse granite (similar to railway ballast) contained significantly larger aggregates than the other materials, with very little variation in particle size, and was closer to the aggregate size typically recommended in the literature *(6)*.

Three of the four materials selected for testing were generally finer than those described in the NAPA manual *(6)*, with the exception of the ASTM No.57 material, which had a similar grading to the finer granite. The coarse granite had a similar grading to the ASTM No.3 material, both of which were finer compared to the ASTM No.1 and No.2 materials.

<u>Test Results: Permeability</u>

Permeability of the four aggregates was determined using ASTM-PS 129. The materials had a void ratio between 20 and 25 percent and all had a permeability close to 0.1 cm/s, which appears to be sufficient for typical California conditions *(4)*.

<u>Test Results: Resilient Modulus</u>

There are no published specimen preparation or testing procedures for the triaxial testing of coarse open-graded materials. The AASHTO T-307 test method was therefore adapted as follows:

1. Weigh sufficient material for the preparation of one specimen (about 11 kg).
2. Place a thick rubber membrane inside the mold and place it on the vibration table.
3. Place the material into the mold in six separate lifts, rodding each lift 20 times to orient the material and optimize particle interlock. Weigh the remaining material.
4. Place the specimen on the testing frame.
5. Remove the mold from the specimen and measure height and diameter according to AASHTO T-307.
6. Position the transducers and test according to AASHTO T-307.

Specimen details for the four materials are summarized in Table 4.12. However, the coarse granite could not be tested as the aggregates were too large to prepare a satisfactory 6.0 in. (152 mm) specimen.

Table 4.12: Triaxial Specimen Details

Material	Mass (kg)	Diameter (mm)	Height (mm)	Density (kg/m³)	Specific Gravity	Void Content (%)
Alluvial – ¾ in.	9.929	152	315	1,737	2.762	37
Basalt – ¾ in.	9.340	152	312	1,650	2.670	38
Granite – 1 in. x #4	10.275	152	318	1,781	2.761	36
Granite – 2 in.	8.890	152	304	1,612	2.761	42

Testing was carried out according to AASHTO T-307, but with the addition of one extra confinement sequence at the beginning of the test (Sequence 00 in Table 4.13) to prevent premature disintegration of the specimen.

Table 4.13: Resilient Modulus Testing Sequence (Modified from AASHTO T-307)

Sequence No.	Confining Pressure, σ_3		Max. Dev. Stress, σ_d		No. of Load Applications
	(kPa)	(psi)	(kPa)	(psi)	
00	103.4	15	0	0	200 sec
0	103.4	15	103.4	15	500
1	20.7	3	20.7	3	100
2	20.7	3	41.4	6	100
3	20.7	3	62.0	9	100
4	34.5	5	34.5	5	100
5	34.5	5	68.9	10	100
6	34.5	5	103.4	15	100
7	68.9	10	68.9	10	100
8	68.9	10	137.9	20	100
9	68.9	10	206.8	30	100
10	103.4	15	68.9	10	100
11	103.4	15	103.4	15	100
12	103.4	15	206.8	30	100
13	137.9	20	103.4	15	100
14	137.9	20	137.9	20	100
15	137.9	20	275.8	40	100

The average results of resilient modulus testing on the three materials are presented in Figure 4.15. The results show that there was very little difference in performance between the three material types, although the finer, more graded samples had a slightly higher resilient modulus, as expected. The resilient modulus values were considerably lower than those typically obtained from testing conventional dense-graded aggregate base course materials. Results were compared to a selection of other results from the literature *(15,16)*. The resilient moduli of the materials tested in this study generally fell between those tested in the other studies, but showed similar trends in terms of the effects of grading and particle size on resilient modulus.

The stress dependency parameters for the K-θ and Universal resilient modulus models, which were used in the mechanistic-empirical pavement analyses, are listed in Table 4.14.

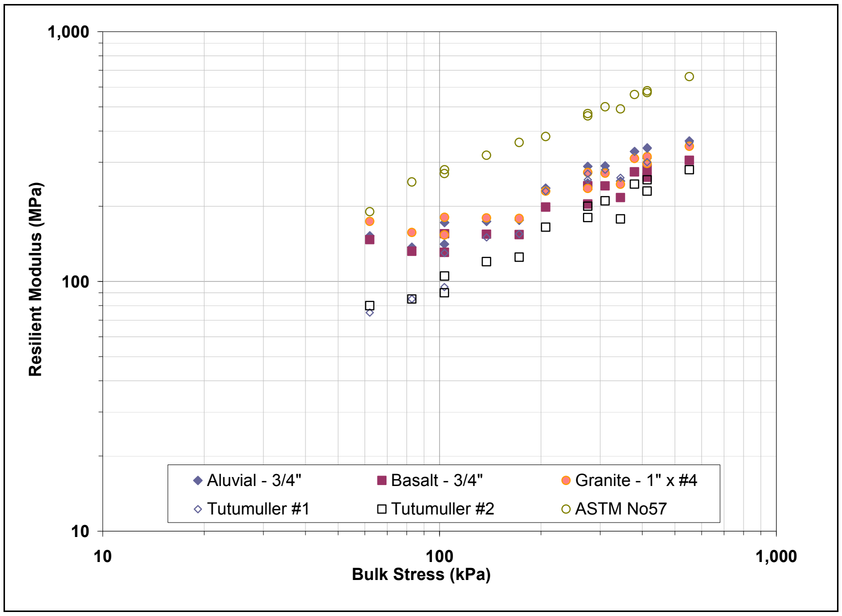


Figure 4.15: Resilient modulus of base materials.

Table 4.14: Resilient Modulus Model Parameters

Material	K-θ Model			Universal Model			
	K_1	K_2	R^2	K_1	K_2	K_3	R^2
Alluvial – ¾ in.	12.610	0.538	0.937	11.797	0.775	-0.267	0.993
Basalt – ¾ in.	16.145	0.465	0.929	15.254	0.667	-0.228	0.983
Granite – 1 in x #4	21.274	0.440	0.926	20.175	0.628	-0.213	0.979
Tutumuller #1	3.075	0.776	0.959	2.556	1.040	-0.274	0.982
Tutumuller #2	5.658	0.620	0.964	4.788	0.858	-0.247	0.994
ASTM No.57	21.624	0.544	0.992	21.536	0.550	-0.006	0.992

Test Results: Dynamic Cone Penetrometer

Dynamic Cone Penetrometer (DCP) tests were carried out on the base course materials, confined in barrels to determine whether this equipment could be used as a rapid indicator of layer bearing capacity. Typical layer thicknesses anticipated in fully permeable pavements were assessed and the material was confined on the surface with a 25 mm thick steel plate to simulate an overlying layer. All specimens were penetrated to a depth of 800 mm in 10 blows or less, indicating that the test set-up was not representative of a base layer on a typical roadway. No attempt was made to relate the findings to bearing capacity or stiffness, since the models developed by a number of practitioners in the United States and internationally and derived from extensive comparisons of DCP results with laboratory and field test results are all based on dense-graded, compacted materials and were therefore considered to be inappropriate for evaluating the materials assessed in this study.

Summary of Test Results on Base Course Materials

The results of tests on four different commercially available permeable base-course aggregates indicate that these materials will probably provide sufficient support for typical traffic loads in parking lots, basic access streets and driveways, and on highway shoulders, whilst serving as a reservoir layer for the pavement structure. Although three of the four materials tested had smaller maximum aggregate sizes than those typically discussed in the literature, the permeability was still adequate for California rainfall events.

4.3.3 Open-Graded Hot-Mix Asphalt

Considerable research on porous asphalt has been undertaken in past years by a number of institutions worldwide, and so-called open-graded friction courses are commonly used as a maintenance and pavement preservation strategy in California. Benefits include reduced splash and spray, improved skid resistance, and lower noise. However, all past research has been based on the existence of a dense-graded, impermeable layer underneath the porous asphalt layer, with water draining to the edge of the road and then into existing drainage structures.

The research discussed in this section describes the work undertaken to determine optimum mix designs for open-graded asphalt concrete wearing courses (or bases) for use in fully permeable pavements. This part of the study was undertaken in conjunction with another laboratory project being undertaken on behalf of Caltrans by the UCPRC to assess the properties of noise-reducing wearing courses, which allowed the testing of a far larger experimental matrix than originally planned. Testing was carried out in two phases. The first phase, carried out on 19 different mixes, focused on permeability, rutting resistance, moisture sensitivity, and durability (resistance to raveling). The three best mixes were then subjected to fatigue testing to assess resistance to fatigue cracking, and to frequency sweep tests to characterize the influence of temperature and time of loading on stiffness. The stiffness and fatigue results were inputs for the structural analysis calculations described in Chapter 5 of this report.

Material Sampling

Three different commercially available aggregate samples of different geological origin (granite, basalt, and alluvial) were sourced from the same three suppliers discussed earlier. These materials were considered to be representative of sources in the Central Valley and coastal regions of the state. The European mix specimens sampled from the test track in Spain contained porphyry (coarse aggregates) and limestone (sand and fine fraction).

Five different binders, sourced from two different refineries, representing those typically used in California and other states were used in this study:

- PG64-16. This is a standard PG grade used in California and is widely used for open-graded mixes since it is the specified grade when placement temperatures are greater than 70°F (21°C) in the North Coast, Low Mountain, and South Mountain regions (Table 632.1 of the *Highway Design Manual*, per *Design Information Bulletin 86*, November 30, 2006). It is also widely used where PG64-10 binders are specified (e.g., South Coast, Central Coast, and Inland Valley regions), since it exceeds the specifications of the PG64-10, but allows the refineries to save costs by producing one instead of two binders. PG64-16 is also the base stock binder for most of the rubberized asphalt specified by Caltrans.
- PG58-34PM. This is a standard PG grade used in California, and is the recommended grade for open-graded wearing courses in all regions of the state when the placement temperature is less than 70°F (21°C). The PM indicates that the binder is polymer-modified. It is softer than PG64-16 at both high and low temperatures.
- PG76-22PM. This is a much stiffer binder than PG58-34PM at both high and low temperatures, and is also polymer-modified. This binder is specified in Georgia DOT Standard Specifications for use in open-graded friction course mixes, which have reportedly performed very well and deserved assessment for use in California.
- PG76-22TR. This binder has similar stiffness to PG76-22, but is modified with between 10 and 15 percent recycled tire rubber instead of polymer. The rubber is blended into the binder at the refinery and is known as terminal blend rubberized asphalt binder.
- Asphalt Rubber. Asphalt rubber binders typically contain between 15 and 20 percent recycled tire rubber (19 percent in this study). These binders are produced at the asphalt plant using a wet process.

Mix Designs

The mix designs used in the study were selected from a comprehensive literature search on the topic, past experience in California, as well as some experimentation. The mixes tested in the first phase are summarized in Table 4.15. The D125 mix is a Caltrans conventional dense-graded mix included for comparison with the permeable open-graded mixes. The G125, RW95 and AR95 mixes were tested in Phase 2, together with a European mix not tested in Phase 1 (these specimens were sawn from a test track in Spain and shipped to UCPRC for another project, but had sufficient permeability to warrant testing in this study).

Mix designs for all of the open-graded mixes, except the Georgia and Arizona mixes, were performed following California Test Method CT-368, (*Standard Method for Determining Optimum Bitumen Content (OBC) for Open-Graded Asphalt Concrete*). In this test, the binder contents are determined based on the calculation of the approximate bitumen ratio determined from surface area estimates calculated from the aggregate gradation, and a "drain-down" test. The binder contents for the mixes with rubberized asphalt binders were also determined following CT-368, in which the binder content determined for conventional binders is increased by a factor of 1.2 for rubberized binders.

Table 4.15: Mix Designs Used in Phase 1 and Phase 2 Testing

Mix ID	Mix Description			
	Aggregate	Nominal Max. Aggregate Size (mm)	Binder	Comments
D125	Basalt	12.5	PG64-16	Dense-graded control mix. All other mixes are open-graded.
RW19		19.0	PG64-16	-
RW125		12.5	PG64-16	-
RW95		9.5	PG64-16	-
RW475		4.75	PG64-16	-
AR95		9.5	AR	-
AR475		4.75	AR	-
AR475P		4.75	AR	Coarser aggregate than other 4.75 mm gradations.
P475LM		4.75	PG64-16	Contains hydrated lime for moisture resistance.
TR475		4.75	PG76-22TR	-
P58LF		4.75	PG58-34PM	Contains cellulose fibers to hold binder in mix and hydrated lime for moisture resistance.
P475		4.75	PG76-22PM	-
G125		12.5	PG76-22PM	Georgia DOT mix. Coarser gradation than Caltrans 12.5 mm. Contains mineral fibers to hold more binder in mix and hydrated lime for moisture resistance.
AZ95		9.5	AR	Arizona mix. Slightly finer gradation than Caltrans 9.5 mm. Contains hydrated lime for moisture resistance.
E8		8.0	PG64-16	Danish mix. Contains some cellulose fibers to hold more binder in mix.
PG95T	Alluvial	9.5	PG64-16	-
AR475T		4.75	AR	-
AR95W	Granite	9.5	AR	-
PG475W		4.75	PG64-16	-
Cedex	Porphyry	12.5	N/A	Spanish mix. Binder was classified as BM-3c.

The mix design for the dense-graded control mix was performed following Caltrans standard practice. The mix design for the Georgia mix was performed following Georgia test method GDT-114. The mix design for the Arizona mix followed a method documented in the literature.

Aggregate gradations for each mix are shown in Table 4.16. The 12.5 mm, 9.5 mm and 4.75 mm open gradations are the same for each maximum size aggregate to permit comparison of other variables, except for the Arizona, Georgia, Danish, and AR475P mixes.

Table 4.16: Aggregate Gradations of Mixes Tested

Mix ID	Percent Passing										NMAS[1] (mm)
	19-mm	12.5-mm	9.5-mm	4.75-mm	2.36-mm	1.18-mm	0.6-mm	0.3-mm	0.15-mm	0.075-mm	
D125	100	97.5	87.5	62.5	46	35	22.5	16	9	5	12.5
RW19	95	54	36	20	15	10	7	5	4	2	19.0
RW125	100	97.5	83.5	32.5	12.5	5	5	4	3	1.5	12.5
RW95	100	100	95	32.5	12.5	5	5	4	3	1.5	9.5
RW475	100	100	100	91	14	12	10	8	7	6	4.75
AR95	100	100	95	32.5	12.5	5	5	4	3	1.5	9.5
AR475	100	100	100	91	14	12	10	8	7	6	4.75
AR475P	100	100	100	65	14	12	10	7	6	5	4.75+
P475LM	100	100	100	91	14	12	10	8	7	6	4.75
TR475	100	100	100	91	14	12	10	8	7	6	4.75
P58LF	100	100	100	91	14	12	10	8	7	6	4.75
P475	100	100	100	91	14	12	10	8	7	6	4.75
G125	100	92.5	65	20	7.5	5	5	4	3	3	12.5
AZ95	100	100	100	40	9	5	4	3	2	2	9.5
E8	100	100	100	29	9	8	8	8	8	8	8.0
PG95T	100	100	95	32.5	12.5	5	5	4	3	1.5	9.5
AR475T	100	100	100	91	14	12	10	8	7	6	4.75
AR95W	100	100	95	32.5	12.5	5	5	4	3	1.5	9.5
PG475W	100	100	100	91	14	12	10	8	7	6	4.75
Cedex[2]	100	100	80	24	19	-	10	-	-	7	N/A

[1] Nominal maximum aggregate size [2] Gradings are approximate, converted from European metric sieve sizes.

The binder contents, lime contents, filler contents, and mixing and compaction temperatures are shown in Table 4.17, together with the Fineness Modulus, Coefficient of Curvature (C_c) and Coefficient of Uniformity (C_u) for each mix.

The Fineness Modulus is a measure of the uniformity of the aggregate gradation. The higher the fineness modulus, the coarser the asphalt mix (a higher percentage of coarse material) and the more uniform the gradation.

The Coefficient of Curvature (C_c) is a measure of the shape of a gradation curve. In the Unified Soil Classification System (USCS), a Coefficient of Curvature value between one and three is considered to be well graded. The Coefficient of Curvature is defined as:

$$C_c = D30^2/(D10 * D60) \tag{4.1}$$

Where D10 is the sieve size (mm) through which 10 percent of the aggregate passes
D30 is the sieve size (mm) through which 30 percent of the aggregate passes
D60 is the sieve size (mm) through which 60 percent of the material passes.

The Coefficient of Uniformity (C_u = D60/D10) is used to distinguish between open- and more dense-graded mixes. Lower coefficients indicate that most of the material is approximately the same size, resulting in a uniform or open gradation, while higher values indicate that the gradation has a range of particle sizes resulting in a more well-graded or dense-graded mix.

Table 4.17: Properties of Mixes Tested

Mix ID	Binder Content (%)	Fiber[1] (%)	Hydrated Lime (%)	Mixing Temp (°C)	Compact Temp (°C)	Fineness Modulus	C_c[2]	C_u[3]
D125	6.0	0	0	144	125	4.22	1.19	25.60
RW19	5.0	0	0	135	125	6.08	0.70	2.14
RW125	5.9	0	0	135	125	5.55	1.38	3.72
RW95	5.9	0	0	135	125	5.43	1.47	3.48
RW475	7.9	0	0	135	125	4.58	0.91	1.60
AR95	7.1	0	0	163	149	5.43	1.47	3.48
AR475	9.5	0	0	163	149	4.58	0.91	1.60
AR475P	8.4	0	0	163	149	4.86	0.91	1.91
P475LM	7.9	0	1.5	135	125	4.58	0.91	1.60
TR475	9.5	0	0	163	149	4.58	0.91	1.60
P58LF	7.9	0.30 CF	1.5	155	138	4.58	0.91	1.60
P475	7.9	0	0	163	149	4.58	0.91	1.60
G125	6.3	0.40 MF	1.4	165	160	5.91	1.32	3.16
AZ95	9.2	0	1.0	163	149	5.37	1.03	2.60
E8	6.4	0.25 CF	1.5	135	125	5.30	1.37	2.75
PG95T	5.9	None	0	135	125	5.43	1.47	3.48
AR475T	9.5	None	0	163	149	4.58	0.91	1.60
AR95W	7.1	None	0	163	149	5.43	1.47	3.48
PG475W	7.9	None	0	135	125	4.58	0.91	1.60
Cedex	5.3	None	None	N/A	N/A	N/A	N/A	N/A

[1] CF = Cellulose Fiber and MF = Mineral Fiber [2] C_c = Coefficient of Curvature [3] C_u = Coefficient of Uniformity

In the basalt aggregate mixes, the binder contents increase with decreasing aggregate maximum size (e.g., RW19, RW125, RW95, and RW475). This is attributed to smaller size aggregates having a larger surface area-to-density ratio, and allows for more binder in the mix for a given mass of aggregate. The increase in binder content for asphalt rubber binders using the Caltrans open-graded mix design procedure can be seen by comparing RW475 (conventional binder) with AR475 (rubberized) and RW95 (conventional binder) with AR95 and AR95W (both rubberized).

Test Methods

Laboratory testing included measurement of permeability, shear, moisture sensitivity, and durability on prepared specimens of all mixes. Limited beam fatigue and flexural frequency sweep testing was then carried out on the three mixes with the best performance in the other tests. Only three mixes were selected due to the time and complexity of fatigue testing, and the limited time available for this testing. The bulk specific gravity and bulk density of the specimens were also measured to determine air-void contents. AASHTO or ASTM standard test methods were followed during testing as shown in Table 4.18. Permeability testing is illustrated in Figure 4.16

Table 4.18: Test Methods for Asphalt Materials

Attribute	Test	Test Method
Permeability	Permeability	ASTM PS 129-01
Rutting resistance	Repeated Simple Shear Test	AASHTO T-320
Fatigue cracking resistance	Beam fatigue	AASHTO T-321
Moisture sensitivity	Hamburg Wheel Track	AASHTO T-324
Raveling resistance	Cantabro Test	ASTM D7064 x2
Max. Specific Gravity	Max. Specific Gravity	AASHTO T-209
Bulk Specific Gravity	Bulk Specific Gravity	AASHTO T-331
Air-void Content	Air-void Content	AASHTO T-269

Figure 4.16: Permeability testing on compacted slabs.

Test Results

The results for each set of tests are discussed in the following sections. Results shown are average values of the replicates. Plots include a bar indicating plus and minus one standard deviation variability of the results. Ranked results for permeability, moisture sensitivity, rutting resistance (shear strength), and raveling resistance on all mixes and beam fatigue and flexural frequency sweep on three mixes are summarized in Table 4.19 through Table 4.21.

Table 4.19: Ranked Results of Permeability, Moisture Sensitivity, and Rutting Resistance Tests

Permeability (cm/s)			Moisture Sensitivity (Hamburg Wheel Track) (Repetitions to 10 mm rut)			Rutting Resistance (Shear Modulus) (MPa)		
Mix	**Average**	**Std Deviation**	**Mix**	**Average**	**Std Deviation**	**Mix**	**Average**	**Std Deviation**
D125	0.0009	0.0007	PG475W	317	159.1	P58LF	29.2	6.6
TR475	0.0284	0.0054	PG95T	377	88.4	P475	56.7	0.0
AZ95	0.0337	0.0067	RW125	425	77.8	TR475	57.5	6.0
P475	0.0529	0.0094	P475LM	681	51.6	PG95T	63.5	6.1
AR95W	0.0581	0.0170	RW95	725	318.2	AR475P	63.7	6.9
PG475W	0.0582	0.0102	E8	861	139.3	AR475T	63.9	1.6
P58LF	0.0638	0.0377	RW475	919	128.7	AR95W	65.0	2.3
AR475	0.0640	0.0559	TR475	2,013	108.9	AR475	65.3	0.0
AR475P	0.0758	0.0194	AR475	2,565	233.3	RW125	65.8	1.2
P475LM	0.0865	0.0287	P58LF	2,827	243.9	AZ95	66.9	0.6
AR475T	0.0919	0.0294	AR475P	2,930	21.2	RW95	69.4	3.3
AR95	0.1103	0.0244	AR95	3,030	169.7	RW475	92.9	2.1
RW475	0.1714	0.0211	AR475T	3,200	0.0	G125	93.9	1.0
PG95T	0.2144	0.0677	AZ95	3,967	272.2	E8	104.8	2.8
E8	0.2551	0.0486	P475	4,482	944.0	RW19	110.2	37.3
RW125	0.3006	0.0866	D125	5,170	650.5	PG475W	120.3	4.7
G125	0.3120	0.0807	RW19	5,250	424.3	P475LM	123.0	9.8
RW95	0.3223	0.1174	AR95W	6,222	328.8	D125	369.8	0.0
RW19	0.5833	0.3252	G125	17,981	3,119.8	AR95	-	-

Table 4.20: Ranked Results of Raveling Resistance and Fatigue Resistance Tests.

Raveling Resistance (% Loss)			Fatigue Resistance (Fatigue Life)		
Mix	Average[1]	Std Deviation	Mix	Average	Std Deviation
P58LF	2.4	Not determined for summation of three conditions	G125	See Table 4.22	
AR475T	2.7		AR95		
TR475	3.6		RW95		
AR475P	8.1				
P475	10.4				
PG475W	12.3				
P475LM	17.1				
AR475	19.4				
RW475	20.2				
AZ95	20.3				
D125	20.9				
AR95W	28.3				
G125	32.9				
RW125	45.8				
PG95T	50.9				
AR95	53.2				
E8	54.7				
RW95	59.1				
RW19	63.2				

[1] Summation of three conditions (unaged, aged, and freeze-thaw cycle).
[2] Average of four tests after highest and lowest excluded.

Table 4.21: Ranked Results for Flexural Frequency Sweep Tests

Mix	Average Flexural Frequency Sweep Values (E^*) (MPa)[1]										
	15 Hz	10 Hz	5 Hz	2 Hz	1 Hz	0.5 Hz	0.2 Hz	0.1 Hz	0.05 Hz	0.02 Hz	0.01 Hz
G125	2,768	2,640	2,367	1,998	1,743	1,501	1,232	1,052	899	723	619
RW95	2,779	2,635	2,312	1,870	1,567	1,282	970	766	588	398	292
AR95	1,088	1,066	970	811	525	603	491	419	361	297	257
	Standard Deviation										
G125	1,381	1,368	1,288	1,167	1,078	980	859	769	685	575	515
RW95	1,824	1,797	1,684	1,496	1,337	1,165	961	797	657	480	354
AR95	578	563	526	465	399	381	332	293	262	219	198

[1] Average of six beam specimens

Test Results: Permeability

Permeability results for all mixes are plotted in Figure 4.17. Comparisons with a parallel study of hydraulic calculations for pervious pavements *(4)* indicates that a permeability of 0.1 cm/second would be sufficient for typical rainfall events in California, and with multiple traffic lanes draining into a 10 ft (3.0 m) wide shoulder. Many of the mixes included in this study have permeabilities near that value.

Variables that will need to be used with these test results to determine which mixes will provide sufficient permeability include the extent of clogging over time (being investigated in the parallel study *[4]*), and the number of lanes of traffic that need to be drained. The permeability for the control dense-graded mix (D125) is shown for comparison.

Figure 4.18 shows the comparison of the aggregate size for open-graded mixes with four aggregate sizes (3/4, 1/2, 3/8 in., and #4 sieves [19, 12.5, 9.5 and 4.75 mm]). The results show that permeability tends to increase with increasing aggregate size. However, all of the mixes with conventional PG64-16 binder appeared to have sufficient initial permeability.

Figure 4.19 shows the comparison of mixes with different binders and 4.75 mm (#4) and 9.5 mm (3/8 in.) open-graded aggregate gradations. Permeability of the higher binder content asphalt rubber 9.5 mm mix (AR95) was lower than that of the same mix with conventional binder (RW95). Mixes with polymer-modified binders and with fibers also tended to reduce the permeability of the 4.75 mm mixes compared with the conventional binder mix (RW475).

Figure 4.20 shows that additional compaction to obtain an air-void content of approximately 15 percent (instead of between 18 and 22 percent) did not decrease the permeability of the two 4.75 mm mixes with asphalt rubber binder.

Figure 4.21 plots permeability against aggregate type. There was no consistent or significant trend of permeability in terms of aggregate source, although both of the mixes with granite aggregates had somewhat lower permeabilities than the corresponding mixes with basalt aggregate. This was attributed to the different shapes of the two aggregate sources.

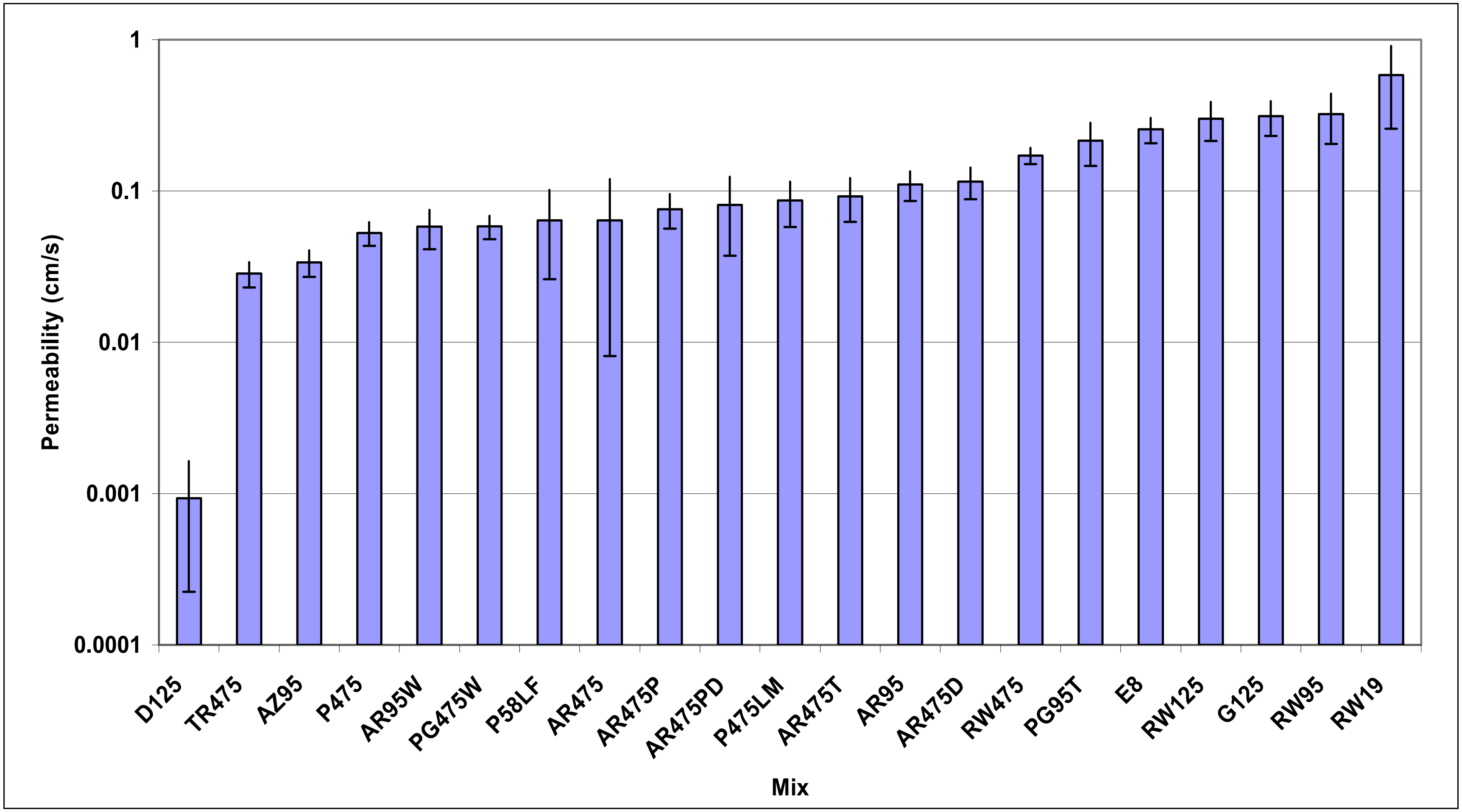


Figure 4.17: Summary plot of ranked permeability results for all mixes.
(Note log scale for permeability)

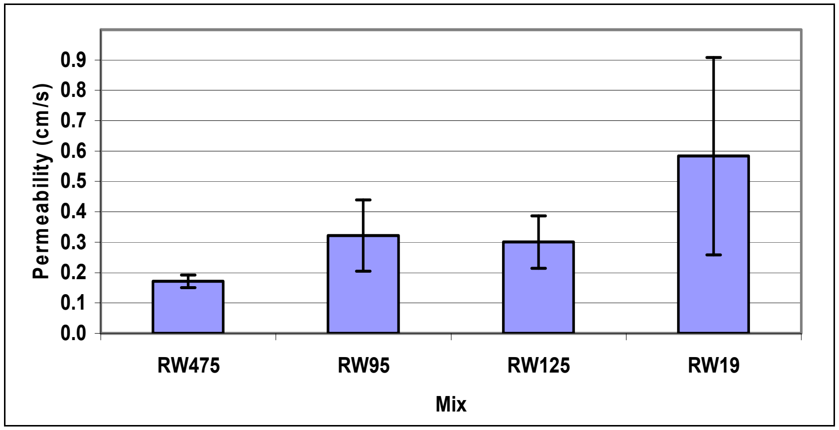


Figure 4.18: Comparison of effect of maximum aggregate size on permeability.

(Results for mixes with basalt aggregate and PG64-16 binder)

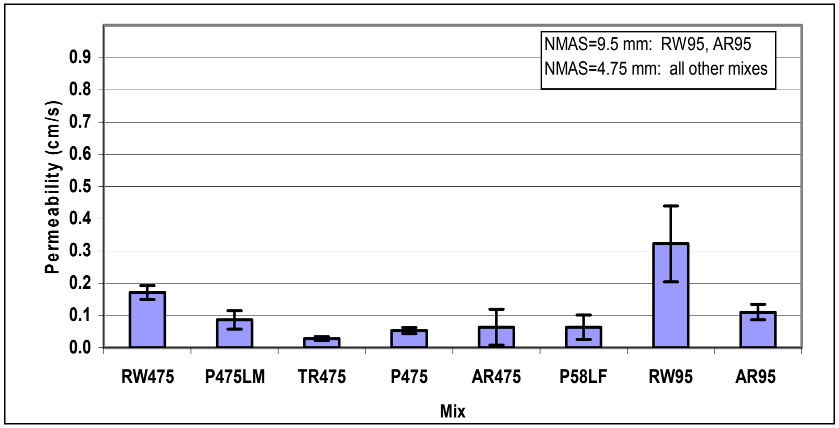


Figure 4.19: Comparison of effect of different binders on permeability.

(Results for mixes with basalt aggregate and 4.75 mm and 9.5 mm maximum aggregate size)

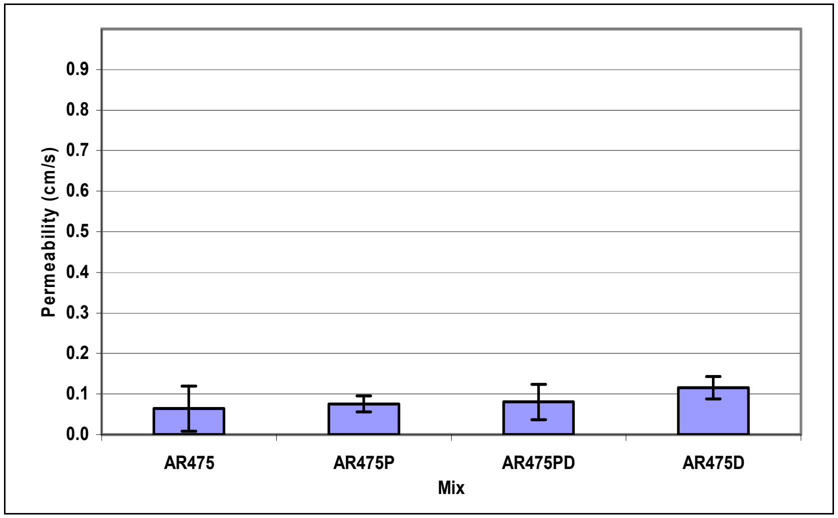


Figure 4.20: Comparison of effect of better compaction on permeability (4.75 mm mixes).

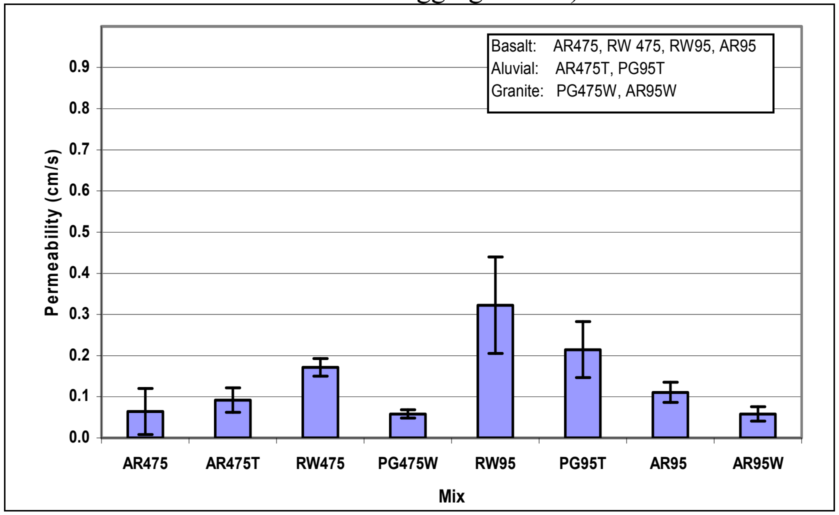


Figure 4.21: Comparison of effect of different aggregate types on permeability.

(Results for PG64-16 and asphalt rubber mixes with 4.75 mm and 9.5 mm maximum aggregate sizes)

Test Results: Moisture Sensitivity

Hamburg Wheel Tracking Test (HWTT) results for all mixes are shown in Figure 4.22. It is interesting to note that the Georgia DOT open-graded mix (G125) had the best results, even higher than those of the control dense-graded mix, despite having nearly the highest permeability. This was attributed to the polymer-modified binder and use of fibers. Other open-graded mixes that had better HWTT results than the control mix were AR95W (attributed to rubberized binder) and RW19 (attributed to larger aggregate size).

Figure 4.23 shows the effects of aggregate size with the control mix (D125) for comparison. Generally the open-graded mixes had less rutting and moisture sensitivity resistance at high temperatures under soaked conditions compared to the dense-graded mix under the same conditions, which is expected.

Figure 4.24 shows the results for mixes with different binders and 4.75 mm (#4) and 9.5 mm (3/8 in) gradations. The polymer-modified mix and asphalt rubber mixes appeared to offer superior resistance for the 4.75 mm mixes. Similarly the asphalt rubber mix appeared to be better than the same mix with conventional binder for the 9.5 mm mixes.

Figure 4.25 shows the effects of better compaction for 4.75 mm asphalt rubber mixes with two different gradations. The results indicate that the better compaction improved the results for both gradations, despite both gradations showing similar permeabilities (see Figure 4.20).

Figure 4.26 shows the effects of different aggregate types on moisture sensitivity. There was no clear trend when the alluvial and granite aggregates were compared with mixes with basalt aggregate.

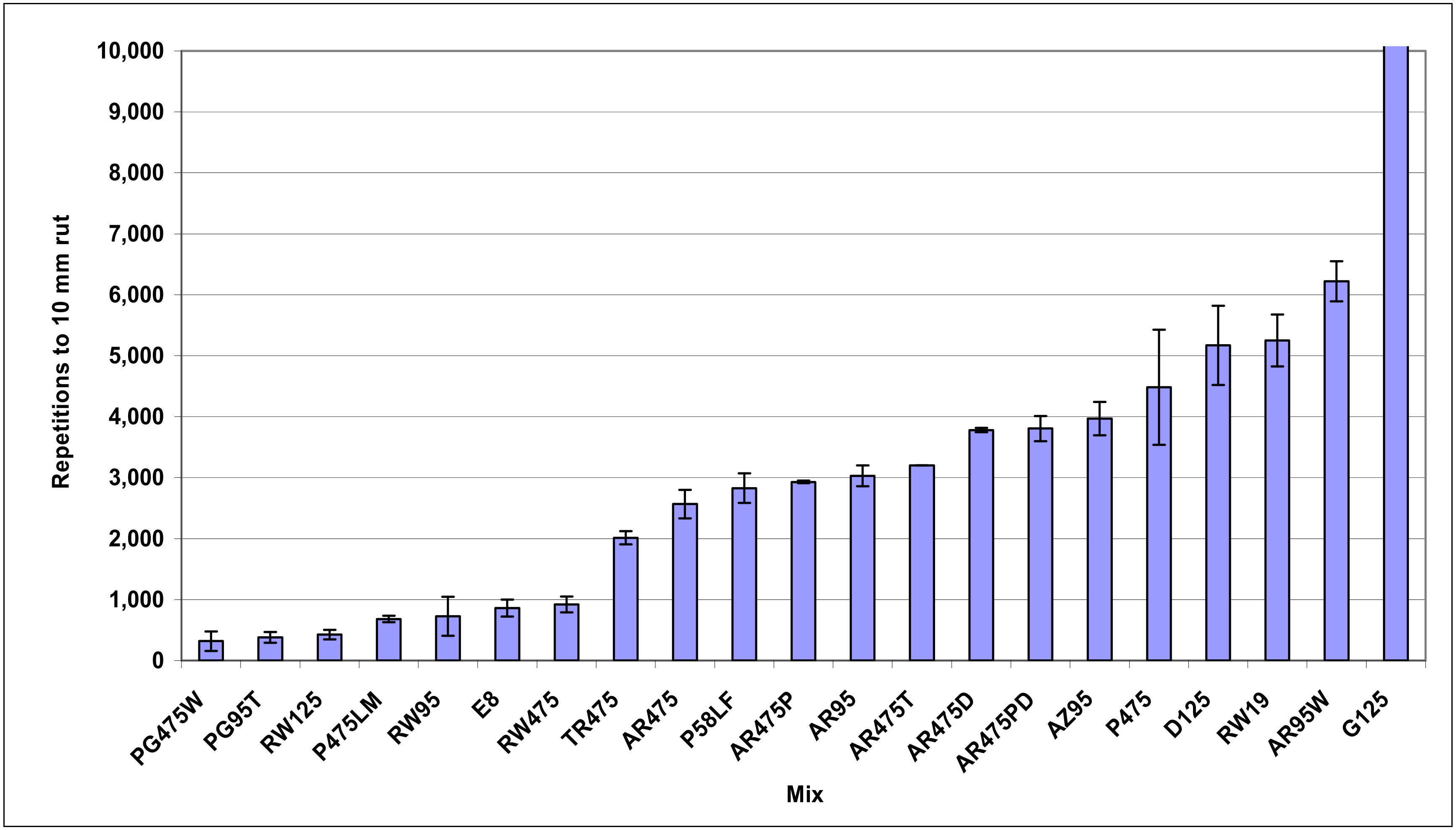


Figure 4.22: Summary plot of ranked HWTT results for all mixes.

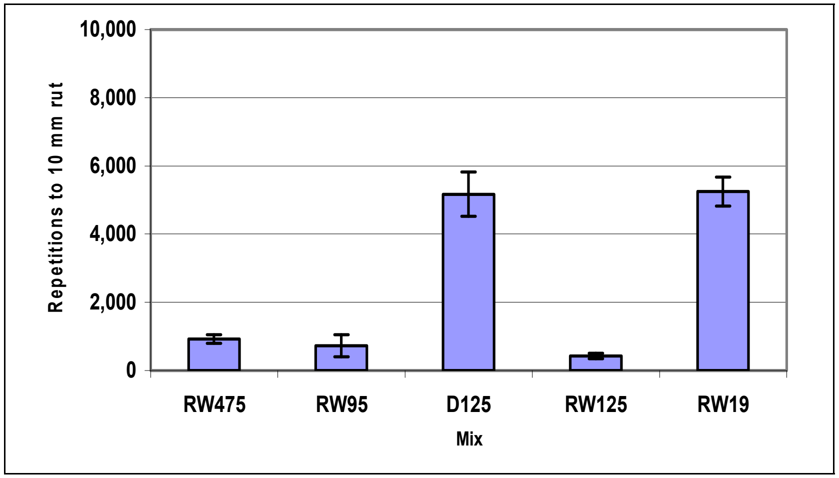


Figure 4.23: Comparison of effect of maximum aggregate size on moisture sensitivity.

(Results for mixes with basalt aggregate and PG64-16 binder.)

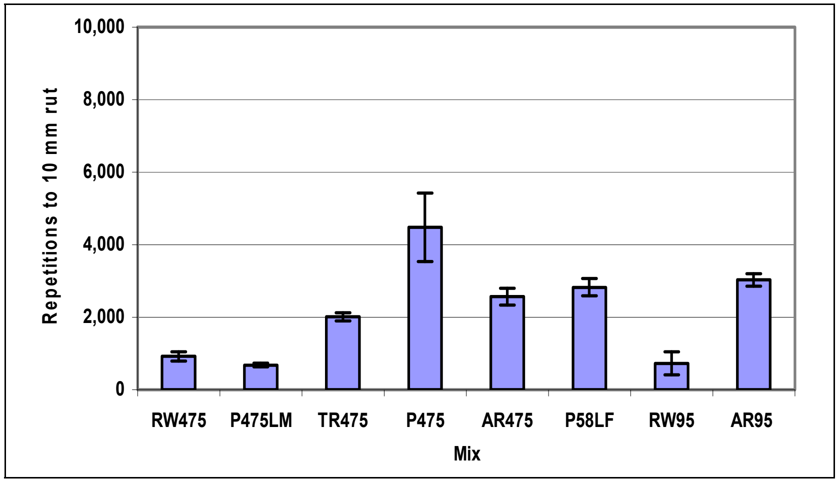


Figure 4.24: Comparison of effect of different binders on moisture sensitivity.

(Results for mixes with basalt aggregate and 4.75 mm and 9.5 mm maximum aggregate size.)

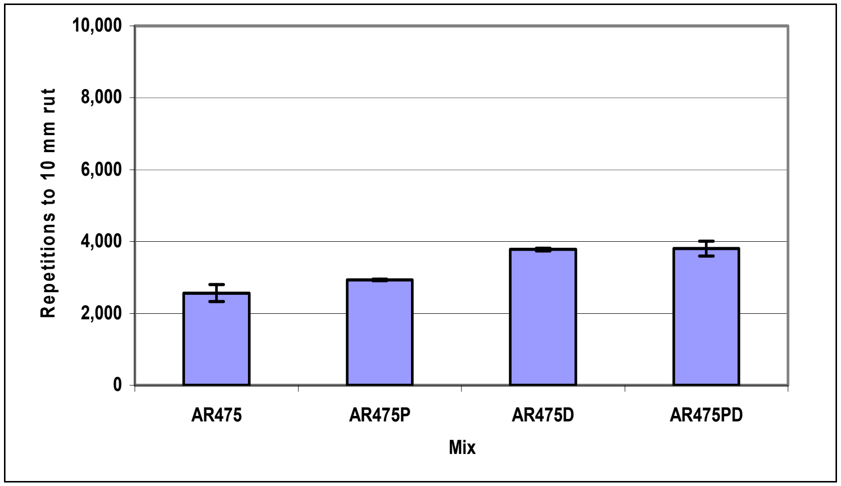


Figure 4.25: Comparison of effect of better compaction on moisture sensitivity (4.75 mm mixes).

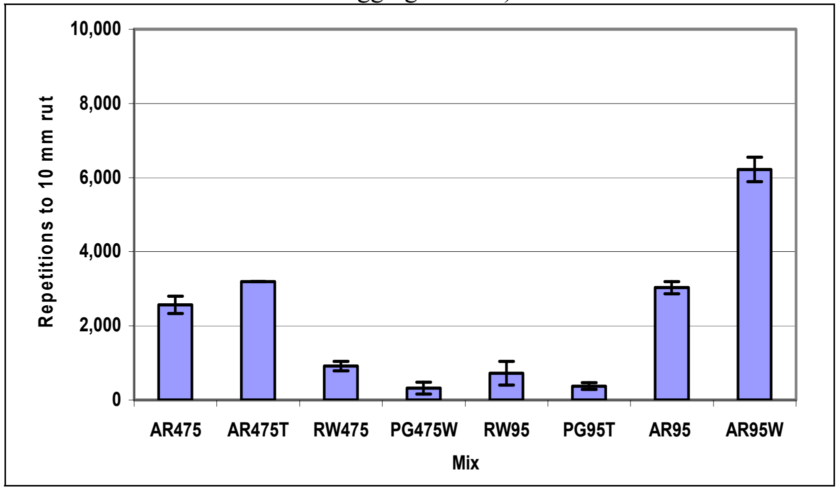


Figure 4.26: Comparison of effect of different aggregate types on moisture sensitivity.

(Results for PG64-16 and asphalt rubber mixes with 4.75 mm and 9.5 mm maximum aggregate size.)

Test Results: Rutting Resistance

Figure 4.27 shows results for all mixes tested for shear stiffness at 113°F (45°C) and 0.1 second loading time. The control dense-graded mix was considerably stiffer than the open-graded mixes, as expected. Ten of the eighteen open-graded mixes had similar stiffnesses. Generally, the courser mixes (>1/2 in [12.5 mm]) and some of the mixes with lime had higher stiffnesses. Fibers did not appear to have a significant influence on stiffness. Pavement thickness design will be dependent on stiffness; however, lower stiffness can be compensated for by a thicker asphalt layer, provided that the material also provides adequate rutting resistance (as indicated for example by the HWTT).

Figure 4.28 provides a comparison of the effects of maximum aggregate size on shear stiffness (45°C and 70 kPa) for mixes with basalt aggregate and PG64-16 binder. The 19 mm (3/4 in.) mix was somewhat stiffer than the mixes with smaller aggregates, but it also had more variability between replicate specimens. Stiffnesses were similar in the other three mixes, with a slight decrease in stiffness with increasing aggregate size.

Figure 4.29 provides a comparison of the effects of different binders on shear stiffness (45°C and 70 kPa) for mixes with basalt aggregate and 4.75 mm (#4) and 9.5 mm (3/8 in.) maximum aggregate size. Mixes with conventional binders appeared to have slightly higher stiffnesses than those with rubber or polymer modification.

Figure 4.30 provides a comparison of the effect of different aggregate sources (4.75 and 9.5 mm maximum aggregate size only) on shear stiffness (45°C and 70 kPa) for the mixes with PG64-16 and asphalt rubber binders. There was no clear trend in the results, although the more cubical granite aggregate tended to have a slightly higher stiffness for the same aggregate size and binder compared to the other two aggregates.

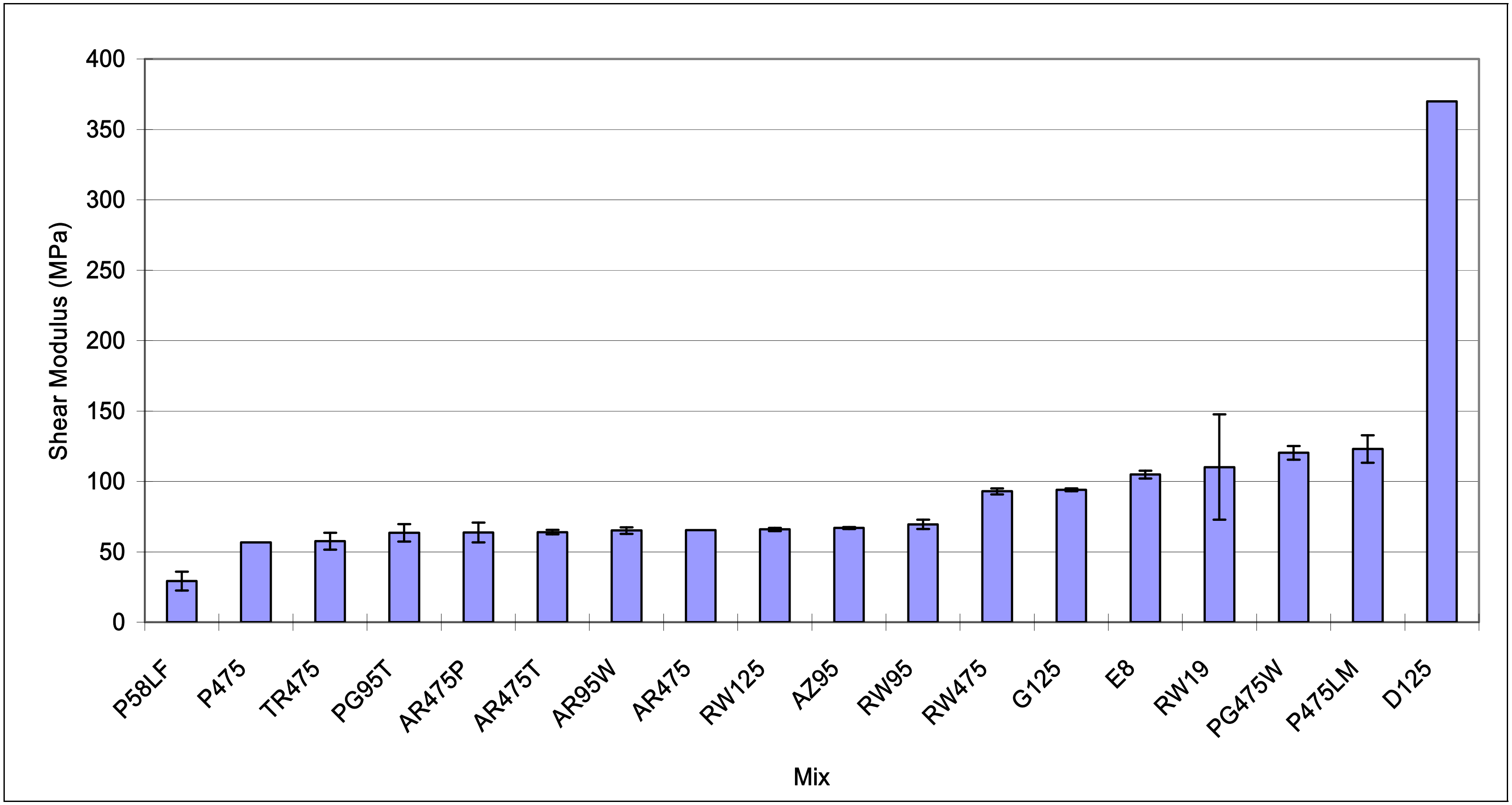


Figure 4.27: Summary plot of ranked shear stiffness (45°C & 70 kPa shear stress) results for all mixes.

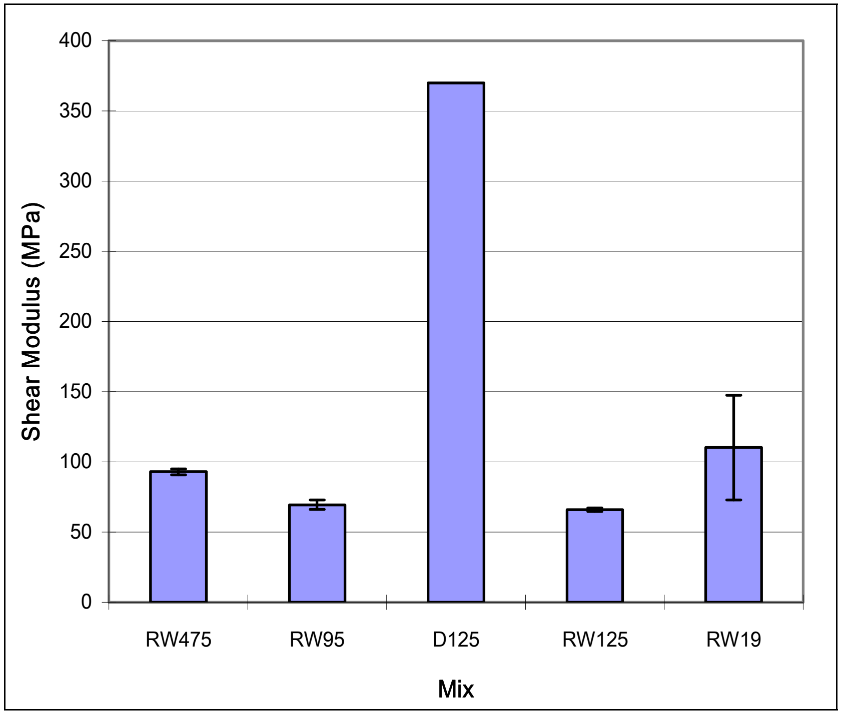


Figure 4.28: Comparison of effect of maximum aggregate size on shear stiffness.

(Results at 45°C and 70 kPa shear stress for mixes with basalt aggregate and PG64-16 binder.)

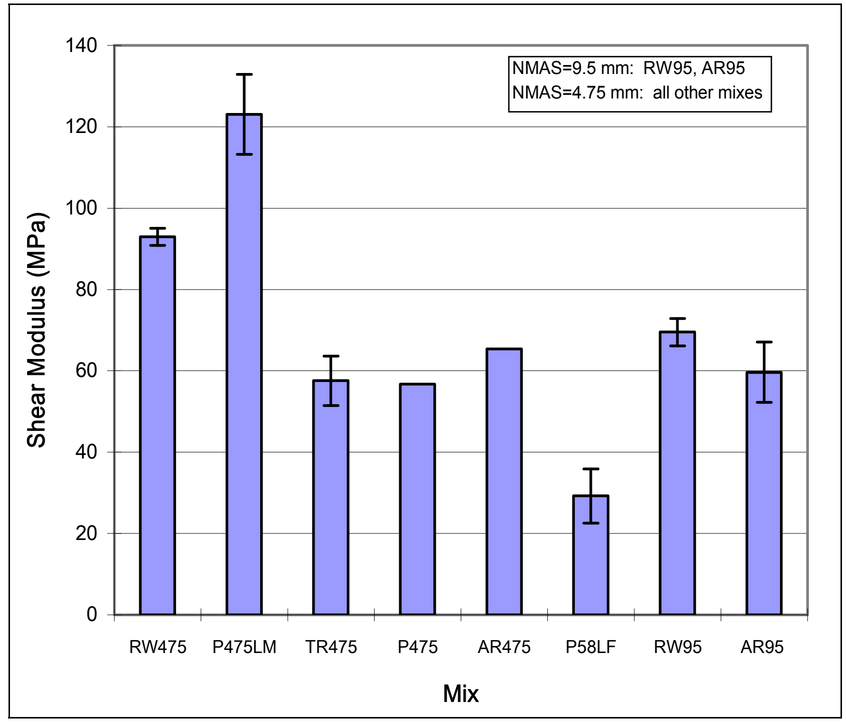


Figure 4.29: Comparison of effect of different binders on shear stiffness.

(Results at 45 C and 70 kPa shear stress for mixes with basalt aggregate and 4.75 mm and 9.5 mm maximum aggregate size)

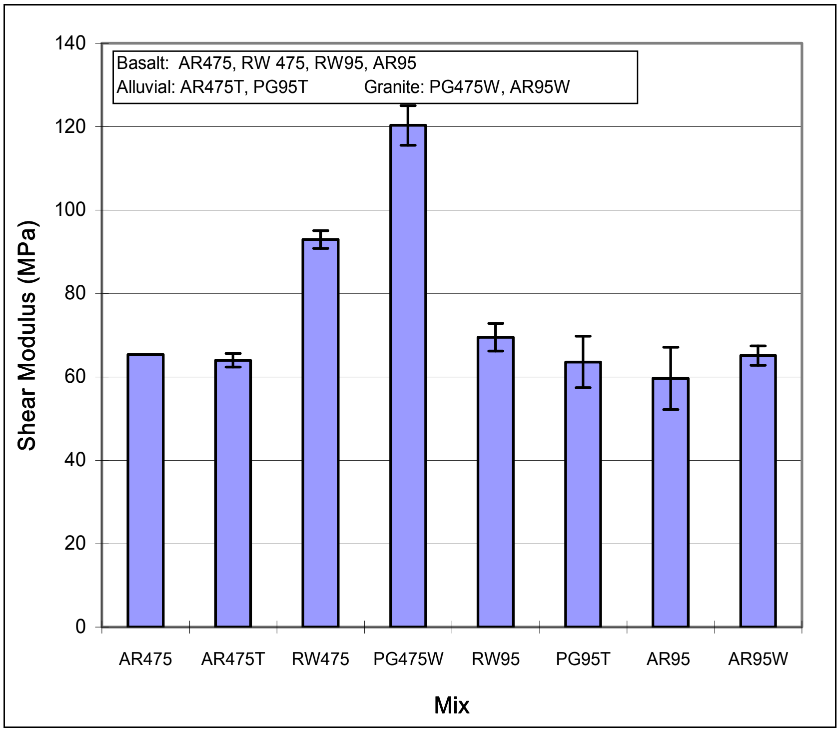


Figure 4.30: Comparison of effect of different aggregate types on shear stiffness.
(Results at 45°C and 70 kPa shear stress for mixes with PG64-16 and asphalt rubber binders and 4.75 mm and 9.5 mm maximum aggregate size.)

Test Results: Raveling Resistance

Raveling resistance was determined for both unaged and aged specimens, as well as for selected specimens subjected to one freeze/thaw cycle (specimens were selected based on best overall performance in earlier tests). Figure 4.31 shows the average raveling resistance for each condition. The results indicate that raveling generally increases with increasing aggregate size. Mixes with modified binders (rubberized or polymer-modified) performed better than those with unmodified binders. The addition of lime and fibers also appeared to result in some improvement in performance. The 12.5 mm (1/2 in.) dense-graded control mix performed better than the open-graded 12.5 mm mixes tested, but was outperformed by the mixes with finer aggregates and modified binders.

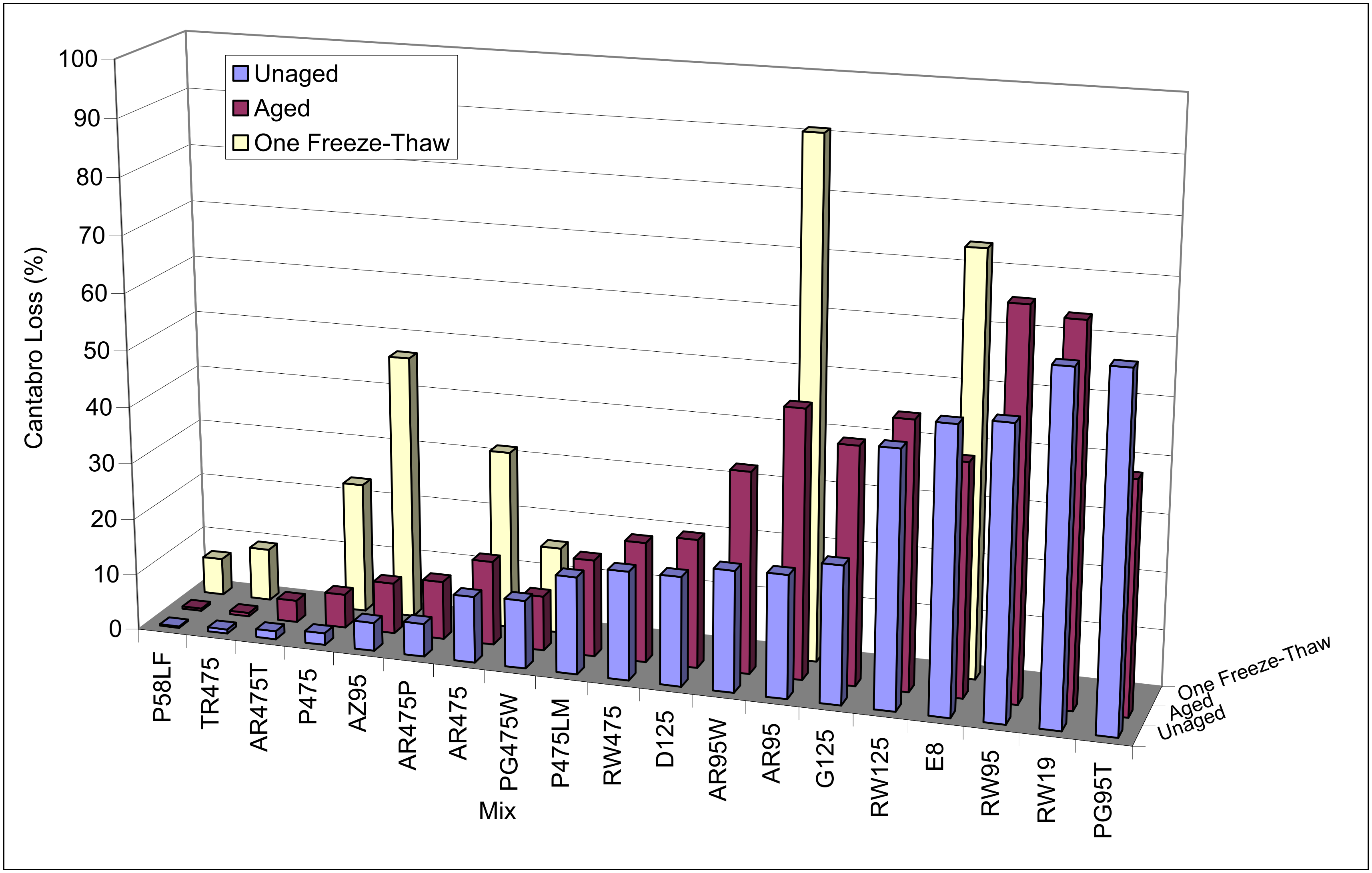


Figure 4.31: Summary plot of ranked raveling resistance results for all mixes.

Test Results: Fatigue Cracking Resistance

Due to the complexity of specimen preparation and duration of the test, only three mixes were selected for fatigue testing. The three mixes chosen for testing of fatigue cracking resistance were the G125, AR95, and RW95 mixes. The AR95 mix was selected as a control, as this is a commonly used mix in current Caltrans OGFC projects. The G125 and RW95 mixes were selected based on their overall performance in the other tests, with particular emphasis on permeability, Hamburg Wheel Track Test, and shear stiffness performance.

The fatigue cracking resistance test results for the six specimens from each mix are shown in Table 4.22. All tests were conducted at a nominal temperature of 67°F (20°C), with two nominal strains of 400 and 700 microstrain, and three replicates at each strain. The deformation frequency was 10 Hz as detailed in the AASHTO T-321 test method.

Table 4.22: Flexural Fatigue Test Results for Three HMA-O Mixes

Specimen	Temperature (°C)	Tensile Strain	Phase Angle (degrees)	Initial Stiffness (MPa)	Repetitions to 50% Stiffness Reduction (N_f)
AR95-3A2	23.5	0.000473	26.3	1176	6,615,354
AR95-4B1	19.8	0.000407	29.6	686	832,549
AR95-6B1	19.7	0.000411	24.0	967	6,472,341
AR95-2B1	19.8	0.000711	26.2	977	87,319
AR95-2B2	19.8	0.00071	28.3	1051	170,856
AR95-3A1	21.2	0.000717	30.0	895	323,646
G125-1A1	19.7	0.000409	22.8	1943	5,879,064
G125-1A2	21.4	0.000413	29.0	1645	2,246,757
G125-2b1	21.2	0.000429	25.5	1987	14,749,979
G125-3A1	19.6	0.000708	26.3	2091	105,029
G125-3A2	19.8	0.000706	23.4	2346	132,488
G125-6B1	20.5	0.000739	28.6	1849	58,270
RW95-1A1	20.3	0.000425	31.7	2241	67,626
RW95-2B2	19.9	0.000402	29.6	2285	53,651
RW95-6B1	20.4	0.000421	35.0	1499	179,343
RW95-2B1	20.1	0.000716	30.9	2140	7,013
RW95-3A2	21.4	0.000709	30.4	2328	8,748
RW95-6B2	20.1	0.000709	35.1	1525	33,587

The results for the AR95 and RW95 mixes had greater variability than is typical for dense-graded HMA, likely due to the open-graded nature of the material and resultant high air-void content, which tends to result in more erratic performance compared to dense-graded mixes. The variability for the G125 mix was less than that of the other two mixes. The results indicate that the G125 mix and AR95 mixes had similar performance, with the G125 mix with polymers and fibers outperforming the Caltrans rubberized AR95 mix (RHMA-O) mix at the smaller strain, and the AR95 mix performing somewhat better at the larger strain (Figure 4.32). Both the G125 and AR95 mixes significantly outperformed the Caltrans RW95 mix

(HMA-O) with conventional binder at both strains. It must be remembered that these laboratory results indicate fatigue performance at a given strain, and that the expected performance of the mix in the pavement structure, and the strain under a given load for each mix, will depend largely on the stiffness of that mix.

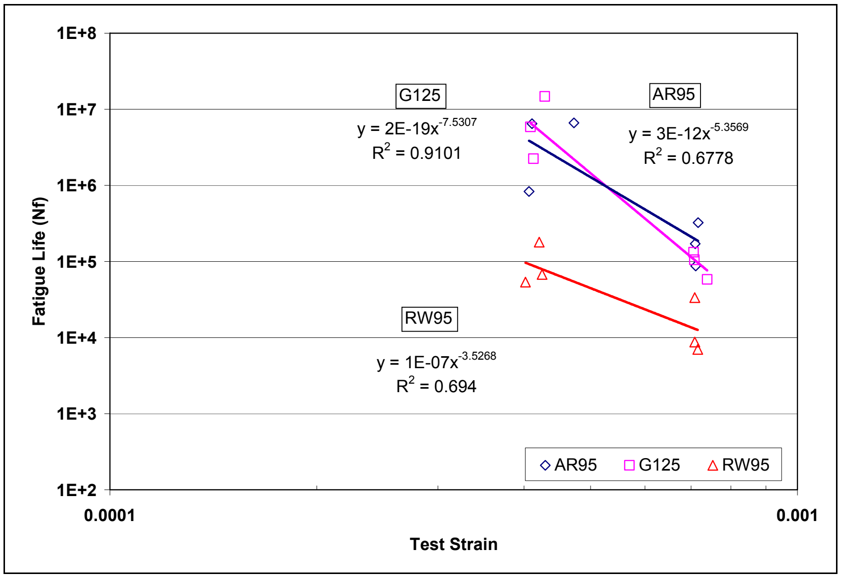


Figure 4.32: Summary of HMA fatigue life equations for fully permeable pavements.

Test Results: Flexural Stiffness

The dynamic stiffness of the G125, AR95, and RW95 mixes were measured at different temperatures and strain frequencies using flexural frequency sweep testing. Results are tabled in Appendix A. The frequency sweep results were fitted with a Gamma function to create stiffness master curves, which permit calculation of dynamic stiffness for any temperature and frequency. A summary of the master curves and time-temperature relationships is provided in Table 4.23. The data and master curve fits are shown in Figure 4.33, and the time-temperature shift factors for use with the master curve equations are shown in Figure 4.34.

The results indicate that the G125 mix was stiffer than the other two mixes except at short loading times (higher speed/frequencies), which also corresponds to colder temperatures, where the conventional Caltrans HMA-O mix (RW95) had similar stiffness. The Caltrans RHMA-O (AR95) mix generally had lower stiffness than the other two mixes, which results in higher tensile strains from truck loads, but lower tensile strains from cold temperatures.

Table 4.23: Summary of Master Curves and Time-Temperature Relationships

Mix Type	Master Curve					Time-Temperature Relationship	
	N	A	B	C	D	A	B
AR95	3	21,478.93	15.77917	-9.57447	94.4856	-17.8532	53.2251
G125	3	22,927.80	10.79402	-10.01293	147.9806	12.0135	-35.4865
RW95	3	8,420.84	3.976235	-5.32720	143.6314	7.62143	-24.3910

Notes:

1. The reference temperature is 20°C.
2. The flexural controlled-deformation frequency sweep tests were conducted at following testing conditions:
   Frequencies: 15, 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz;
   Temperatures: 10°C, 20°C, and 30°C; and
   Strain level: 100 or 200 microstrain.
   Master curve Gamma fitting equations:
   If $n = 3$, $E^* = D + A \cdot \left(1 - \exp\left(-\frac{(x-C)}{B}\right) \cdot \left(1 + \frac{x-C}{B} + \frac{(x-C)^2}{2B^2}\right)\right)$,
   where $x = \ln freq + \ln aT$
3. Time-temperature relationship: $\ln(aT) = A \cdot \left(1 - \exp\left(-\frac{T - Tref}{B}\right)\right)$

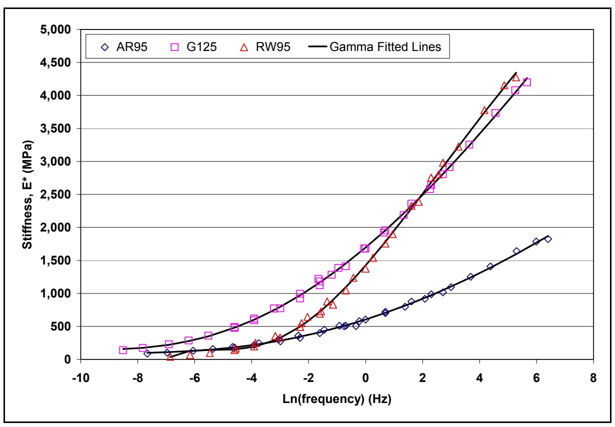


Figure 4.33: Summary of flexural stiffness master curves for HMA materials.

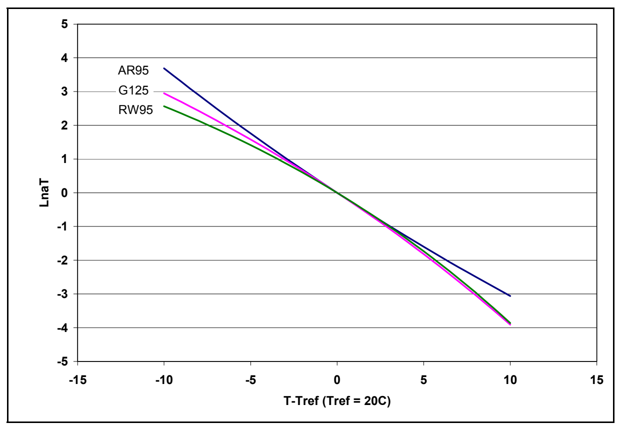


Figure 4.34: Time-temperature shift relationships for HMA materials.

Summary of Testing on Open-Graded Hot-Mix Asphalt

Test results indicate that the aggregate particle size distribution in the mix and the binder type will be the two most critical factors in designing permeable asphalt concrete wearing courses. Sufficient permeability for anticipated needs in California *(4)* was obtained on a range of mixes tested. Adequate resistance to rutting of the surface material appears to be mostly a problem for the RW95 with conventional binder and the AR95 mix with rubberized binder, based on shear modulus. The AR95 and G125 mixes had better rutting resistance in the Hamburg Wheel Tracking Test (which also considers moisture sensitivity), in particular the G125 mix containing polymers and fibers. Some moisture sensitivity was evident, but this can be overcome by the use of appropriate anti-strip treatments. Most of the mixes of interest had adequate durability (resistance to raveling) compared to the dense-graded control. Fatigue cracking resistance at a given strain was better for the rubberized and polymer-modified mixes (AR95 and G125) compared with the conventional mix at a given strain. The polymer-modified G125 mix was stiffest at higher temperatures and under slower traffic (lower frequency of loading), while the conventional RW95 mix had similar stiffness to the G125 mix at lower temperatures and under faster traffic. The rubberized AR95 mix generally had lower stiffness than the other two mixes. The flexural stiffness and the fatigue test results must be used together to simulate cracking behavior under truck loading to determine expected fatigue cracking life in a pavement structure.

4.3.4 Open-Graded Portland Cement Concrete

Portland cement concrete (PCC) materials are an alternative to hot-mix asphalt (HMA) as a wearing course. They provide a more rigid surface than HMA and are therefore typically more rut-resistant but more prone to cracking. As with HMA wearing courses, the material grading needs to be optimized to provide a balance between strength and permeability. The testing of PCC wearing course materials in this study focused on tensile, compressive, and flexural strengths, and associated permeability. A phased approach was followed in that preliminary testing (Phase 1) was carried out on a broad range of gradings identified in the literature. This was followed by more comprehensive testing (Phase 2) on specimens prepared with the three most promising gradings identified in Phase 1. Additional testing (Phase 3) was then carried out to assess the effects of a number of other parameters including cement content, water-to-cement ratio, and particle shape.

Material Sampling

Three different commercially available aggregate samples of different geological origin (granite, basalt, and alluvial) were sourced from the same three suppliers discussed in Section 4.3.2. These materials were considered to be representative of sources in the Central Valley and coastal regions of the state. The first two phases of testing were carried out on the granite material, while Phase 3 testing was carried out on the basalt and alluvial materials.

Test Methods

Laboratory testing consisted of measurement of compressive strength, tensile strength, flexural strength, fatigue resistance, and permeability on prepared specimens. The bulk specific gravity and bulk density of the specimens were also measured to determine the air-void content of the specimens. AASHTO or ASTM standard test methods were followed during testing as shown in Table 4.24.

Table 4.24: Test Methods for PCC Materials

Test	Test Method	Preliminary Specimens	Comprehensive Specimens	Supplementary Specimens
Specimen preparation	ASTM C-31	30	33	18
Compressive Strength	ASTM C-39	30	15 (5 per mix)	9 (3 per mix)
Split Tensile Strength	AASHTO T-198	--	15 (5 per mix)	9 (3 per mix)
Flexural Strength	ASTM C-78	--	3 (1 per mix)	--
Fatigue Resistance	Mod ASTM C-78	--	3 (1 per mix)	--
Max. Specific Gravity	AASHTO T-209	29	--	6 (2 per mix)
Bulk Specific Gravity	AASHTO T-331	29	--	6 (2 per mix)
Air-void Content	AASHTO T-269	29	--	6 (2 per mix)
Permeability	ASTM PS 129-01	All specimens	All specimens	All specimens

Specimen Preparation

All concrete was mixed in a 9.0ft^3 (0.25 m^3) electric concrete mixer using Type II portland cement. Water content was adjusted to obtain zero slump to better control the density of the concrete. The tamping rod method was chosen over the Modified Proctor method for compacting the specimens based on results and recommendations in the literature. Specimens were cured at 68°F (20°C) in a wet cure room for 28 or 56 days, depending on the phase of testing. Bulk specific gravity and bulk density were determined after curing.

Phase 1: Preliminary Testing

The six gradations for preliminary testing were chosen to maximize the connected voids in the specimens and are summarized in Table 4.25 and Figure 4.35. The Bailey Method, often used in HMA mix design for optimizing air-void contents, was used for two of the gradations.

Table 4.25: Phase 1 Testing Mix Proportions.

Parameter		Mix Proportions (kg/m^3)					
		Mix 1 trial	Mix 2 9.5	Mix 3 4.75s	Mix 4 Bailey-1	Mix 5 Bailey-2	Mix 6 9.5s
Aggregate	12.5 mm	4.5	0.0	4.5	0.0	0.0	0.0
	9.5 mm	87.0	1,500.0	87.0	900.0	900.0	1,500.0
	4.75 mm	1,387.5	0.0	1,387.5	600.0	600.0	0.0
	2.36 mm	7.5	0.0	18.4	10.9	21.8	10.9
	1.18 mm	1.5	0.0	23.7	22.2	44.4	22.2
	0.6 mm	0.0	0.0	24.0	24.0	48.0	24.0
	0.3 mm	0.0	0.0	20.5	20.5	41.0	20.5
	0.15 mm	1.5	0.0	13.9	12.4	24.8	12.4
	0.075 mm	1.5	0.0	5.5	4.0	8.0	4.0
Cement	-	455.0	350.0	350.0	350.0	350.0	350.0
Water	-	98.0	105.0	98.0	98.0	98.0	98.0
W/C ratio	-	0.22	0.30	0.28	0.28	0.28	0.28

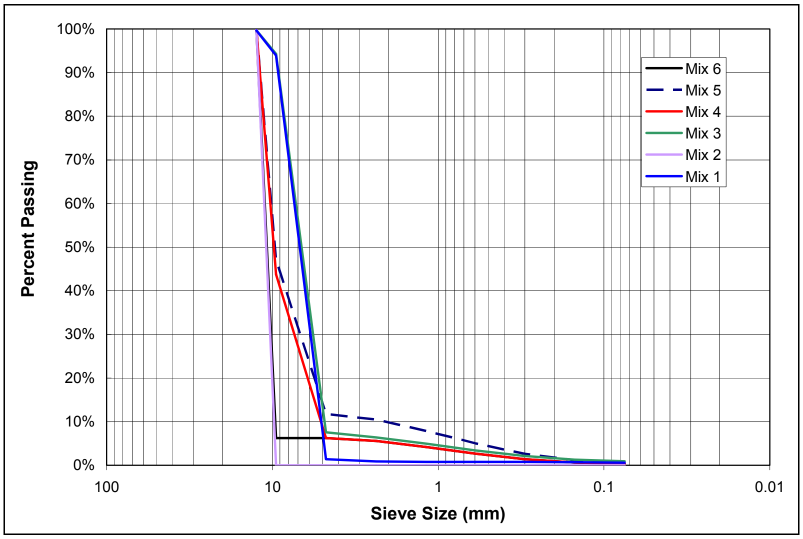


Figure 4.35: Gradations of six preliminary mix proportions.

Test results are summarized in Table 4.26 and Figure 4.36. The average permeability tended to increase with increasing air-void content and the compressive strength tended to decrease with increasing air-void content, as expected. The standard deviations for the permeability values were relatively large compared to the average values. This was attributed to variations in the interconnectivity of the voids between specimens. The air-void contents were similar within each of the mix gradations, but differed by up to 25 percent between gradations. Mix 2 (uniform gradation using 9.5 mm aggregate) had the highest air-void content, greatest permeability, and lowest compressive strength of all the specimens. Strengths were generally significantly lower than comparative typical dense-graded concrete. It should be noted that permeability is highly dependent on void connectivity and consequently high variability when testing laboratory specimens is expected.

Table 4.26: Test Results from Preliminary Testing

Mix	Air-Void Content (%)		Permeability (cm/s)		Compressive Strength (MPa)	
	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
1	29.8	0.00	4.52	2.94	4.48	0.33
2	35.4	0.94	6.75	3.75	1.45	0.35
3	31.7	0.63	5.23	0.97	2.71	0.38
4	30.7	2.00	5.84	3.06	4.33	1.58
5	28.6	0.53	3.97	1.46	5.06	0.72
6	29.1	1.27	4.53	2.48	3.99	0.72

Based on these results, Mixes 4, 5 and 6, which showed the best balance between strength and permeability, were selected for more comprehensive testing. Initial results indicate that the permeability exceeded requirements *(4)* and that the gradings could be densified (i.e., permeability reduced) to improve strength.

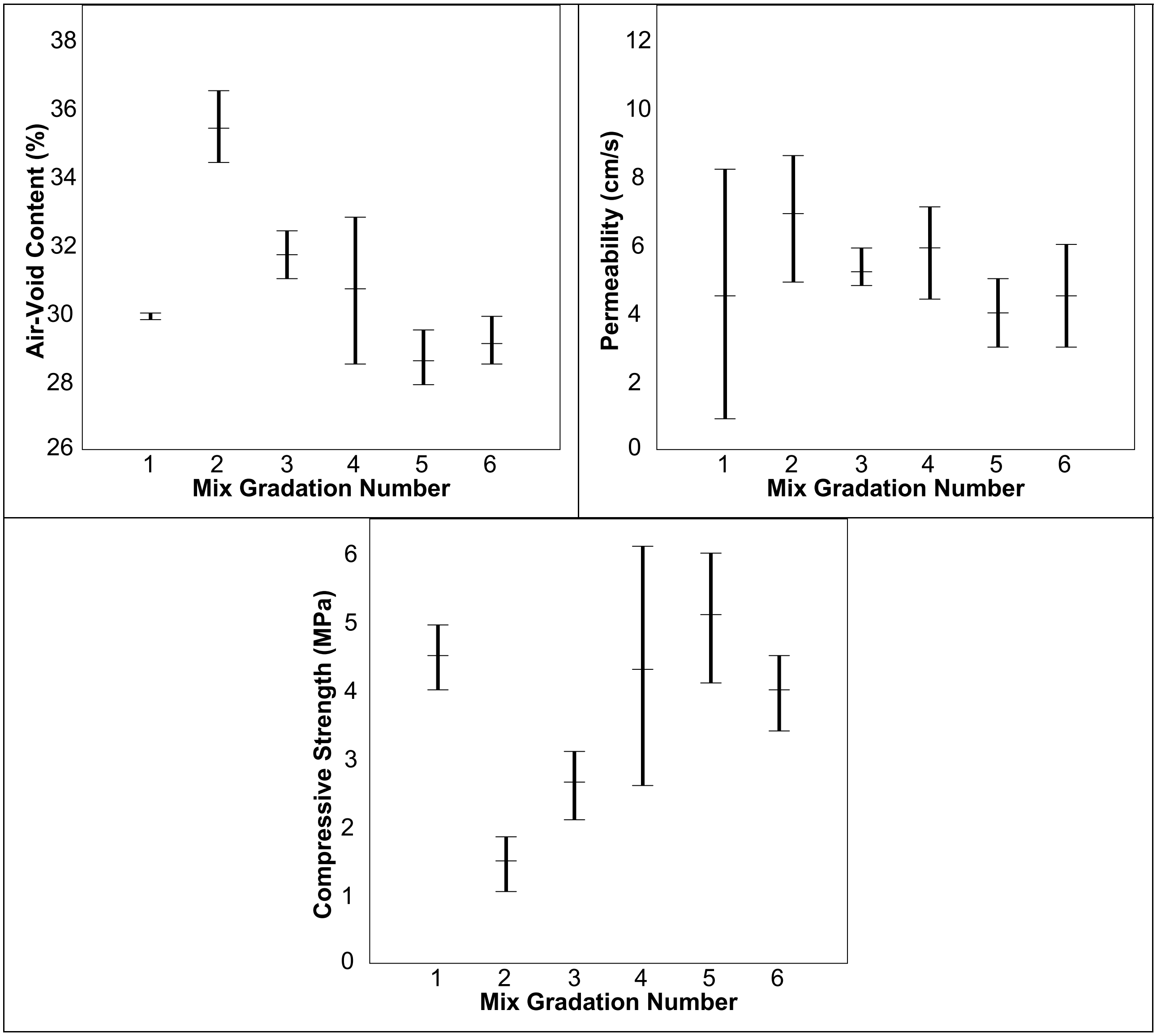


Figure 4.36: Test results from preliminary testing.

<u>Phase 2: Comprehensive Testing</u>

Based on the initial findings discussed above, the gradings for the selected mixes (Mixes 4, 5, and 6) were not altered. However, the cement contents were increased by 30 kg per mix in an attempt to increase the strengths. Water contents were also increased to raise the water/cement ratio. Attempts to produce mixes using lower water contents were unsuccessful due to poor workability. The revised mix proportions used in the second phase of testing are summarized in Table 4.27.

Table 4.27: Comprehensive Testing Mix Proportions.

Parameter		Mix Proportions (kg/m^3)		
		Mix 4 Bailey-1	**Mix 5 Bailey-2**	**Mix 6 9.5+sand**
Aggregate	9.5 mm	900.0	900.0	1,500.0
	4.75 mm	600.0	600.0	0.0
	2.36 mm	10.9	21.8	10.9
	1.18 mm	22.2	44.4	22.2
	0.6 mm	24.0	48.0	24.0
	0.3 mm	20.5	41.0	20.5
	0.15 mm	12.4	24.8	12.4
	0.075 mm	4.0	8.0	4.0
Cement	-	380.0	380.0	380.0
Water	-	120.0	121.0	128.0
W/C ratio	-	0.32	0.32	0.34

Test results are summarized in Table 4.28 and Table 4.29. Figure 4.37 provides a graphical display of the variance of strength with time, showing only a marginal increase in strength over the second 28-day curing period. The trend between tensile strength and permeability is shown in Figure 4.38, with a general decrease in tensile strength with increase in permeability evident, as expected. The fatigue life of the different mixes at the different stress ratios is plotted in Figure 4.39. Results from other studies *(17-21)* are plotted for comparative purposes. The eight percent increase in cement content between the preliminary and comprehensive test specimens caused an increase of approximately 97 to 150 percent in compressive strength and a decrease in permeability of approximately 55 to 60 percent. An exception was the Bailey-1 mix, which had lower strengths compared to the other two mixes. The compressive strength of this mix only increased approximately 10 percent with the increase in cement content. The specimens did not gain a significant amount of additional strength between 28 and 56 days.

Although the compressive strengths increased significantly with the higher cement content, they were still considerably lower than typical dense-graded mixes tested at the UCPRC in other projects (28-day compressive strengths of between 28 MPa and 30 MPa were obtained *[22]*). Flexural strengths were also lower than comparative dense-graded mixes. The Bailey-2 and 9.5 + sand mixes had higher flexural strengths than the Bailey-1 mix. However, these strengths were about 1.2 MPa lower than strengths obtained on dense-graded mixes *(22)*.

Fatigue performance was very dependent on the stress ratio, as expected. Performance compared favorably with dense-graded mixes in certain field studies conducted elsewhere in the United States *(17,18,19)*, but poorer when compared to other studies *(20,21)*. The Bailey-2 had the best fatigue performance, followed by the 9.5 + sand and Bailey-1 mixes.

Table 4.28: Average Strength and Permeability Values for Comprehensive Test Specimens

Mix	28-Day Compressive Strength (MPa)		56-Day Compressive Strength (MPa)		28-Day Tensile Strength (MPa)		56-Day Tensile Strength (MPa)		56-Day Flexural Strength (MPa)		Permeability (cm/s)	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
Bailey-1	4.74	0.30	5.35	0.76	0.97	0.06	1.10	0.34	1.25	-	2.64	2.41
Bailey-2	9.95	1.48	9.58	0.01	2.03	0.14	2.25	0.10	2.33	-	1.62	1.02
9.5 + sand	9.97	0.84	11.28	0.11	2.56	0.37	2.39	0.03	2.35	-	1.81	1.05

Table 4.29: Average Fatigue Life Values for Comprehensive Test Specimens

Mix	Fatigue Life at Different Stress Ratios		
	0.85	0.70	0.55
Bailey-1	28	5,932,036	1,931,252
Bailey-2	84	5,352,649	6,319,311
9.5 + sand	26	Specimen broke	3,056,037

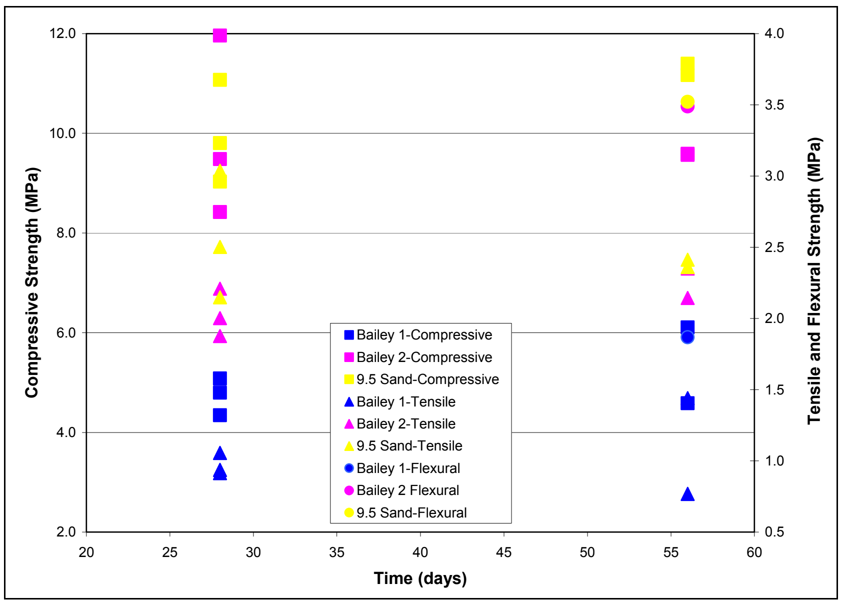


Figure 4.37: Strength vs. time for comprehensive specimens.

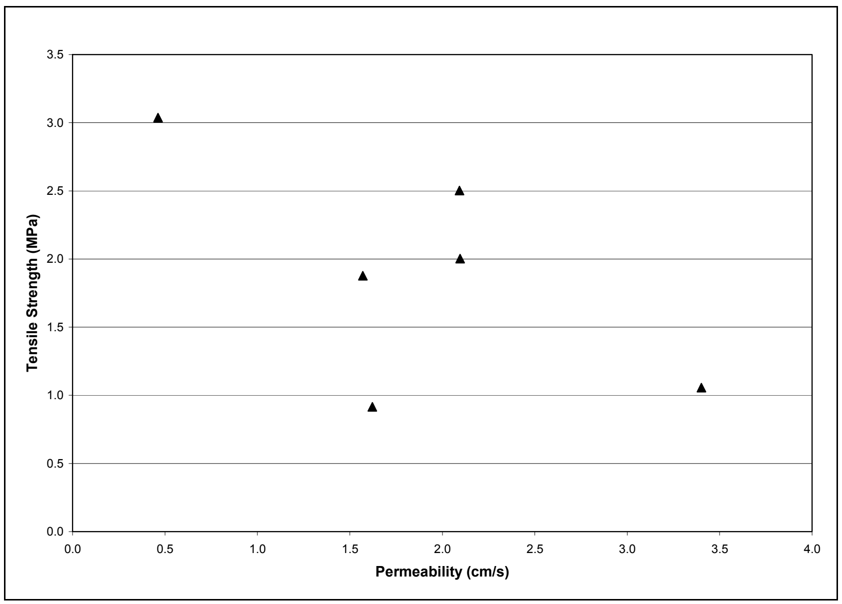


Figure 4.38: Tensile strength vs. permeability for comprehensive specimens.

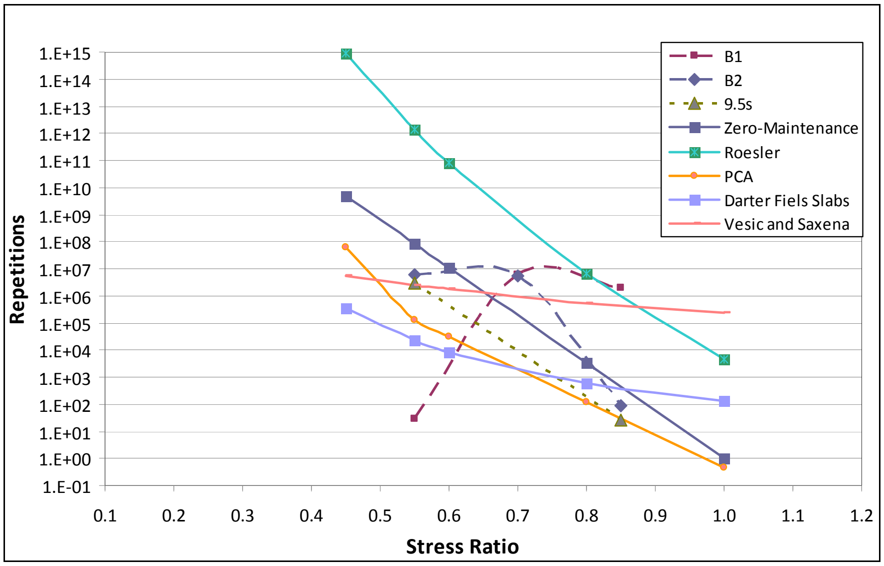


Figure 4.39: Fatigue life of comprehensive specimens.

<u>Phase 3: Supplementary Testing</u>

In this phase, the influence on performance of different aggregate type and additional cement was investigated. Two additional, different aggregate types and one additional cement content were investigated. The 9.5 mm aggregate-with-sand gradation (Mix 6) was chosen for this testing because it showed the best combination of strength and permeability in the Phase 2 testing. The revised mix proportions are summarized in Table 4.30. A slightly lower water/cement content ratio was used compared to the Phase 2 testing to assess the impact of this variable on workability, permeability, and strength. Permeability was measured after 28 days of curing, while the compressive and tensile strengths were determined after 56 days of curing. The results are summarized in Table 4.31.

Table 4.30: Supplementary Testing Mix Proportions.

Parameter		Mix Proportions (kg/m^3)	
		Different Aggregate	Additional Cement
Aggregate	9.5 mm	1,500.0	1,500.0
	4.75 mm	0.0	0.0
	2.36 mm	10.9	10.9
	1.18 mm	22.2	22.2
	0.6 mm	24.0	24.0
	0.3 mm	20.5	20.5
	0.15 mm	12.4	12.4
	0.075 mm	4.0	4.0
Cement	-	380.0	410.0
Water	-	108.0	115.0
W/C ratio	-	0.28	0.28

Table 4.31: Test Results from Supplementary Testing

Mix	Compressive Strength (MPa)		Tensile Strength (MPa)		Permeability (cm/s)	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
Granite	5.59	-	4.44	-	1.78	1.14
Basalt	9.11	-	6.83	-	1.17	0.50
Alluvial	6.00	-	-	-	1.48	-
Add. cement	3.89	-	4.02	-	2.95	2.95

The Phase 3 compressive strengths were considerably lower than the Phase 2 (comprehensive testing) results for the granite material that was used in both tests as well as in the test to assess the influence of additional cement. The compressive strength of the alluvial material was higher than that of the granite in this phase of testing, but lower compared to the results obtained in the Phase 2 testing. Tensile strength values from the supplementary testing were between 1.5 and 2.5 times higher than the tensile strength values obtained in Phase 2.

Lower permeability values were obtained with the basalt and alluvial materials compared to the granite, probably due to the aggregate shape. Permeability increased with increasing cement content, which was not expected. The increase in permeability and decrease in strength for the specimens with additional cement was attributed to the lower water-to-cement ratio, which led to clumping of the cement during mixing and consequent poor coating of the aggregate. The drier clumps of cement also reduced the workability of the concrete, leading to poor consolidation during rodding.

It should be noted that although no durability testing was carried out, some stone loss was evident on most of the specimens during handling, indicating that the mixes are likely to have some susceptibility to raveling under traffic. Since completion of the laboratory testing, the use of revised mix designs and proprietary additives has been discussed with a number of readymix suppliers as a means to limit raveling. These should be considered when constructing full-scale experiments, with recommendations for laboratory durability testing and, if appropriate, restrictions on areas of use based on the results of these experiments.

Summary of Test Results on Open Graded Concrete

Test results indicate a clear relationship between aggregate grading, cement content, water-to-cement ratio, and strength and permeability. All specimens tested exceeded the anticipated permeability requirements, indicating that aggregate gradings and cement contents can be adjusted to increase the strength of the material while still retaining adequate water flow through the pavement. The water-to-cement ratio appears to be critical in ensuring good constructability and subsequent performance of the pavement. Although no durability testing was carried out, the mixes are likely to have some susceptibility to raveling under traffic.

4.3.5 Cast Portland Cement Concrete

Testing in this phase investigated the use of standard dense-graded portland cement concrete with precast or cast-in-place holes. Careful consideration needed to be given to the design of the holes to ensure sufficient strength, adequate drainage of water, and safe use for bicycle, motorcycle, motor vehicle, and possibly pedestrian traffic. Testing focused on a comparison of tensile and flexural strengths between specimens with and without holes.

<u>Beam Design</u>

A number of hole/slot configurations were considered. However, the production of laboratory-scale slabs proved to be extremely difficult in terms of removing the mold from the slab and damage to the slab during handling. These problems are not anticipated for slabs cast in place. Ultimately only one design was pursued for laboratory testing. The general design followed is shown in Figure 4.40, based on a 12 ft (3.6 m) wide by 15 ft (4.5 m) long slab. Drain holes are 2.0 in. (50 mm) apart and 0.5 in. (12.5 mm) in diameter and are staggered so as to catch all the water that flows across the slab in a transverse or longitudinal direction. The surface-to-void ratio, defined as the ratio between surface drainage area (holes) and total surface area, was 3.1 percent.

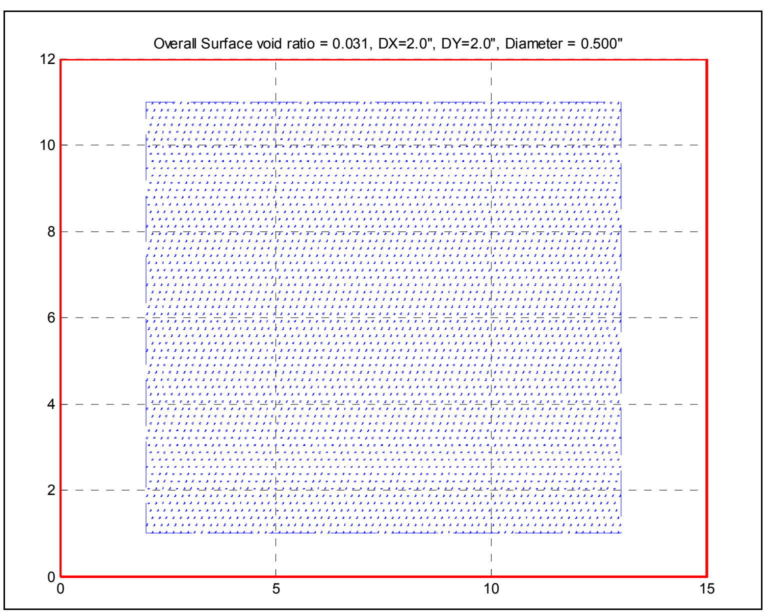


Figure 4.40: Top view of cast porous concrete pavement.

The design of a laboratory scale beam, using actual hole size and hole spacing, is shown in Figure 4.41. The design was based on the assumption that at least five holes across the slab would be necessary to provide an indication of potential behavior in the field. Accommodating five holes across the beam plus sufficient space between the edge of the slab and the first set of holes required a beam width of 11 in. (275 mm). A beam length of 37 in. (925 mm) was used to maintain appropriate beam geometry. The depth of the beam was set at 6.0 in. (150 mm), in line with standard laboratory practice for producing concrete beams.

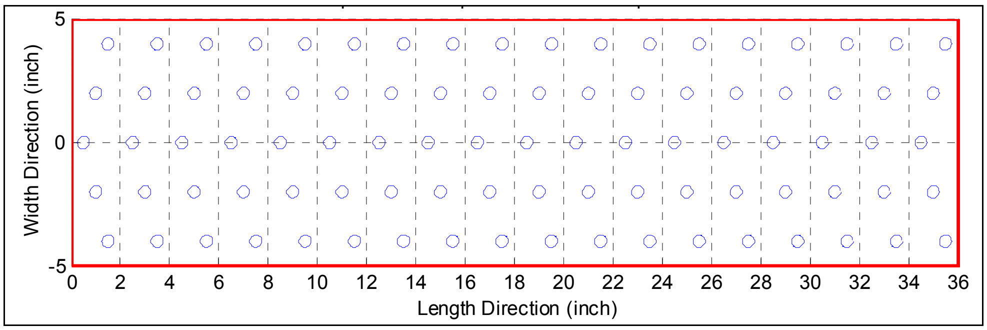


Figure 4.41: Top view of laboratory scale cast porous beam specimen.

Material Sampling

All testing was carried out with the alluvial materials discussed in the previous sections.

Test Methods

Laboratory testing consisted of measurement of compressive tensile and flexural strength, and permeability on prepared specimens. AASHTO or ASTM standard test methods were followed during testing as shown in Table 4.32. The permeability of the specimens was tested using the same procedure discussed in the previous sections.

Table 4.32: Test Methods for Cast PCC Materials

Test	Test Method	No. of Specimens
Specimen preparation	ASTM C-31	12
Split Tensile Strength	AASHTO T-198	12
Flexural Strength	ASTM C-78	6

All specimens were tested under monotonic loading with peak load at failure recorded. Efforts were made to record the complete load-displacement curve, including the post-peak response; however, this was beyond the capability of the testing frame.

Beam Fabrication

Two custom wooden molds were fabricated to cast the specimens (Figure 4.42). This final design was selected after a number of earlier attempts that failed for a number of reasons, including bending/alignment/breakages of the vertical dowels, problems with removing the mold after fabrication, poor distribution of the concrete in the mold (i.e., cavities around dowels and along beam edges), and damage to the specimen during handling after fabrication. The final design incorporates steel dowels with rubber pipe sleeves. Waterproof lubricants were applied between the rubber sleeves and steel dowels as well as the outside surface of the rubber sleeves. It is anticipated that full-scale construction would use plastic tubes for hole casting and that these tubes would remain in the concrete after casting.

A standard Caltrans half-inch maximum aggregate size design was used, although water contents were increased to improve flow within the mold and reduce the formation of cavities. Practice preparation revealed that a generally smooth specimen with no serious cavities could be produced (Figure 4.43).

Figure 4.42: Cast beam specimen molds.

Figure 4.43: Demolded cast beam specimen.

Three sets of specimens were prepared for the study, with each set including four standard beams (impermeable), four cylinders (impermeable), and two permeable beams. Specimens were cured in a moisture room at 68°F (20°C) for 36 days. Testing after curing was carried out after seven days on the first set of specimens and after 134 days on the second and third sets of specimens.

Test Results

Test results are summarized in Table 4.33. The results clearly show that splitting strength (1.6 MPa on average) was significantly lower than the modulus of rupture (3.4 MPa on average for 43-days and 5.0 MPa on average for 170-days). This trend was expected although the ratio between splitting strength and modulus of rupture was lower than expected. The minimal increase in splitting strength with increase in age was also unexpected.

Table 4.33: Modulus of Rupture for Beams and Splitting Strength for Cylinders

Specimen Type	Set	Batch	Specimen	Age (days)	Setup[1]	Result[2] (MPa)
Beam	1	1	RTA249-PEA-B1	43	4PB, no weight correction	2.7
			RTA249-PEA-B2		3PB, weight corrected, 1" notch	3.4
			RTA249-PEA-B3		3PB, weight corrected	3.3
			RTA249-PEA-B4		3PB, weight corrected	4.1
	2	1	RTA249-PEA-B5	170	3PB, weight corrected, 1" notch	4.6
			RTA249-PEA-B6			5.0
	2	2	RTA249-PEA-B7	170	3PB, weight corrected, 1" notch	4.8
			RTA249-PEA-B8		3PB, weight corrected	5.0
	3	1	RTA249-PEA-B9	165	3PB, weight corrected	5.0
			RTA249-PEA-B10			4.7
	3	2	RTA249-PEA-B11	165	3PB, weight corrected	5.0
			RTA249-PEA-B12			5.3
Cylinder	1	1	RTA249-PEA-C1	43	Indirect Tension	2.1
			RTA249-PEA-C2			1.2
			RTA249-PEA-C3			1.6
			RTA249-PEA-C4			1.4
	2	1	RTA249-PEA-C5	170		1.4
			RTA249-PEA-C6			1.8
	2	2	RTA249-PEA-C7	170		1.8
			RTA249-PEA-C8			1.4
	3	1	RTA249-PEA-C9	165		2.1
			RTA249-PEA-C10			1.0
	3	2	RTA249-PEA-C11	165		1.4
			RTA249-PEA-C12			1.9
Beam + holes	1	2	RTA249-PEA-PB1	44	3PB, weight corrected	3.9
			RTA249-PEA-PB2			3.7
	2	1	RTA249-PEA-PB3	170	3PB, weight corrected, 1" notch	3.6
	2	2	RTA249-PEA-PB4	170	3PB, weight corrected	3.2
	3	1	RTA249-PEA-PB5	165	3PB, weight corrected	2.9
	3	2	RTA249-PEA-PB6	165	3PB, weight corrected	1.9

[1] 3PB = Three Point Bending, 4PB = Four Point Bending
[1] Weight corrected indicates bottom support placed at 1/3 division points to balance the self-weight of beams during testing.
[1] 1" notch was sawn from the bottom.
[2] Modulus of rupture/splitting strength for cylinders calculated after accounting for geometry but not self-weight.

The comparison of modulus of rupture between regular beams and beams with holes is shown in Table 4.34 for the three sets of specimens. The ratio between the modulus of rupture for the two types of beam ranged between 0.48 and 1.12 for the three sets of results. The ratio based on the second set of specimens was selected for use in further analyses, given that the beams with holes in the first set of specimens were prepared in a different batch from the regular beams, while those in the third set of specimens were cured under different conditions. It is therefore concluded that the strength ratio between the beams with holes and regular beams is about 0.71.

The permeability was considered adequate for typical California rainfall events *(4)*. Cast beams are unlikely to ravel, although spalling around the holes may be a problem over time.

Table 4.34: Comparison of Modulus of Rupture for Beams and Beams with Holes

Set	Modulus of Rupture (MPa)		Ratio
	Regular Beam	Beam with Holes	
1	3.4	3.8	1.12
2	4.8	3.4	0.71
3	5.0	2.4	0.48

Finite Element Analysis

Finite Element Analysis (FEA) was undertaken to establish the link between regular beam strength (in terms of modulus of rupture) and that of the beams with holes. This was accomplished by evaluating the effect of a circular hole on overall specimen strength. An FEA technique known as the "embedded discontinuity method (EDM)" in the class of strong discontinuity approaches (SDA) was used in a *Matlab* software program to carry out the related analysis *(23)*.

Concrete is a quasi-brittle material that can be described by a cohesive crack model *(24)*. Once the peak strength is reached, residual traction across the crack faces remains in effect although its magnitude decreases with the amount of crack opening. The total specific energy required for a crack to propagate a unit length in concrete is assumed to be a constant. A typical value for peak strength is 3.0 MPa, and a typical value for the energy required is 0.1 N/mm. It is also assumed that the softening function is exponential.

A simplification of the analysis on beams with holes is achieved by analyzing a horizontal slice at the bottom of the test beam, subjected to approximately uniform uniaxial tension over the total area. A further simplification is reached by isolating a 4.0 in. (100 mm) long by 2.0 in. (50 mm) wide area centered around one of the circular holes from the bottom of the slice and then excluding all but the central hole. The simplified model is subjected to uniaxial tension in the horizontal direction. After considering symmetry, a 4.0 in. (100 mm) long by 1.0 in. (25 mm) wide finite element mesh is used to analyze the model (Figure 4.44).

The load displacement curve is shown in Figure 4.45. The peak load for a 0.04 in. (1.0 mm) thick horizontal slice shown in Figure 4.44 is 54.4 N, which corresponds to 73 percent of the peak load (3.0 N/mm^2 x 25 mm x 1 mm = 75 N) for the case without the hole. Since the crack propagates along the narrowest cross section, the presence of a circular hole leads to a 25 percent reduction in effective cross section for the finite element model. The stress concentration around the circular hole leads to an additional two percent reduction in peak load.

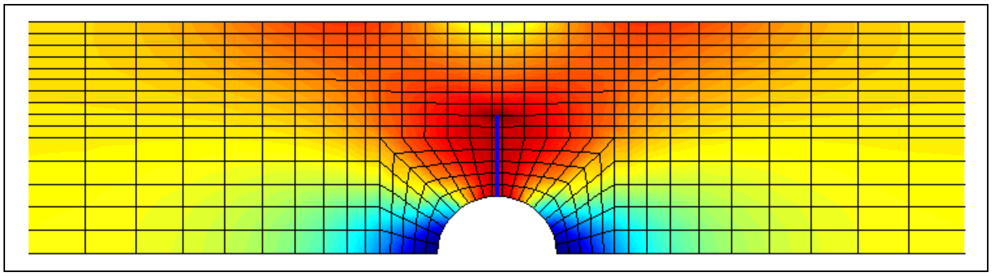


Figure 4.44: Horizontal stress contour after crack has propagated 0.35 in. (9.0 mm).
(Crack indicated by the thick blue line, red area is tension, and blue area is compression).

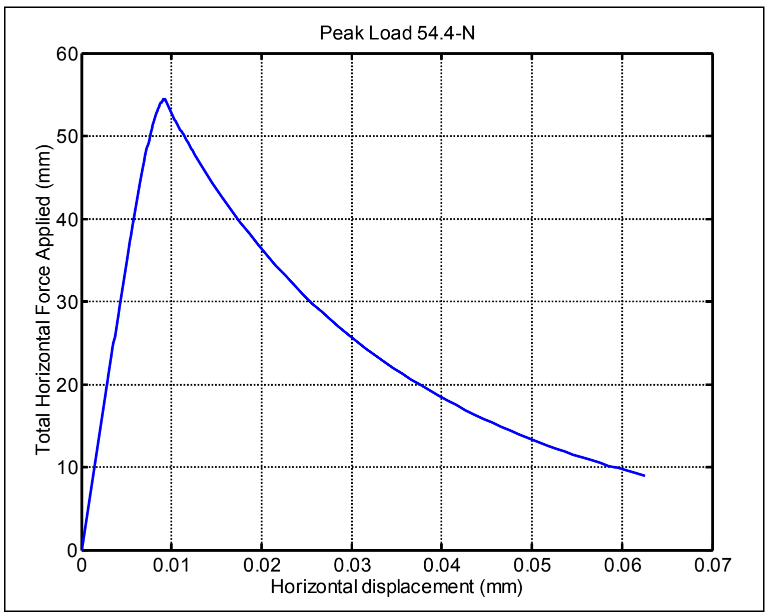


Figure 4.45: Load displacement curve for FEM model shown in Figure 4.44.

Based on the above analysis, it was concluded that weakening in the beams with holes is mostly caused by a reduction in resisting tension area. The bottom view of a cracked beam with holes is shown in Figure 4.46, which indicates that cracks propagate through the holes in a transverse direction and then interconnect in a skewed angle. Since cracks are forced to interconnect along a longer skewed path, a more conservative (larger) effective cross section reduction of 23 percent can be used (5 x 0.5 in. / 11 in. = 23%). In other words, the strength of a beam with holes is approximately 77 percent that of a regular beam. This is slightly higher than the observed values (i.e., 71 percent). The difference can be explained partly by the stress concentration effect caused by the circular holes and partly due to fabrication issues in that it is more difficult to cast a perfect beam with holes given the proximity of the steel pins to each other.

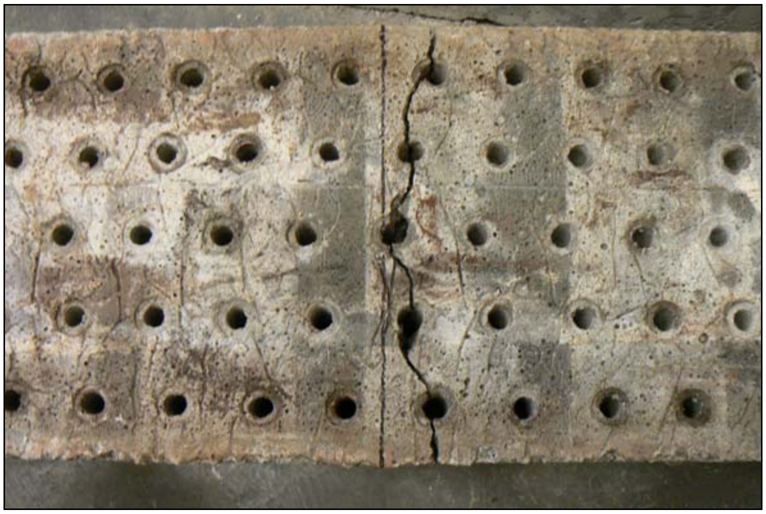


Figure 4.46: Bottom view of beam with holes (RTA249-PEA-PB6) after strength test.

Results were used as input for the computer modeling study and structural design tables discussed in Chapter 5 and Chapter 6 respectively.

<u>Summary of Test Results on Cast Concrete Slabs</u>

The limited results from this study indicate that small-scale permeable beams exhibit a modulus of rupture about 71 percent of that measured for regular beams mixed and cured under exactly the same conditions. Based on a finite element analysis, weakening of the permeable beams is mostly caused by a reduction in crack resistance cross section, while the effect of stress concentration can be ignored. This implies that modulus of rupture values for permeable beams should be about 77 percent that of regular beams. This relatively small discrepancy between observed and calculated values (71 percent vs. 77 percent) is believed to be attributed to poorer consistency in the permeable beams compared to regular beams. For this particular drainage pattern, a 70 percent strength ratio is recommended for use in design.

Permeable concrete pavements with similar surface void ratio (3.1 percent in this study) can be designed the same way as regular non-permeable concrete pavements. The effect of the vertical drainage holes can be accommodated by reducing the modulus of rupture value. This reduction can be estimated by calculating the reduction in crack resisting cross section normal to the direction of maximum principle stress induced by truck traffic. An additional 10 percent reduction in design modulus of rupture is recommended to account for the lower homogeneity caused by the existence of the drainage holes.

Chapter 5 Performance Modeling

5.1 Introduction

The approach used for development of detailed pavement designs in this study is referred to as "mechanistic-empirical" or "ME." Caltrans is in the process of implementing this approach as a replacement for the empirical R-value design method for flexible (asphalt-surfaced) pavement designs, and has replaced the previous design tables for rigid (concrete-surfaced) pavements with a new catalog of designs based on ME analysis. The assumptions of the R-value design method for flexible pavements, including standard compaction and pavement structural layering, are also not appropriate for asphalt-surfaced fully permeable pavements.

For this project, the ME approach was used for both flexible and two types of rigid fully permeable pavements to produce a set of designs for different Traffic Indexes (TI), climate, and soil conditions. The different pavement types are summarized in Figure 5.1. The two types of rigid pavements were those surfaced with open-graded PCC (PCC-O) in which the surface is permeable because of the aggregate gradation, and those surfaced with ordinary dense-graded PCC in which the surface has drainage holes cast into it during construction (cast PCC). The results of the analyses were used to produce a catalog of designs, similar to the catalog designs prepared by the UCPRC for the Caltrans Rigid Pavement Design Catalog currently used in the Caltrans *Highway Design Manual (HDM)*. All calculations considered two subbase options:

- No subbase
- 0.5 ft (150 mm) thick open-graded portland cement concrete subbase to provide support to the granular layer, and help protect the saturated subgrade.

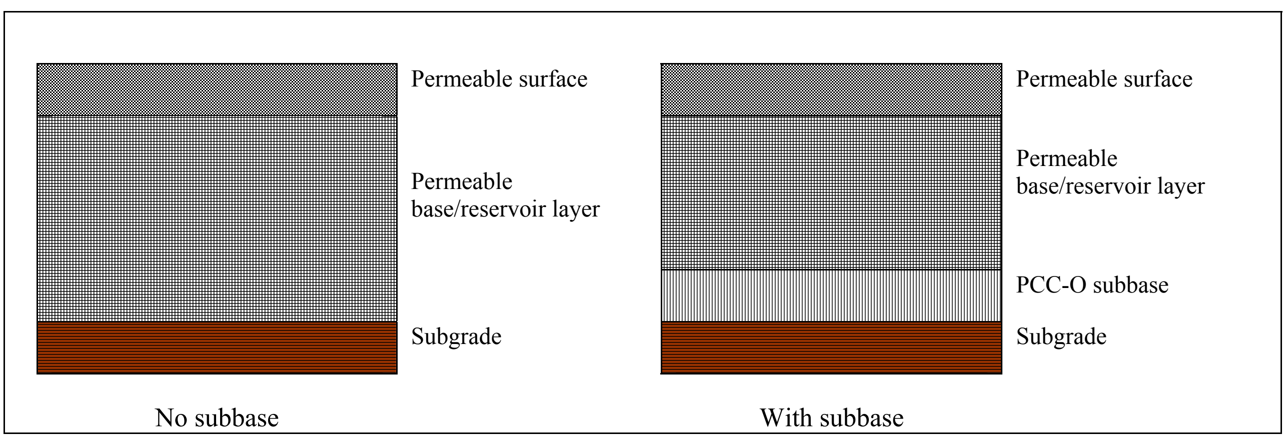


Figure 5.1: Pavement structures analyzed.

5.2 Portland Cement Concrete Surfaced Fully Permeable Pavement

The factorial for performance modeling of fully permeable pavement surfaced with open-graded portland cement concrete (PCC-O) or cast PCC with drainage holes is summarized in Table 5.1. A total of 1,536 different cases were run. Variables for the PCC layer include surface material type (PCC-O or cast PCC), slab thickness, slab length, material properties, climate zone, season, diurnal peak temperature gradient, axle type, axle load, load location, and traffic volume. The analysis process followed is summarized in Figure 5.2.

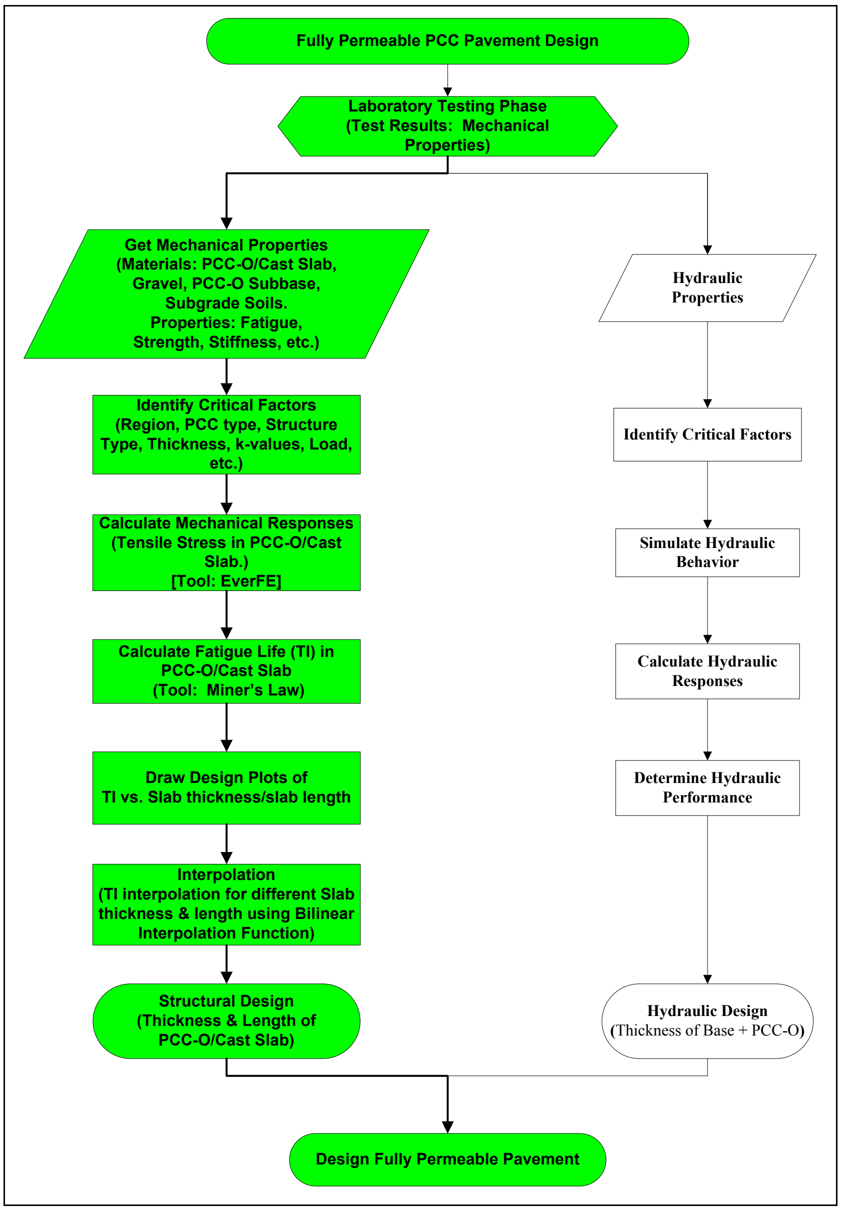


Figure 5.2: Analysis process for developing structural designs for fully permeable PCC pavements.

Table 5.1: Summary of Experimental Design for Performance Modeling of PCC

Layer	Label	Material (M)	Slab/Layer Thickness (Th)	Slab Length (L)	Properties (MP)	Climate Zone (C)	Season (S)	Diurnal Peak[1] (DP)	Axle Type[2] (AT)	Axle Load[2] (AL)	Load Location (LL)	Traffic Volume (TV)
Surface	PCC-O	9.5s	0.25m 0.35m 0.50m	3.0 x 3.5m 4.5 x 3.5m	E= 10 GPa, v=0.2 CTE=6.5^{-6}/°C ρ=2,000kg/m^3	Sac LA	Winter Summer	Day Night	Dual/single Dual/tandem	0.8L ~ L[3] L ~ Max[4]	Corner Mid edge	1
	Cast slab	Slab	0.25m 0.35m 0.50m	3.0 x 3.5m 4.5 x 3.5m	E= 30 GPa, v=0.2 CTE=6.5^{-6}/°C ρ=2,000kg/m^3	Sac LA	Winter Summer	Day Night	Dual/single Dual/tandem	0.8L ~ L[3] L ~ Max[4]	Corner Mid edge	1
Support layer	Base, subbase & subgrade	-	-	-	k=50MPa k=80MPa	-	-	-	Dual/single Dual/tandem	0.8L ~ L[3] L ~ Max[4]	-	1
Base	Base	Alluvial Basalt Granite	0.5m 1.0m 1.5m	-	M_r=30 MPa, v=0.4 M_r=100 MPa, v=0.4 M_r=200 MPa, v=0.4	-	-	-	-	-	-	-
Subbase	Subbase	In situ PCC-O	0.0m 0.15m	-	- E=10 GPa, v=0.2	-	-	-	-	-	-	-
Subgrade	Subgrade	Silt	-	-	M_r=20 MPa, v=0.45 M_r=50 MPa, v=0.45 M_r=100 MPa, v=0.45	-	-	-	-	-	-	-

Number of Calculations

Label	M	Th	L	MP	C	S	DP	AT	AL	LL	Total
Surface	1	3	2	1	2	2	2	2	2	2	384
	1	3	2	1	2	2	2	2	2	2	384
Support layer	1	1	1	2	1	1	1	1	1	1	2
Base	3	3	1	3	1	1	1	1	1	1	27
Subbase	2	2	1	1	1	1	1	1	1	1	4
Subgrade	2	1	1	3	1	1	1	1	1	1	6

[1] Diurnal Peak Calculations

Zone	Thickness (m)	Season	Day[A]	Night[A]
Sac	0.25	Jan	29.3	19.2
		Jul	70.9	-56.5
	0.35	Jan	18.9	-12.9
		Jul	48.7	-37.2
	0.50	Jan	13.8	-9.3
		Jul	36.5	-25.8
LA	0.25	Jan	38.4	-23.9
		Jul	45.8	-30.6
	0.35	Jan	25.3	-15.7
		Jul	31.1	-20.4
	0.50	Jan	18.7	-11.1
		Jul	23.4	-14.0

[A] Thermal Gradient of PCC (°C/m) 30-year average (1961-1990)

[2] Load Geometric Configuration

Axle Type	Load bin	Load (kN)	Tire Pavement Contact[5] (mm)
Dual Single	0.8L ~ L[3]	75	179 x 150
	L ~ Max[4]	93	221 x 150
Dual Tandem	0.8L ~ L[3]	135	161 x 150
	L ~ Max[4]	155	185 x 150

[3] Load midway between the legal load and the maximum load
[4] Load midway between 0.8 times the legal load and the legal load
[5] Tire pavement contact length x width

Material properties for each of the layers were obtained from the laboratory study *(1)*. Climate details were obtained from a database of California climatic data, and the thermal gradient values were calculated from 30 years (1961 to 1990) of data using the *Enhanced Integrated Climate Model (EICM)*. The maximum, minimum, and average of the 30-year thermal gradient at each hour in each day for January and July were calculated as shown in Figure 5.3. The maximum and minimum of the average day for those two months were chosen as the day thermal gradient and night thermal gradients for calculation, respectively (example in Figure 5.3). Axle loads were obtained from a database of California weigh-in-motion (WIM) stations. The rigid pavements were modeled as two layer systems, the slab and the supporting layers, with a composite *k*-value (modulus of subgrade reaction) simulating all layers below the slab acting together. A separate factorial for the supporting layers was used to derive two different input *k*-factors for the supporting layers.

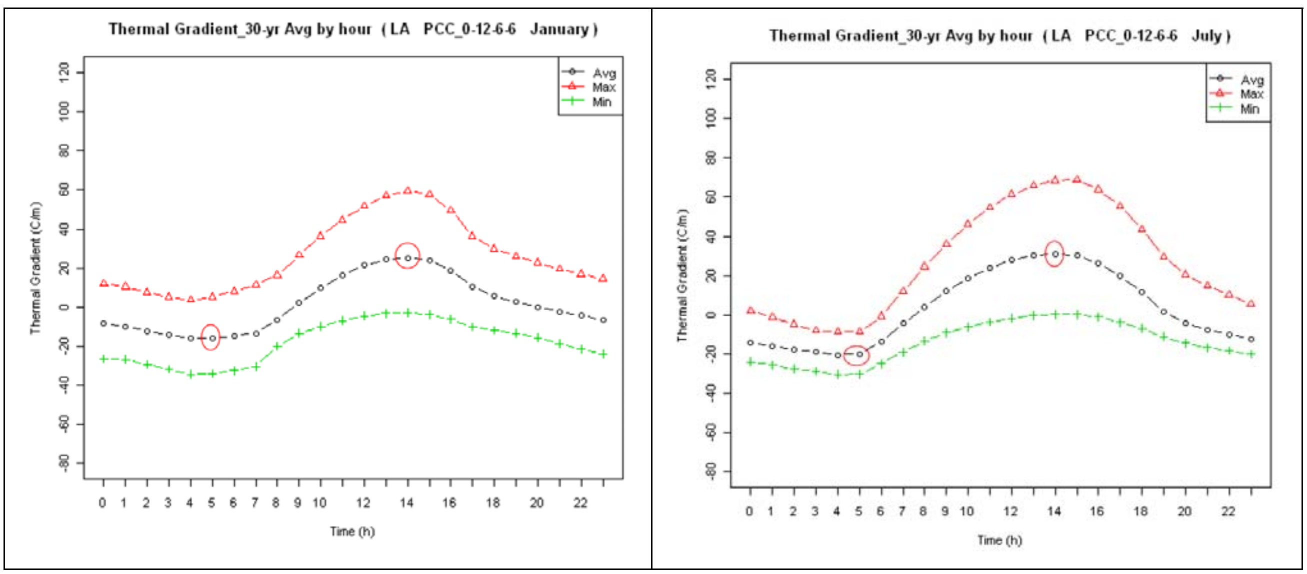


Figure 5.3: Example thermal gradient calculation for PCC pavements.

Due to the thousands of calculations required to determine critical stresses and strains using layer elastic theory for HMA-surfaced pavements and finite element analysis for open-graded concrete and cast concrete, the traffic loads included in the calculations were reduced to two each for both single and tandem axles:

- The traffic repetitions between the 50th percentile load and the legal maximum load, with the representative load taken approximately halfway between the 80th percentile load and the legal maximum load. The representative load selected imparts some conservatism to the designs.
- The traffic repetitions between the legal maximum load and the maximum load (neglecting a few outliers that are heavier), with the representative load taken approximately halfway between the legal maximum load and the maximum load. The representative load selected imparts some conservatism to the designs.

Steering single and tridem axle loads were not considered because they contribute very little to damage, based on the calculations from the UCPRC/Caltrans weigh-in-motion database (WIM)*(25)*. These loads were selected based on the understanding that the vast majority of pavement damage is caused by the heaviest loads, particularly for concrete, and examination of typical axle-load spectra from the UCPRC/Caltrans WIM database which showed that the first load group shown above was representative of a significant percentage of the loaded axles found on California highways, and the second load group was representative of the few loads that cause the most damage.

The allowable truck traffic (ESAL or TI) during the design life was calculated using a set of factors, including seasonal factor (winter or summer), day/night factor, axle type factor (single or tandem), ESAL factor (the average ESALs per axle), and load bin factor (percent of total axle repetitions for each axle in each load range) as shown in Table 5.2. The value of each factor was determined based on the statistical analysis of statewide traffic information from the UCPRC/Caltrans Weigh-in-Motion database *(25)*. As mentioned previously, axle loads less than half the legal load were ignored in order to keep the number of required calculations to an acceptable value, which was considered reasonable since they contribute very little to fatigue damage.

Table 5.2: Load Spectrum Factors for PCC Structures

<table>
<tr><th colspan="2">Seasonal Factor</th><th colspan="2">Day/Night Factor</th><th colspan="2">Axle Type Factor</th><th colspan="2">ESAL Factor</th></tr>
<tr><th>Winter</th><th>Summer</th><th>Day</th><th>Night</th><th>Single</th><th>Tandem</th><th>Single</th><th>Tandem</th></tr>
<tr><td>0.5</td><td>0.5</td><td>0.45</td><td>0.55</td><td>0.2</td><td>0.8</td><td>0.17</td><td>0.3</td></tr>
<tr><th colspan="8">Load Bin Factor</th></tr>
<tr><th colspan="4">Single</th><th colspan="4">Tandem</th></tr>
<tr><th colspan="2">0.8Legal~Legal
(75 kN)</th><th colspan="2">Legal~Max
(93 kN)</th><th colspan="2">0.8Legal~Legal
(135 kN)</th><th colspan="2">Legal~Max
(155 kN)</th></tr>
<tr><td colspan="2">0.492</td><td colspan="2">0.008</td><td colspan="2">0.46</td><td colspan="2">0.04</td></tr>
</table>

The various factors listed in Table 5.2 are explained as follows:

- Seasonal Factor. UCPRC WIM data study *(25)* indicated that axle loads were evenly distributed across all months.
- Day/Night Factor. UCPRC WIM study indicated that more loaded trucks travel at night than during daylight hours.
- Axle Type Factor. UCPRC weigh-in-motion data study indicated that Truck Type 5 (typically with a steering single and one loaded single axle) and Truck Type 9 (typically with a steering axle and two loaded tandem axles) dominate the truck composition on California highways, and that there are twice as many Type 9 than Type 5 trucks on average across the state. This results in one third of the trucks having one single axle, and two thirds of the trucks having two tandem axles, resulting in 20 percent single axles and 80 percent tandem axles in the total population of axles shown in the table. (See Figure 12 in Reference 25 for further information).
- ESAL Factor. The ESAL factor provides the number of equivalent single axle loads (ESAL, based on 18,000 lb [80 kN] single axle) per axle repetition, calculated for each axle type on a statewide average of all Caltrans WIM stations between 1993 and 2001 *(25)*. The ESAL calculations used an

exponent of 3.8, recommended by the Federal Highway Administration, rather than the 4.2 exponent normally used by Caltrans *(25)*. This factor converts the ESALs in the Traffic Index into total axle repetitions. (See Figure 35 in Reference 25 for further information).

- Load Bin Factor: The load bin factor indicates the percentage of axle repetitions for each axle type out of the total repetitions of that axle type for the two load ranges used in the calculations: half the legal load to the legal load, and the legal load to the maximum load.

Cracking due to tensile stresses in the slab was the distress type modeled. Four locations were considered:

- Mid-slab edge at the top of the slab.
- Mid-slab edge at the bottom of the slab.
- Near the corner of the slab at the top of the slab.
- Near the corner of the slab at the bottom of the slab.

Mechanical responses in terms of tensile stress in the slab from different load configurations were determined using the *EverFE* software package *(26)* for finite element analysis of concrete pavement. The stiffness of cast slabs in *EverFE* was estimated from conventional PCC by a factor of 0.92 (i.e., 30 GPa × 0.92 = 27.6 GPa) *(27)*. The stresses from *EverFE* were given a factor of 3.0 to reflect the stress concentration around the holes in the cast slabs, based on separate finite element analyses completed prior to the *EverFE* calculations.

The results of the *EverFE* stress calculations were then used as input in a Miner's Law equation to calculate the fatigue performance of the slabs. The Miner's Law equation *(27)*, also referred to as the Linear Cumulative Damage (LCD) equation, was used to calculate the fatigue damage under specific conditions (pavement structure, traffic loading, climate conditions). The actual repetitions to failure, *n*, were calculated using the Miner's Law equation to determine the number of ESALs (later converted to Traffic Index, *D* = 1.0 in Equation 5.1) for each combination of pavement type, slab dimensions, thicknesses, and climate region. The actual repetitions for failure were then converted back into ESALs, and then into Traffic Index.

The Miner's Law equation is shown in Equation 5.1.

$$D = \sum_i \frac{n_i}{N_i} \tag{5.1}$$

where: D = Damage from fatigue;
n_i = The actual repetitions under i^{th} condition of axle type, climate condition, and pavement structure, calculated from load spectrum;
N_i = The allowable repetition under i^{th} condition, calculated from fatigue equation.

and,

$$n_i = ESAL \times F_{seasonal} \times F_{day/night} \times F_{axletype} \times 1/F_{ESAL} \times F_{LB} \tag{5.2}$$

where: $ESAL$ = ESALs for the Traffic Index.
$F_{seasonal}$ = Seasonal factor.
$F_{day/night}$ = Day/night factor.
$F_{axletype}$ = Axle type factor.
F_{ESAL} = ESALs per axle repetition per ESAL coefficient (calculated for average state network by Lu (Equation 3) using 3.8 exponent and the values used were taken from Figure 35 for years 1991 to 2000).
F_{LB} = Load bin factor.

Based on the laboratory fatigue testing results from this project (Figure 5.4)*(2)*, the Zero-Maintenance fatigue equation *(17)* was used to calculate the allowable repetitions under i^{th} condition (combination of factors shown in Equation 5.2) as follows (Equation 5.3):

$$N_i = 10^{17.61(1-\sigma_i / MR)} \tag{5.3}$$

where: σ_i = Maximum tensile stress in the slab under i^{th} condition;
MR = Modulus of rupture (flexural strength) (MR=2.3 MPa for PCC-O based on testing results [Table 4.28], and MR=2.6 MPa; for cast slabs considering stress concentration based on finite element analysis).

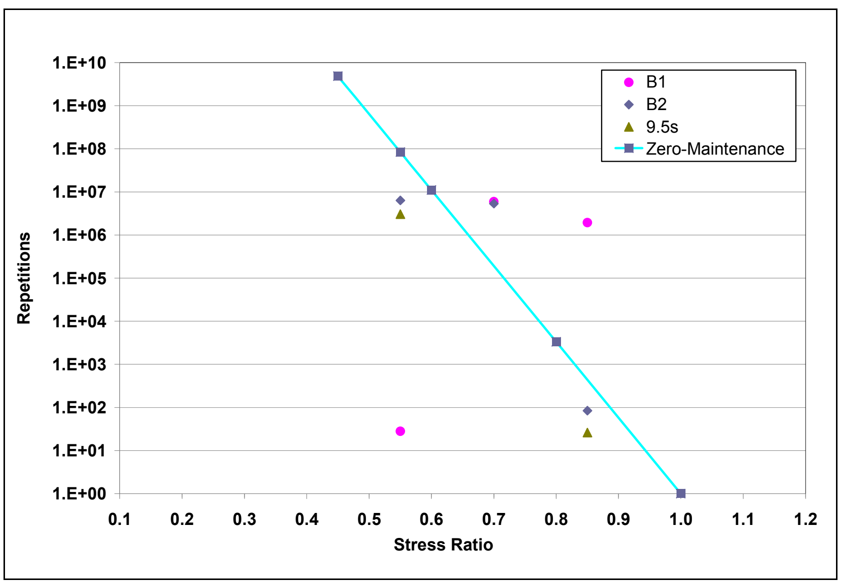


Figure 5.4: Fatigue life of open-graded concrete pavement (PCC-O).

5.2.1 Example Results

Example predictions of design life (Traffic Index [TI]) for various combinations of variables in the experimental design (open-graded PCC, cast slabs, climatic zone, and base stiffness in terms of *k*-values) are shown in the Technical Memorandum on Performance Modeling *(2)*. The design of fully permeable pavements with a PCC-O or cast concrete surfacing using the data collected in this task is discussed in Chapter 6.

5.3 Hot-mix Asphalt Surfacing

The factorial for performance modeling of permeable hot-mix asphalt wearing courses is summarized in Table 5.3. A total of 15,552 different cases were run. The analysis process is summarized in Figure 5.5. Variables for the hot-mix asphalt layer include material type, layer thickness, material properties, climate zone, season, diurnal peak temperature, axle type, axle load, traffic speed, and traffic volume.

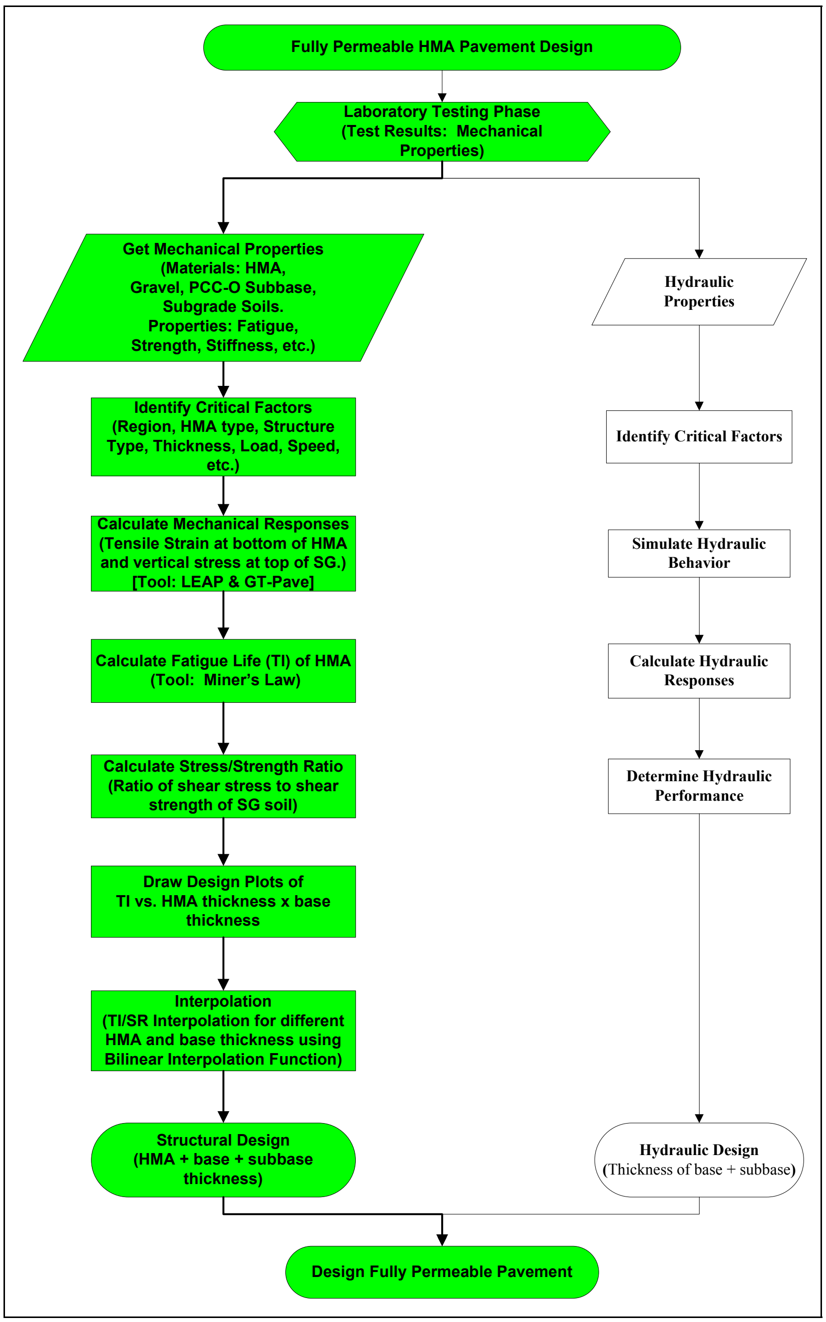


Figure 5.5: Analysis process for developing structural designs for fully permeable HMA pavements.

Table 5.3: Summary of Experimental Design for Performance Modeling of Hot-mix Asphalt

Layer	Label	Material (M)	Layer Thickness (Th)	Properties (MP)	Climate Zone (C)	Season (S)	Diurnal Peak[1] (DP)	Axle Type[2] (AT)	Axle Load[2] (kN) (AL)	Traffic Speed (km/h) (TS)	Traffic Volume (TV)
Surface	HMA-O	AR95 G125 RW95	0.2m 0.3m 0.4m 0.5m	E* v=0.35	Sac LA	Winter Spring Summer	Day Night	Dual/single Dual/tandem	0.8L ~ L[3] L ~ Max[4]	7 40	1
Base	Base	Alluvial Basalt Granite	0.5m 1.0m 1.5m	M_r=60 MPa, v=0.4 M_r=90 MPa, v=0.4 M_r=120 MPa, v=0.4	-	-	-	Dual/tandem	-	-	-
Subbase	Subbase	In situ PCC-O	0.0m 0.15m	- E=6 GPa, v=0.2	-	-	-	Dual/tandem	-	-	-
Subgrade	Subgrade	Clay (winter) Clay (spring) Clay (summer)	-	M_r=20 MPa, v=0.45 M_r=50 MPa, v=0.45 M_r=100 MPa, v=0.45	-	Winter Spring Summer	-	Dual/tandem	-	-	-

Number of Calculations

Label	M	Th	MP	C	S	DP	AT	AL	TS	Total
Surface	3	3	1	2	3	2	2	2	2	864
Base	1	2	1	1	1	1	1	1	1	9
Subbase	1	2	1	1	1	1	1	1	1	2
Subgrade	1	1	1	1	1	1	1	1	1	1
										15,552

[1] Diurnal Peak Temperature Calculations (°C)

Zone	Thickness	Season	Day[A]	Night[A]
Sac	0.2	Jan	15.4	8.2
		Apr	44.4	25.6
		Jul	30.0	15.9
	0.3	Jan	14.4	8.7
		Apr	42.1	27.1
		Jul	28.3	16.8
	0.5	Jan	12.7	9.7
		Apr	37.8	30.0
		Jul	24.9	18.9
LA	0.2	Jan	23.6	14.3
		Apr	35.5	23.2
		Jul	29.5	17.5
	0.3	Jan	22.2	14.8
		Apr	34.0	24.0
		Jul	28.0	18.2
	0.5	Jan	19.8	16.1
		Apr	31.0	25.7
		Jul	25.0	19.9

[A] Temperature at 1/3 depth of HMA (°C) 30-year average (1961-1990)

[2] **Load Geometric Configuration**

Axle Type	Load bin	Load (kN)	Diameter[5] (mm)
Dual Single	0.8L ~ L[3]	75	185
	L ~ Max[4]	93	206
Dual Tandem	0.8L ~ L[3]	135	175
	L ~ Max[4]	155	188

[3] **Traffic Volume Calculation**

Travel lane	Shoulder	Drive Time	# of lanes Drained
Low Medium	Low Medium High	1 week 1 month 1 year 10 years	1 2 3 4

[3] Load midway between the legal load and the maximum load
[4] Load midway between 0.8 times the legal load and the legal load
[5] Tire pavement contact diameter

Material properties for each of the layers were obtained from the laboratory study *(1)*. Three types of open-graded hot-mix asphalt were considered in the calculations. Climate details were obtained from a database of California climatic data, and the temperatures at one-third of the depth of the hot-mix asphalt layer were calculated from 30 years (1961 to 1990) of data using the *Enhanced Integrated Climate Model (EICM)*. The maximum, minimum, and average of the 30-year temperatures at one-third depth at each hour in each day for January, April and July were calculated as shown in Table 5.3. The maximum and minimum of the average day for each of those three months were chosen as the day and night temperatures for layer elastic theory calculations, respectively. Axle loads were obtained from a database of California WIM stations *(25)*.

Two truck traffic speeds (4 and 24 mph [7 and 40 km/h]) were included in the calculations. The slower speed was selected to represent truck operations during traffic congestion on highways (in this case a detour onto the shoulder) and in maintenance yards or parking areas. The faster speed was selected to represent truck operations on a street or on a shoulder which has had traffic diverted on to it but which is not severely congested. Each of these speeds is somewhat slower than the average speed might be for each of these conditions. This provides a conservative assumption because HMA is less stiff under slower speeds, which increases the strains causing fatigue cracking of the HMA layer, and increases the stresses in the granular base and subgrade, which cause rutting.

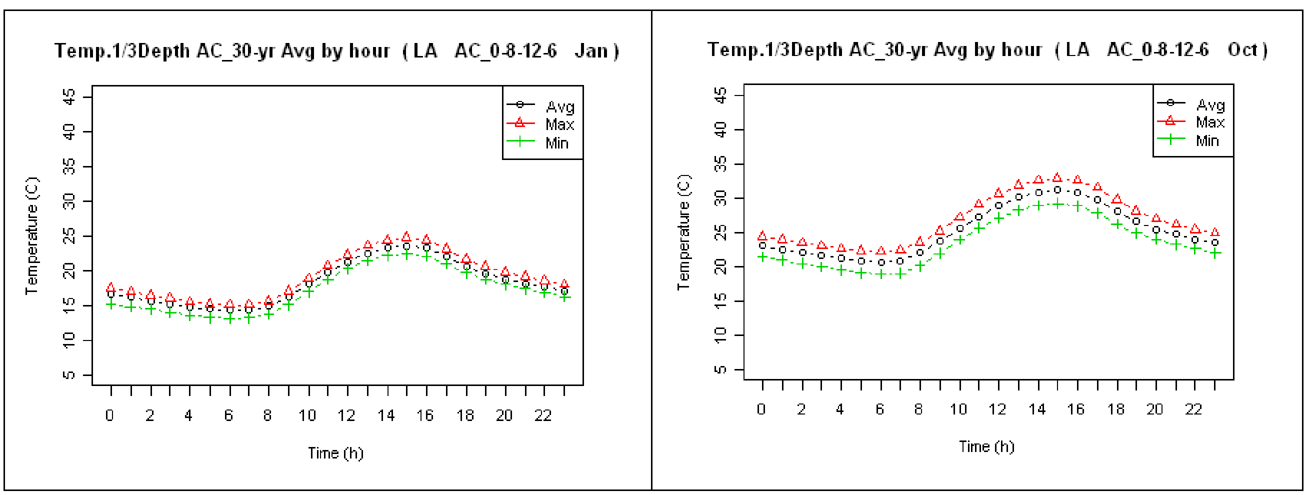


Figure 5.6: Example one-third depth temperatures for hot-mix asphalt pavements.

The stiffness of the hot-mix asphalt was calculated from the master curves for each combination of temperature and load frequency corresponding to loading time from flexural beam frequency sweep testing during the laboratory study *(1)*. The loading frequency at one-third thickness of the hot-mix asphalt layer was calculated using Equation 5.4. The stiffness of each type of hot-mix hot-mix asphalt material was averaged for the thickness of each layer to reduce the number of calculation combinations. Consequently, the stiffness of the hot-mix asphalt used in the calculations was independent of the thickness of the layer. A summary of the master curves and time-temperature relationships used is provided in Table 4.23.

$$freq = \frac{1}{t} = \frac{1}{L/v} = \frac{v}{L} = \frac{v}{D + 2 \times Th/3} \qquad (5.4)$$

Where: t = loading time
L = loading distance
v = loading speed
D = loading tire/pavement contact diameter
Th = thickness of HMA layer

The distresses analyzed included fatigue cracking of the HMA layer associated with the tensile strain at the bottom of the HMA layer, and unbound layer rutting associated with the vertical stresses at the top of the base, subbase (where included) and subgrade. Mechanical responses in terms of tensile strains at the bottom of the HMA layer from different load configurations were determined using the layer elastic model in the *LEAP* software package *(29)*.

Vertical stresses at the top of the subgrade were also calculated using *LEAP*. The stiffness of the cemented subbase (PCC-O) was estimated from flexural strength test results (example for the B2 grading shown in Figure 5.7). Prior to the layer elastic analysis, the stiffness of the granular base was evaluated using non-linear elastic models in the *GT-Pave* software package *(13)*. A range of values for different structural factors were selected for the structural response values of the granular base stiffness (Table 5.4). The Uzan model *(30)* was used to consider the non-linear behavior of the granular base using *GT-Pave*. The procedure proposed by Tutumuller and Thompson *(31)* was used to obtain cross-anisotropic parameters of the granular base for *GT-Pave* (Table 5.5). Based on the results of these calculations, three representative values of granular base stiffness, namely 60 MPa, 90 MPa, and 120 MPa, were chosen for the final structural calculations. The equation for the Uzan model is shown in Equation 5.5.

$$M_R = K_1 (\frac{\theta}{p_0})^{K_2} (\frac{\sigma_d}{p_0})^{K_3} \qquad (5.5)$$

where M_R= resilient modulus (MPa)
θ = $\sigma_1 + \sigma_2 + \sigma_3$=bulk stress (kPa)
σ_d = $\sigma_1 - \sigma_3$=deviator stress (kPa)
p_0 = unit reference pressure (1 kPa or 1 psi)
K_1, K_2, K_2 = material constants obtained from repeated-load triaxial tests performed on granular materials.

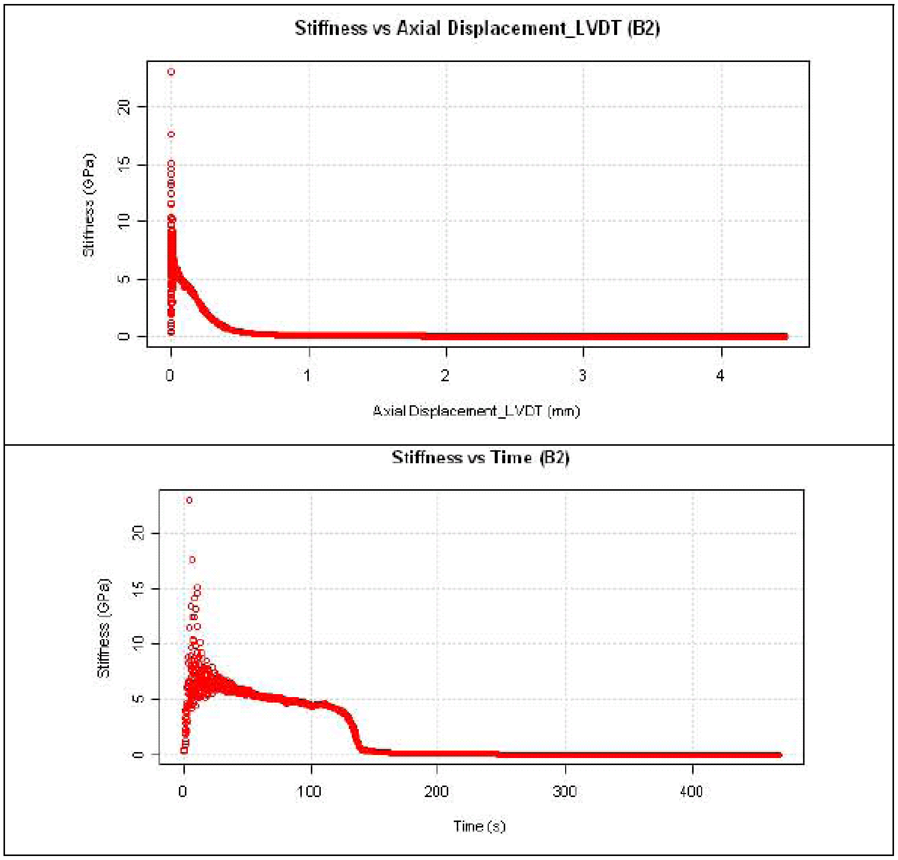


Figure 5.7: Example stiffness test results of PCC-O subbase material (B2 grading).
(Figure shows stiffness time from flexural strength test.)

Table 5.4: Factors for Granular Base Stiffness Calculation in *GT-Pave*

Layer	Stiffness		Thickness	
	MPa	**psi**	**mm**	**inches**
HMA-O (*v*=0.35)	1,000 3,000[a] 5,000	145,138 435,414[a] 725,689	200 300[a] 500	8 12[a] 20
Granular Base (*v*=0.40)	Uzan Model (Table 5.5)		500 1,000[a] 1,500	20 40[a] 60
PCC-O Subbase (*v*=0.20)	6,000	870,827	0 150	0 6
Subgrade (*v*=0.45)	20 50[a] 100	2,903 7,257[a] 14,514	NA	
Load[b] (Single-Single)	**Single Axial Load**		**Tire/Pavement Contact Radius**	
	kN	**lb**	**mm**	**inches**
Tire Pressure p=100psi	68 78 90[a]	15,287 17,535 20,232	125 132 145	4.9 5.2 5.7[a]

Note: [a] -- Default fixed values during combination calculations.
[b] -- Axisymmetric Modeling for calculations.

Table 5.5: Parameters of Uzan Model for Granular Base in *GT-Pave* (Alluvial)

Strain Type	Uzan (Universal) Model (Equation 3.5)					
Vertical	K1-V		K2-V		K3-V	
	(MPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)
	45.0	6,531	4.0	0.628	-1.0	-0.213
Horizontal	K1-H		K2-H		K3-H	
	(MPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)
	3.9	565	22.0	3.128	-19.0	-2.713
Shear	K1-S		K2-S		K3-S	
	(MPa)	(psi)	(kPa)	(psi)	(kPa)	(psi)
	12.6	1,831	6.0	0.828	-3.0	-0.413

The allowable truck traffic (ESAL or TI) during the design life was calculated using a set of factors, including seasonal factor, day/night factor, axle type factor, ESAL factor (the average ESALs per axle), and load bin factor (percent of total axles in each load range) as shown in Table 5.6. The value for each factor was determined based on the statistical analysis of statewide traffic information from the UCPRC/Caltrans Weigh-in-Motion database *(25)*. Axle loads less than half the legal load were ignored in order to keep the number of required calculations to an acceptable value, which was considered reasonable since they contribute very little to the fatigue damage.

Table 5.6: Load Spectrum Factors for HMA-O Structures

Season Factor			Day/Night Factor		Axle Type Factor		ESAL Factor	
Winter	Spring	Summer	Day	Night	Single	Tandem	Single	Tandem
0.33	0.25	0.42	0.45	0.55	0.5	0.5	0.17	0.3

Load Bin Factor			
Single		Tandem	
0.8Legal~Legal (75 kN)	Legal~Max (93 kN)	0.8Legal~Legal (135 kN)	Legal~Max (155 kN)
0.492	0.008	0.46	0.04

Justification for the selection of factors was the same as that for the PCC-O pavement analysis. However, in the seasonal factor, three seasons were used for the HMA pavement calculations to better capture the changes in stiffness that occur in HMA with temperature and the changes in subgrade stiffness and shear strength that control subgrade rutting for a fully permeable pavement.

These data were then used as input in a Miner's Law equation (Equations 5.1 and 5.2) to calculate the fatigue performance of the HMA in terms of an allowable traffic index. The fatigue equations for the three types of HMA-O are shown in Figure 4.32. As with the PCC-O analysis discussed previously, the actual repetitions to failure, *n*, were calculated using the Miner's Law equation to determine the number of ESALs (later converted to Traffic Index, $D = 1.0$ in Equation 5.1) for each combination of HMA-O type, thicknesses, and climate region. The actual repetitions for failure were then converted back into ESALs, and then into Traffic Index.

The ratio of shear stress to shear strength at the top of subgrade was estimated to evaluate the permanent deformation potential of the subgrade. Based on the Federal Aviation Administration (FAA) subgrade soil evaluation report *(14)* and personal communication with Dr. Manuel Bejarano, the shear stress was estimated as half the vertical stress at the top of subgrade. The saturated shear strength for clay was estimated as 7.5 psi (51.7 kPa) (i.e., a worst case scenario, but taking natural confinement in the pavement into consideration). Continued permanent deformation of the subgrade after initial densification under traffic is unlikely when the stress/strength ratio (SR) is less than 0.3 *(29)*, which was the design criteria selected for this project. Continual rutting at a steady rate after initial embedment is expected when the stress/strength ratio is less than 0.7 but greater than 0.3 times the shear strength.

Results from these calculations were plotted to assess the influence of pavement layer combinations on the subgrade stress/strength ratio *(2)*. Stress/strength ratio values for different HMA-O and base thicknesses were then interpolated to identify a range of appropriate layer thicknesses for the heaviest traffic loads and each traffic speed and temperature condition. The structural design selection process involves using both the fatigue life results and the subgrade stress/strength results.

5.3.1 Example Results

Example predictions of the shear stress/strength ratio at the top of the subgrade, which is the main contributing factor to permanent deformation (rutting) of the granular base and subgrade, for various combinations of variables in the experimental design (mix type, subbase inclusion, traffic speed, climatic zone), as well as example plots of the fatigue design life of the same pavements are provided in the Technical Memorandum on Performance Modeling *(2)*. The design of fully permeable pavements with open-graded hot-mix asphalt surfacing using the data collected in this task is discussed in Chapter 6.

Chapter 6 Proposed Structural Design Procedure

6.1 Introduction

A preliminary catalogue-type design procedure based on region (rainfall), storm event design period, design , traffic, design truck speed, surfacing (HMA or PCC), subbase type, and the shear stress-to-shear strength ratio at the top of the subgrade has been developed for preliminary design of fully permeable pavement test sections in California. The example design tables provided in Appendix B through Appendix J were prepared from the computer modeling cases and calculations run as part of the computer modeling task described in Chapter 5. The example hydraulic design table (Appendix B) includes 2-year, 50-year, and 100-year storm design events (considering infiltration and draw down for full storm duration and repeat storm events) for three California regions (Sacramento, Los Angeles, and Eureka, as described in the companion hydrological modeling study *[see Chapter 5 in Reference 4]*). These three storm design events were selected to test the sensitivity of the design to a wide range of events (e.g., effect of storm intensity, storm duration, geometry, draw down, and degree of clogging on infiltration) and were not necessarily intended to be representative of typical Caltrans storm event design procedures. Example design tables for PCC-O and Cast PCC (Appendix C and Appendix D respectively) include two regions (Sacramento and Los Angeles), and two truck speeds (4 mph [7 km/h] and 25 mph [40 km/h]). Example design tables for asphalt concrete (Appendix E through Appendix J) include three different mix designs (HMA-O, RHMA-O, and G125), the same two regions and truck speeds as the PCC options, and two subbase options (with PCC-O subbase and no subbase). All example tables assume a shoulder width of 10 ft (3.0 m) and cover designs up to a TI of 18. The shoulder is considered as lane for drainage design purposes. The design tables have **not** been validated in full-scale experiments and are only intended for the design of experimental test sections.

The proposed procedure generally entails the following:

1. **Select the permeability of the subgrade, region, storm design event period, and number of lanes drained.** For HMA pavements, selection of a subbase option is also required. This information is used to determine the thickness of the gravel base/reservoir layer in terms of hydraulic performance. Consideration should be given to whether occasional overflows are permitted (e.g., during a series of heavy storms on consecutive days, prolonged rainfall, etc.) or not, as this will influence the choice of storm design period and dictate the thickness of the base/reservoir layer. Permeabilities should be measured for each project at a range of depths around the expected depth of the top of the subgrade after excavation of material for the reservoir layer(s). The lowest permeability should be used in the design. It should be noted that clay lenses between silt layers are common in the Central Valley of California, and these will influence permeability.

2. **Select the surface type.** For PCC pavements, slab length, base thickness, design traffic (note that design life is dependent on project circumstances), and design speed are then used to identify the thickness of the surfacing layer. For HMA pavements, base thickness, design traffic, and design speed are used to identify the thickness of the HMA layer. Once the HMA layer thickness has been determined, this and base thickness are used to determine whether the shear stress-to-shear strength ratio at the top of the subgrade is adequate to prevent permanent deformation in the subgrade.

The design method assumes that water should only reach the top of the granular base layer for the design storm, and not be stored in the surface layer during the infiltration period, in order to improve the durability of the surface material.

These preliminary tables can be used for designs of test sections for both shoulder retrofit of highways and for parking lots, maintenance yards, and similar facilities. Two typical cross sections for shoulder retrofits were developed (Figure 6.1 and Figure 6.2) and two contractors asked to review them in terms of constructability. Both contractors indicated that construction appeared to be feasible and that they would be comfortable to bid on projects with similar designs. The selection of the most appropriate structure will depend on whether the existing pavement structure can maintain a vertical cut face equal to the height of the fully permeable pavement shoulder structure or not. If it can, then the cross section shown in Figure 6.2 would be the preferred option, providing a greater reservoir area for the permeable pavement. If the cut face cannot be maintained, then the cross section shown in Figure 6.1 should be used. A drain (e.g. Multi-Flow [www.varicore.com]) between the existing travelled way and the new fully permeable shoulder will need to be installed to allow any water in the travelled way to drain away from the road, while not allowing any water from the permeable area to flow into the pavement structure. The different layer options in the fully permanent pavement structure are shown in Figure 5.1. An impermeable composite liner is included in the diagrams to prevent water flowing sideways from the reservoir layer and causing a slip failure in the embankment. The inclusion of this liner will be project dependent and not always required.

6.2 Example Design Procedures

Four design examples were prepared to illustrate the combined use of the structural and hydraulic design results developed as part of this project:

- An example RHMA-O shoulder retrofit structure with no subbase
- An example HMA-O shoulder retrofit structure with a PCC-O subbase
- An example PCC-O shoulder retrofit structure with no subbase
- An example cast PCC maintenance yard/service road structure with no subbase

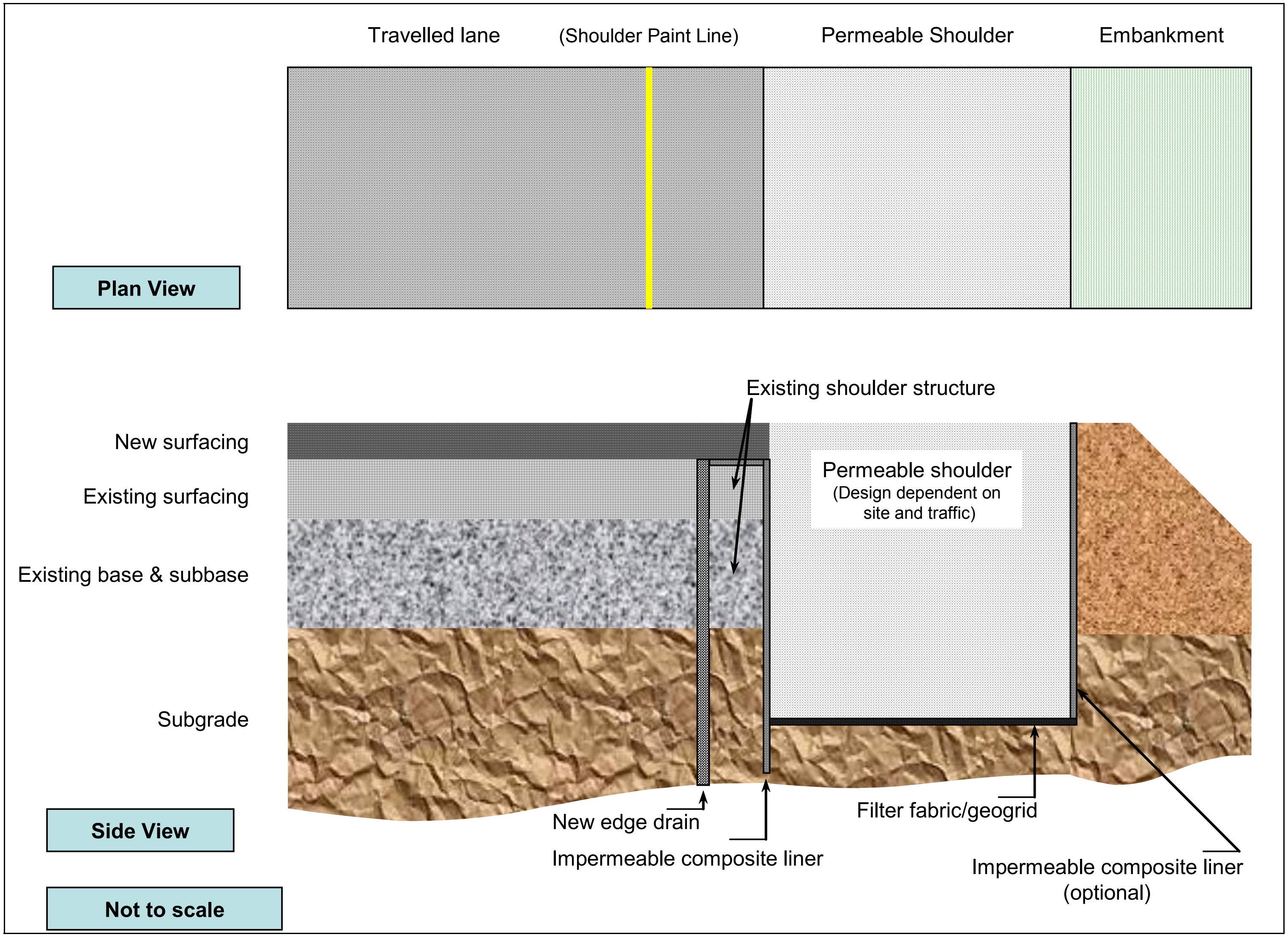


Figure 6.1: Example fully permeable pavement shoulder retrofit #1.
(Portion of existing shoulder is retained to prevent damage to pavement layers and to maintain separation from reservoir)

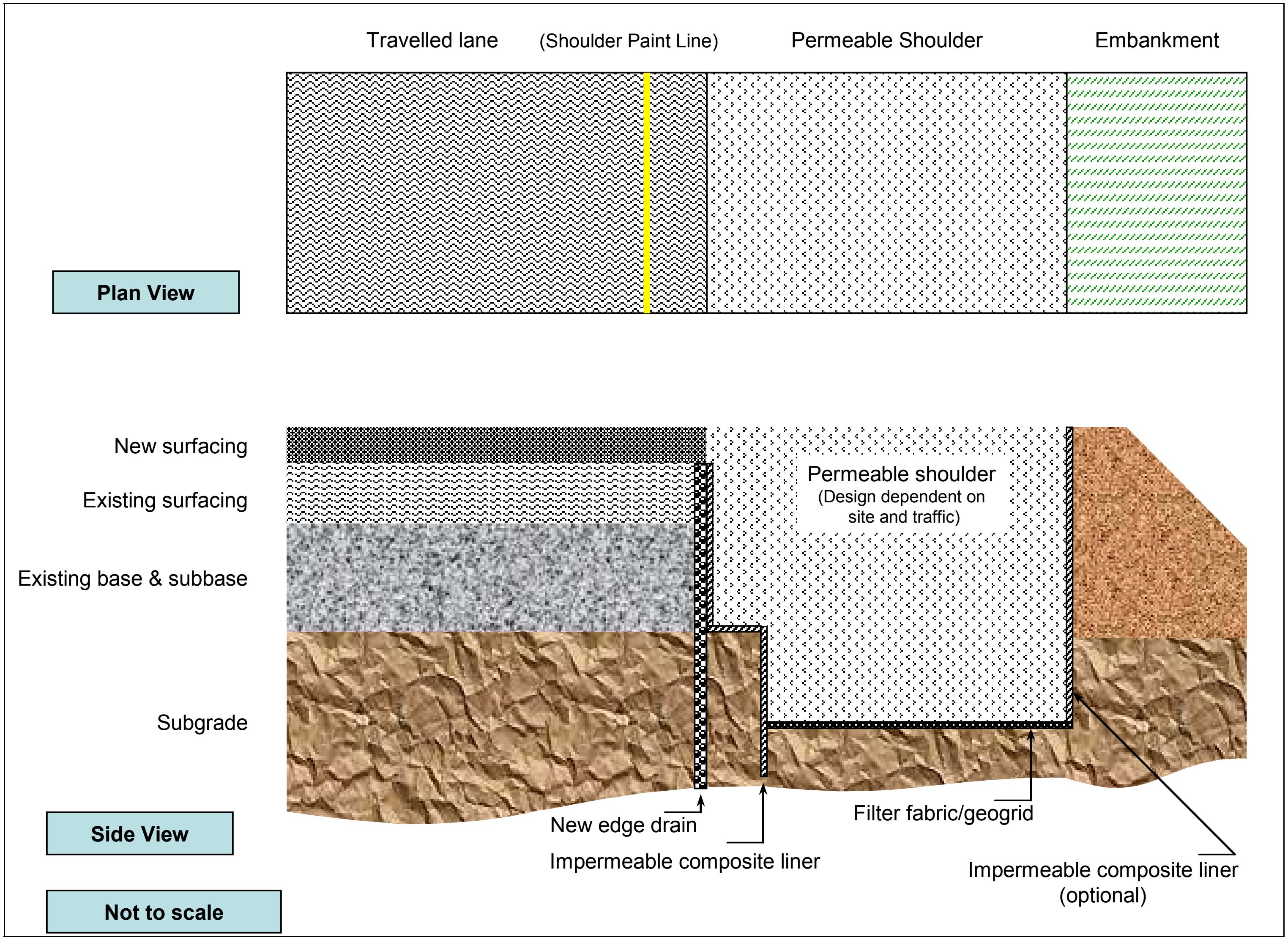


Figure 6.2: Example fully permeable pavement shoulder retrofit #2.
(Permeable shoulder placed against pavement layers with fabric separator)

6.2.1 Example 1: RHMA-O Shoulder Retrofit in Sacramento Area

Project Design

RHMA-O shoulder retrofit of three lanes of highway, without subbase, in Sacramento area:

- Compacted subgrade permeability: 10^{-4} cm/s.
- Storm design: 50 years
- Design Traffic Index: 13 (design life dependent on project circumstances)
- Design truck speed: 4 mph (7 km/h) due to congestion.
- Surface layer: 9.5 mm (3/8 in.) nominal maximum aggregate size (NMAS) open-graded rubberized hot-mix asphalt (RHMA-O)
- Subbase: No subbase

Design Procedure

The design procedure discussed below refers to a series of tables in Appendix B through Appendix J. The tables referred to are provided on the following pages. Cells that are referred to in the tables are circled and highlighted in orange.

- **Step 1: Choose base thickness based on hydraulic performance.**
  Using Table 6.1 (Table B.1 in Appendix B), select the minimum thickness of granular base for a subgrade soil permeability of 10^{-4} cm/s, 50-year design storm, and Sacramento region. These variables require a minimum base/reservoir layer thickness of 680 mm for a shoulder retrofit of a highway draining three lanes plus the shoulder (i.e., select 4 lanes in the table).
- **Step 2: Choose RHMA-O layer thickness based on RHMA-O fatigue damage for given TI.**
  Using Table 6.2 (Table E.5 in Appendix E), select the minimum RHMA-O layer thickness for a base thickness of 700 mm (rounded up from 680 mm from Step 1), and a TI of 13. The minimum required thickness of RHMA-O is 395 mm.
- **Step 3: Check the stress/strength ratio at the top of the subgrade.**
  Using Table 6.3 (Table E.6 in Appendix E), check the shear stress-to-shear strength ratio at the top of subgrade based on the minimum required thickness of granular base of 700 mm and minimum required thickness of RHMA-O of 395 mm. The stress/strength ratio is "G," which implies that the shear stress is less than 0.3 of the shear strength. Consequently, permanent deformation in the subgrade should not be a problem for this pavement design.

Therefore, in this example, the minimum required thickness of granular base is 700 mm and the minimum thickness of RHMA-O is 395 mm for the design requirements and site conditions.

Table 6.1: Example 1 Design Chart for Hydraulic Performance (Appendix B)

Table B.1: Preliminary Granular Base Thickness based on Hydraulic Performance Simulations

Subgrade soil permeability (cm/s)[1]	Storm design (years) (Full storm duration)	Rainfall Region											
		Sacramento (Sac)				Riverside (LA)				Eureka			
		Thickness of Granular Base + PCC-O Subbase (mm)				Thickness of Granular Base + PCC-O Subbase (mm)				Thickness of Granular Base + PCC-O Subbase (mm)			
		Number of highway lanes[2]				Number of highway lanes[2]				Number of highway lanes[2]			
		2	3	4	5	2	3	4	5	2	3	4	5
1.00E-05	2	270	450	600	700	270	400	480	680	600	900	1270	1570
1.00E-04		130	180	250	420	130	150	320	400	350	650	850	1200
1.00E-03		130	130	130	130	130	130	130	130	130	130	130	150
1.00E-05	50	480	700	1050	1250	580	860	1180	1600	800	1270	1720	2150
1.00E-04		190	420	680	950	360	700	950	1350	500	850	1300	1770
1.00E-03		130	130	130	130	130	130	130	230	130	130	220	500
1.00E-05	100	600	800	1150	1430	680	1050	1300	1800	1150	1720	2300	2900
1.00E-04		210	500	750	1070	400	850	1200	1450	830	1300	1890	2500
1.00E-03		130	130	130	150	130	130	150	320	130	220	650	950

[1] Note that draw down times will vary significantly and are dependent primarily on subgrade soil permeabilities, but also on other factors such as number of lanes drained, storm recurrence interval, etc as well. Draw down times could vary between one hour for subgrades with a permeability of 1.00E-03 to several months for subgrades with a permeability of 1.00E-05 and higher. Refer to Reference 4 for discussion on the calculation of drain down times.

[2] The number of highway lanes must include the shoulder. Shoulder width is 10 ft. (3.0 m).

Table 6.2: Example 1 Design Chart for Selecting RHMA-O Thickness (Appendix E)

Table E.5: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County (RHMA-O, no Subbase, E_GB = 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
215	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
230	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
245	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
260	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
275	9.5	9.5	9.5	9.0	9.5	9.5	9.5	9.0	9.5	9.5	9.5	9.5	9.5	9.0	9.5	9.5	9.5	9.0	9.5	9.5	9.5
290	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
305	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
320	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
335	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
350	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
365	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
380	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
395	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
410	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
425	14.0	14.0	14.0	13.5	14.0	14.0	14.0	13.5	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.5	14.5	14.5	14.5
440	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.5	14.5	14.5	14.5	15.0	15.0	15.0	15.0	15.5	15.5
455	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	15.0	15.0	15.0	15.5	15.5	15.5	16.0	16.0	16.0	16.5
470	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.5	15.5	15.5	16.0	16.0	16.5	16.5	17.0	17.0	17.0
485	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	16.0	16.0	16.5	16.5	17.0	17.0	17.5	17.5	18.0	18.0
500	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.5	16.5	17.0	17.0	17.5	18.0	18.0	18.0	18.0	18.0

Table 6.3: Example 1 Design Chart for Checking Stress-to-Strength Ratio at Top of Subgrade

Table E.6: Preliminary Stress-to-Strength Ratio at Top of Subgrade for HMA-O Structure, Sacramento County (RHMA-O, no Subbase, E_GB = 60 MPa, Speed = 7 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	Y	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3= < Stress-to-Strength Ratio < = 0.7; R--Stress-to-Strength Ratio > 0.7

6.2.2 Example 2: HMA-O Shoulder Retrofit in Los Angeles

Project Design

HMA-O shoulder retrofit of five lanes of highway, with 150 mm PCC-O subbase, in Los Angeles area:

- Compacted subgrade permeability: 10^{-5} cm/s.
- Storm design: 2 years
- Design Traffic Index: 18 (design life dependent on project circumstances)
- Design truck speed: 25 mph (40 km/h) simulating speed of traffic diverted onto shoulder.
- Surface layer: 1/2 in. (12.5 mm) nominal maximum aggregate size (NMAS) open-graded hot-mix asphalt (HMA-O)
- Subbase: 6.0 in (150 mm) PCC-O subbase

Design Procedure

- **Step 1: Choose base thickness based on hydraulic performance.**
  Using Table 6.4 (Table B.1 in Appendix B), select the minimum thickness of granular base (i.e., base plus subbase) for a subgrade soil permeability of 10^{-5} cm/s, two-year design storm, and Los Angeles region. These variables require a minimum base/reservoir layer thickness of 680 mm (rounded up to 700 mm) for a shoulder retrofit of a highway draining four lanes plus the shoulder (i.e., 5 lanes in the table). Subtract the thickness of the PCC-O subbase (150 mm), giving a minimum granular base thickness of 550 mm.
- **Step 2: Choose HMA-O layer thickness based on HMA-O fatigue damage for given TI.**
  Using Table 6.5 (Table H.3 in Appendix H), select the minimum HMA-O layer thickness for a minimum granular base thickness of 550 mm (i.e., total base thickness minus subbase thickness) and a TI of 18. The minimum required thickness of HMA-O is 260 mm.
- **Step 3: Check the stress/strength ratio at the top of the subgrade.**
  Using Table 6.6 (Table H.4 in Appendix H), check the shear stress-to-shear strength ratio at the top of subgrade based on the minimum thickness of granular base (i.e., base minus subbase) of 550 mm and minimum thickness of HMA of 260 mm. The stress/strength ratio is "G," which implies that the shear stress is less than 0.3 of the shear strength. Consequently, permanent deformation in the subgrade should not be a problem for this pavement design.

Therefore, in this example, the minimum required combined granular base and subbase thickness is 700 mm (i.e., total thickness of base is 550 mm granular base plus 150 mm PCC-O subbase) and the minimum thickness of HMA-O is 260 mm for the design requirements and site conditions.

Table 6.4: Example 2 Design Chart for Hydraulic Performance (Appendix B)

Table B.1: Preliminary Granular Base Thickness based on Hydraulic Performance Simulations

Subgrade soil permeability (cm/s)[1]	Storm design (years) (Full storm duration)	Rainfall Region											
		Sacramento (Sac)				Riverside (LA)				Eureka			
		Thickness of Granular Base + PCC-O Subbase (mm)				Thickness of Granular Base + PCC-O Subbase (mm)				Thickness of Granular Base + PCC-O Subbase (mm)			
		Number of highway lanes[2]				Number of highway lanes[2]				Number of highway lanes[2]			
		2	3	4	5	2	3	4	5	2	3	4	5
1.00E-05	2	270	450	600	700	270	400	480	680	600	900	1270	1570
1.00E-04		130	180	250	420	130	150	320	400	350	650	850	1200
1.00E-03		130	130	130	130	130	130	130	130	130	130	130	150
1.00E-05	50	480	700	1050	1250	580	860	1180	1600	800	1270	1720	2150
1.00E-04		190	420	680	950	360	700	950	1350	500	850	1300	1770
1.00E-03		130	130	130	130	130	130	130	230	130	130	220	500
1.00E-05	100	600	800	1150	1430	680	1050	1300	1800	1150	1720	2300	2900
1.00E-04		210	500	750	1070	400	850	1200	1450	830	1300	1890	2500
1.00E-03		130	130	130	150	130	130	150	320	130	220	650	950

[1] Note that draw down times will vary significantly and are dependent primarily on subgrade soil permeabilities, but also on other factors such as number of lanes drained, storm recurrence interval, etc as well. Draw down times could vary between one hour for subgrades with a permeability of 1.00E-03 to several months for subgrades with a permeability of 1.00E-05 and higher. Refer to Reference 4 for discussion on the calculation of drain down times.

[2] The number of highway lanes must include the shoulder. Shoulder width is 10 ft. (3.0 m).

Table 6.5: Example 2 Design Chart for Selecting HMA-O Thickness (Appendix H)

Table H.3: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County (G125, with Subbase, E_GB= 60 MPa, Speed = 40 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	13.0	13.0	13.0	12.5	12.5	12.5	12.5	12.5	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
215	14.5	14.5	14.0	14.0	14.0	14.0	14.0	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
230	15.5	15.5	15.5	15.5	15.5	15.0	15.0	15.0	15.0	15.0	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
245	17.0	17.0	17.0	17.0	16.5	16.5	16.5	16.5	16.5	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
260	18.5	18.5	18.0	18.0	18.0	18.0	18.0	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5
275																					
290																					
305																					
320																					
335																					
350																					
365																					
380																					
395																					
410																					
425																					
440																					
455																					
470																					
485																					
500																					

Table 6.6: Example 2 Design Chart for Checking Stress-to-Strength Ratio at Top of Subgrade

Table H.4: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County (G125, with Subbase, E_GB = 60 MPa, Speed = 40 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio < 0.3; Y--0.3 = < Stress-to-Strength Ratio < = 0.7; R--Stress-to-Strength Ratio > 0.7

6.2.3 Example 3: PCC-O Shoulder Retrofit in Sacramento Area

Project Design

PCC-O shoulder retrofit of five lanes of highway, with no subbase, in Sacramento area:

- Compacted subgrade permeability: 10^{-5} cm/s.
- Storm design: 100 years
- Design Traffic Index: 18 (design life dependent on project circumstances)
- Design truck speed: 25 mph (40 km/h) simulating speed of traffic diverted onto shoulder.
- Surface layer: Jointed, no dowels, PCC-O with 12 ft (3.6 m) slab length, and *k*-value of 0.05 MPa. Note that joints are either sawn or formed to link with existing joints in the adjacent lanes.
- Subbase: no subbase

Design Procedure

- **Step 1: Choose base thickness based on hydraulic performance.**
  Using Table 6.7 (Table B.1 in Appendix B), select the minimum thickness of granular base for a subgrade soil permeability of 10^{-5} cm/s, 100-year design storm, and Sacramento region. These variables require a minimum base/reservoir layer thickness of 1,430 mm for a shoulder retrofit of a highway draining four lanes plus the shoulder (i.e., 5 lanes in the table).
- **Step 2: Choose PCC-O slab thickness based on PCC-O fatigue damage for given TI.**
  Using Table 6.8 (Table C.3 in Appendix C), select the minimum PCC-O slab thickness for a slab length of 3,600 mm and TI of 18. The minimum required slab thickness of PCC-O is 280 mm.

Therefore, in this example, the minimum required granular base thickness is 1,450 mm and the minimum thickness of PCC-O is 280 mm for the design requirements and site conditions.

Table 6.7: Example 3 Design Chart for Hydraulic Performance (Appendix B)

Table B.1: Preliminary Granular Base Thickness based on Hydraulic Performance Simulations

Subgrade soil permeability (cm/s)[1]	Storm design (years) (Full storm duration)	Rainfall Region											
		Sacramento (Sac)				Riverside (LA)				Eureka			
		Thickness of Granular Base + PCC-O Subbase (mm)				Thickness of Granular Base + PCC-O Subbase (mm)				Thickness of Granular Base + PCC-O Subbase (mm)			
		Number of highway lanes[2]				Number of highway lanes[2]				Number of highway lanes[2]			
		2	3	4	5	2	3	4	5	2	3	4	5
1.00E-05	2	270	450	600	700	270	400	480	680	600	900	1270	1570
1.00E-04		130	180	250	420	130	150	320	400	350	650	850	1200
1.00E-03		130	130	130	130	130	130	130	130	130	130	130	150
1.00E-05	50	480	700	1050	1250	580	860	1180	1600	800	1270	1720	2150
1.00E-04		190	420	680	950	360	700	950	1350	500	850	1300	1770
1.00E-03		130	130	130	130	130	130	130	230	130	130	220	500
1.00E-05	100	600	800	1150	1430	680	1050	1300	1800	1150	1720	2300	2900
1.00E-04		210	500	750	1070	400	850	1200	1450	830	1300	1890	2500
1.00E-03		130	130	130	150	130	130	150	320	130	220	650	950

[1] Note that draw down times will vary significantly and are dependent primarily on subgrade soil permeabilities, but also on other factors such as number of lanes drained, storm recurrence interval, etc as well. Draw down times could vary between one hour for subgrades with a permeability of 1.00E-03 to several months for subgrades with a permeability of 1.00E-05 and higher. Refer to Reference 4 for discussion on the calculation of drain down times.

[2] The number of highway lanes must include the shoulder. Shoulder width is 10 ft. (3.0 m).

Table 6.8: Example 3 Design Chart for Selecting PCC-O Thickness (Appendix C)

Table C.3: Preliminary TI for PCC Fatigue Damage=1, Sacramento County (PCC-O, k= 0.05 MPa/mm)

PCC Layer Thickness (mm)	Slab Length (mm)															
	3000	3100	3200	3300	3400	3500	3600	3700	3800	3900	4000	4100	4200	4300	4400	4500
250	10.0	9.5	9.5	9.0	9.0	8.5	8.5	8.0	8.0	7.5	7.5	7.0	7.0	6.5	6.5	6.0
260	14.0	13.5	13.0	13.0	12.5	12.0	11.5	11.0	11.0	10.5	10.0	9.5	9.5	9.0	8.5	8.0
270	18.0	17.5	17.0	16.5	16.0	15.5	15.0	14.5	14.0	13.5	13.0	12.5	12.0	11.0	10.5	10.0
280							18.0	17.5	17.0	16.0	15.5	15.0	14.0	13.5	13.0	12.5
290											18.5	17.5	16.5	16.0	15.0	14.5
300														18.5	17.5	16.5
310																18.5
320																
330																
340																
350																
360																
370																
380																
390																
400																
410																
420																
430																
440																
450																
460																
470																
480																
490																
500																

Note: Slab Width = 3.5m

6.2.4 Example 4: Cast PCC Maintenance Yard Service Road in Sacramento Area

Project Design

Cast permeable PCC maintenance yard two-lane service road with no subbase, in Sacramento area:

- Compacted subgrade permeability: 10^{-4} cm/s
- Storm design: 50 years
- Design Traffic Index: 1 (design life dependent on project circumstances)
- Design truck speed: 4 mph (7 km/h) simulating speed of vehicles moving around a maintenance yard
- Surface layer: Cast PCC with 11 ft (3.3 m) slab length, and *k*-value of 0.08 MPa
- Subbase: no subbase

Design Procedure

- **Step 1: Choose base thickness based on hydraulic performance.**
  Using Table 6.9 (Table B.1 in Appendix B), select the minimum thickness of granular base for a subgrade soil permeability of 10^{-4} cm/s, 50-year design storm, and Sacramento region. This requires a minimum base/reservoir layer thickness of 200 mm (i.e., rounded up from 190 mm) for the service road (i.e., 2 lanes in the table).
- **Step 2: Choose Cast PCC slab thickness based on PCC-O Fatigue Damage for Given TI.**
  Using Table 6.10 (Table D.3 in Appendix D), select the minimum cast PCC slab thickness for a slab length of 3,300 mm and TI of 1. The minimum slab thickness of cast PCC is 350 mm.

Therefore, in this example, the minimum required granular base thickness is 200 mm and the minimum thickness of cast PCC is 350 mm for the design requirements and site conditions.

6.2.5 Accelerated Pavement Test and Pilot Study Test Section Design

Specific designs for accelerated pavement test and pilot study test sections have not been developed. These can be designed using the approach described in this chapter once test locations and test parameters have been indentified.

Table 6.9: Example 4 Design Chart for Hydraulic Performance (Appendix B)

Table B.1: Preliminary Granular Base Thickness based on Hydraulic Performance Simulations

Subgrade soil permeability (cm/s)[1]	Storm design (years) (Full storm duration)	Rainfall Region											
		Sacramento (Sac)				Riverside (LA)				Eureka			
		Thickness of Granular Base + PCC-O Subbase (mm)				Thickness of Granular Base + PCC-O Subbase (mm)				Thickness of Granular Base + PCC-O Subbase (mm)			
		Number of highway lanes[2]				Number of highway lanes[2]				Number of highway lanes[2]			
		2	3	4	5	2	3	4	5	2	3	4	5
1.00E-05	2	270	450	600	700	270	400	480	680	600	900	1270	1570
1.00E-04		130	180	250	420	130	150	320	400	350	650	850	1200
1.00E-03		130	130	130	130	130	130	130	130	130	130	130	150
1.00E-05	50	480	700	1050	1250	580	860	1180	1600	800	1270	1720	2150
1.00E-04		190	420	680	950	360	700	950	1350	500	850	1300	1770
1.00E-03		130	130	130	130	130	130	130	230	130	130	220	500
1.00E-05	100	600	800	1150	1430	680	1050	1300	1800	1150	1720	2300	2900
1.00E-04		210	500	750	1070	400	850	1200	1450	830	1300	1890	2500
1.00E-03		130	130	130	150	130	130	150	320	130	220	650	950

[1] Note that draw down times will vary significantly and are dependent primarily on subgrade soil permeabilities, but also on other factors such as number of lanes drained, storm recurrence interval, etc as well. Draw down times could vary between one hour for subgrades with a permeability of 1.00E-03 to several months for subgrades with a permeability of 1.00E-05 and higher. Refer to Reference 4 for discussion on the calculation of drain down times.

[2] The number of highway lanes must include the shoulder. Shoulder width is 10 ft. (3.0 m).

Table 6.10: Example 4 Design Chart for Selecting Cast PCC Thickness (Appendix D)

Table D.4: Preliminary TI for PCC Fatigue Damage=1, Sacramento County
(Cast Slab, k= 0.08 MPa/mm)

PCC Layer Thickness (mm)	Slab Length (mm)															
	3000	3100	3200	3300	3400	3500	3600	3700	3800	3900	4000	4100	4200	4300	4400	4500
250	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
260	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
270	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
280	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
290	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
300	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
310	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
320	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0
330	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0
340	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0
350	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0
360	3.0	3.0	2.5	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.0	1.0	0.5	0.5	0.5	0.0
370	5.0	4.5	4.5	4.0	3.5	3.5	3.0	3.0	2.5	2.0	2.0	1.5	1.5	1.0	0.5	0.5
380	7.0	6.5	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0	2.5	2.5	2.0	1.5	1.0	0.5
390	8.5	8.0	7.5	7.0	6.5	6.0	5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
400	10.5	10.0	9.5	8.5	8.0	7.5	7.0	6.0	5.5	5.0	4.0	3.5	3.0	2.5	1.5	1.0
410	12.5	12.0	11.0	10.5	9.5	9.0	8.0	7.5	6.5	6.0	5.0	4.0	3.5	2.5	2.0	1.0
420	14.5	13.5	13.0	12.0	11.0	10.0	9.5	8.5	7.5	6.5	6.0	5.0	4.0	3.0	2.5	1.5
430	16.5	15.5	14.5	13.5	12.5	11.5	10.5	9.5	8.5	7.5	6.5	5.5	4.5	3.5	2.5	1.5
440	18.5	17.5	16.0	15.0	14.0	13.0	12.0	10.5	9.5	8.5	7.5	6.0	5.0	4.0	3.0	2.0
450			18.0	16.5	15.5	14.0	13.0	12.0	10.5	9.5	8.0	7.0	5.5	4.5	3.0	2.0
460				18.5	17.0	15.5	14.0	13.0	11.5	10.0	9.0	7.5	6.0	5.0	3.5	2.0
470					18.5	17.0	15.5	14.0	12.5	11.0	9.5	8.0	7.0	5.5	4.0	2.5
480						18.5	16.5	15.0	13.5	12.0	10.5	9.0	7.5	5.5	4.0	2.5
490							18.0	16.5	14.5	13.0	11.0	9.5	8.0	6.0	4.5	3.0
500								17.5	15.5	14.0	12.0	10.0	8.5	6.5	5.0	3.0

Note: Slab Width = 3.5m

Chapter 7 Life-Cycle Considerations

7.1 Introduction

In this project, life-cycle analysis is defined to include a cost analysis and an environmental assessment. For the cost analysis, a preliminary Life-Cycle Cost Analysis (LCCA) is undertaken to evaluate the net present value (NPV) economic costs of each project alternative, while in the environmental assessment part, a preliminary Life-Cycle Assessment (LCA) is performed to understand the environmental impacts of each alternative. As decision-assisting tools, LCCA and LCA both provide information for decision making, but not the decision itself. Conclusions from both these analyses need to be coordinated to support a final decision when choosing an appropriate best management practice (BMP) for stormwater management.

7.2 Life-Cycle Cost Analysis

7.2.1 Introduction

LCCA allows the costs associated with each project alternative to be equitably compared against one another. To perform an LCCA, the future cost is converted to present value through a discount rate, thereby taking the time value of money into account. Since LCCA should be performed on alternatives which carry out the same function, it is assumed that fully permeable pavements and currently available treatment BMPs will have the same performance in accommodating stormwater runoff and in the treatment of pollutants from runoff.

Two fully permeable pavement scenarios are considered in this chapter:

- **Shoulder retrofit for high-speed highway scenario**: Comparison of conventional pavement shoulders on a two-lane highway and a six-lane highway (three lanes in each direction) with a conventional treatment BMP versus a fully permeable pavement shoulder. The example project length was one direction for one lane-mile (1,600 m) and the shoulder is 10 ft (3.0 m) wide.
- **Low-speed highway or parking lot/maintenance yard scenario**: Conventional pavement for low-speed traffic with a conventional treatment BMP versus fully permeable pavement. The example project has an area of 107,000 ft^2 (10,000 m^2).

These scenarios were considered for an example project in the Sacramento region to provide an example for LCCA for fully permeable pavement and comparison with LCCA for other BMPs.

7.2.2 Basic Elements of Life-Cycle Cost Analysis

The basic elements of life-cycle cost analysis include analysis period, discount rate, costs, and salvage value. Each element is briefly discussed in the following sections.

Analysis Period

The analysis period is a fundamental component of the life-cycle cost analysis process and is essentially a policy decision dependent on the agency, circumstances, and infrastructure involved. It should be long enough to include the maintenance, rehabilitation, and necessary reconstruction activities that are a consequence of the initial strategy selected, but the period should not fall outside what can be reliably predicted into the future from historical records. Furthermore, any costs anticipated far into the future that are discounted back to present worth will become negligible in terms of the other costs earlier on in the life-cycle. The analysis period is usually longer than the design life.

A general rule to determine the analysis period is approximately 1.5 times the design life of the strategy selected. The recommended analysis periods for comparing alternatives from the California *Life-Cycle Cost Analysis Procedures Manual* are listed in Table 7.1 *(32)*. These periods vary from 20 to 55 years, depending on the different pavement service life. Since this project needs to compare the fully permeable pavement and conventional treatment BMPs, the analysis period is constrained by the information of these treatment BMPs. The design life for BMPs currently used in California is generally fixed at 20 years *(33,34)*. When it has reached this design life, the treatment BMP is demolished and a new treatment BMP is constructed. Therefore, to make an equitable comparison between fully permeable pavement (which would typically have a project life of more than 20 years) and currently used BMPs, an analysis period of 40 years was used in this study. It was assumed that a specific treatment BMP would be constructed twice during this period, and that the surface of the fully permeable pavement would be replaced every 10 to 20 years. The same 40-year analysis period was used for the comparison of all alternatives. For the purposes of this study, the costs of installing and maintaining treatment BMPs were annualized to simplify comparisons.

Table 7.1: Recommended Analysis Periods for Comparing Alternatives

Alternative Design Life	CAPM[1]	10-Year	15-20 Year	20-40 Year
	Analysis Period in Years			
CAPM[1]	20	20	20	-
10-Year	20	20	35	55
15 to 20-Year	20	35	35	55
20 to 40-Year	-	55	55	55

[1] Capital Asset Preventative Maintenance

Discount Rate

The discount rate takes the time value of money into account and is essentially the difference between inflation and the interest rate. The selection of an appropriate discount rate is critical since it essentially determines the portion of future cost (maintenance, rehabilitation, and reconstruction) relative to the cost of initial construction. If the discount rate is set too low, then the future cost will dominate the total cost. Conversely, if the discount rate is set too high, the initial construction cost will dominate the total cost. Caltrans typically uses four percent in its LCCA studies. In this project, zero percent and four percent discount rates were both used for calculation to assess the influence that this parameter has on the calculation outcome.

Salvage Value

Salvage value is used to make equitable comparisons between alternative pavement designs with different service lives. The salvage value of a pavement represents its economic value at the end of the analysis period. The Federal Highway Administration (FHWA) characterizes the salvage value as the cost of the last rehabilitation activity multiplied by the ratio of years until the end of the analysis period to the years until the next activity (e.g., rehabilitation or reconstruction) beyond the analysis period. This is essentially a straight line depreciation of the pavement asset *(35)*. Salvage values are typically small in comparison with the other costs associated with the life-cycle of a pavement. The Caltrans LCCA software used in this study also adopts a straight line depreciation to the end of the project's design life. In this study, the salvage value at the end of the analysis period was assumed to be zero because the analysis period is either four times or two times the design life.

Costs

The cost of a project usually includes agency cost and user cost. Agency costs include initial construction, maintenance and rehabilitation, salvage value at the end of the design period (discussed in the previous section), administration, traffic control, etc. User costs are basically the costs that the road user incurs, including vehicle operating costs, time delay cost, damage to freight when transporting goods on rough roads, etc. However, because of the high uncertainty in calculating user costs and given that user cost is unlikely to change significantly between the choices of BMP, only agency costs were analyzed in this project.

Mr. Bill Clarkson of Teichert Construction in Sacramento, California, volunteered to develop cost estimates for each of the example scenarios. Thickness designs were taken from the structural design calculations for open-graded hot-mix asphalt (HMA-O), open-graded portland cement concrete (PCC-O) and cast PCC pavements. The agency cost estimates from Teichert Construction include the following components:

- Mobilization of equipment
- Temporary K-Rail construction (only for shoulder retrofit)
- Roadway excavation
- Pavement material and construction (These costs include conventional HMA, rubberized hot-mix asphalt [RHMA-O], PCC-O, granular base, PCC-O subbase, Class-2 aggregate base [only with conventional HMA surface], and relevant construction costs.)
- Other material and placement (These costs include geofabrics [Mirafi NT100 Fabric, Mirafi 140NC Fabric], drainage systems [Multiflow 1200 Drainage Media, and Multiflow 12003 Outlet], membrane placement, and drainage placement).

The cost of scheduled maintenance and rehabilitation for conventional HMA was determined using the Caltrans *Life-Cycle Cost Analysis Procedures Manual (32)*. The annual maintenance schedule for fully permeable pavement was determined from a study performed by the United States Environmental Protection Agency (U.S. EPA) *(36)*, which suggests vacuum sweeping twice per year. The cost of vacuum sweeping is about \$400 to \$500 per year per half acre in total *(37)*. Therefore, an annual maintenance cost of \$0.02/ft^2 (\$0.22/m^2) was used for fully permeable pavement. Design lives of 10 years and 20 years were both used for calculation to assess the influence of this parameter on the calculation outcome, and to assist with designing cost-effective fully permeable pavement structures.

The construction cost and operation and maintenance (O&M) cost for unit volume of annual runoff treatment capacity for the treatment BMPs in this project were imported from the Caltrans report *BMP Retrofit Pilot Program – Final Report (33)* and the Caltrans' technical memorandum *BMP Operation and Maintenance Cost Analysis (34)*, both of which are based on individual BMP projects (including Wet Basin, Austin Sand Filter, etc) that were evaluated in Caltrans Districts 7 and 11. The total construction, operation, and maintenance cost were acquired by multiplying the unit cost (sourced from the above mentioned reports) by the annual runoff volume from a particular pavement section to obtain the total cost for the BMPs. The cost information from these reports is based on 1999 dollars, which was converted to 2007 dollars using a Consumer Price Index (CPI) conversion factor of 0.804 *(38)*. Table 7.2 shows an example runoff calculation for the Sacramento area, sourced from the results of the companion project *(4)* to this study which investigated hydraulic performance of fully permeable pavements.

It must be emphasized that the example cost comparisons included in this technical memorandum are based on current available relevant information for the Sacramento area, which is limited, and that these example comparisons are also likely to vary widely over time and between regions, and will depend on the specific constraints of a given project. These constraints will include but are not limited to the distance from available materials, traffic control requirements, site conditions, number of contractors interested in building these types of pavements, etc.

Table 7.2: Computation of Annual Runoff Volume for Different Scenarios in Sacramento Area

Input Parameter	Value
Annual rainfall for Sacramento	0.43 m/yr
Shoulder width	3.0 m
Lane width	3.7 m
Project length	1,600 m
Runoff coefficient[1]	1
Drained area: 2-lane road with shoulders (one direction)	10,780 m^2
Drained area: 6-lane road with shoulders (one direction)	20,434 m^2
Drained area: Maintenance yard/parking lot	10,000 m^2
Runoff Volume: 2-lane road with shoulders (one direction)	4,636 m^3/yr
Runoff Volume: 6-lane road with shoulder (one direction)	8,787 m^3/yr
Runoff Volume: Maintenance yard	4,300 m^3/yr
[1] Highway is highly impervious	

7.2.3 LCCA Analysis Software

The Caltrans *RealCost* LCCA software *(32)* was used for calculating the pavement-related costs. Inputs include agency cost of each activity (including initial construction, maintenance, and rehabilitation, and reconstruction), design life, annual maintenance cost, discount rate, and analysis period. Output from the analysis is the Net Present Value (NPV), which is used to compare difference project alternatives.

7.2.4 LCCA Calculations

In this project, the standard engineering economics method was used to calculate the NPV. Each cash flow is discounted back to its present value, and the sum of these values is the NPV. The function for calculating present value is shown in Equation 7.1. The Caltrans *RealCost* LCCA software *(32)* was used to check the results.

$$NPV = \sum \frac{R_t}{(1+\alpha)^t} \tag{7.1}$$

Where: t is the time of cash flow, α is the discount rate, and R_t is the net cash flow.

<u>Conventional HMA Pavement with BMP</u>

Table 7.3 shows the BMP cost per cubic meter of water processed for a range of currently used BMPs. Pavement construction costs are not included as it is assumed that the BMPs are constructed adjacent to existing pavements. Construction and operation and maintenance cost data are only available for certain treatments and consequently only those treatment BMPs with both these costs were used for the life-cycle cost calculation. Table 7.4 shows the NPV for different BMPs for the first year of construction per cubic meter of water processed. In the 40-year analysis period, a treatment BMP will be constructed twice (i.e., in the first year and in the 21st year), based on a 20-year design life. These two construction events and all follow-up maintenance and operation are assumed the same in both design periods. In each 20-year period, the present value of the total cost was calculated for the first year of this period, and then these values were discounted to the first year of the 40-year analysis period to get final NPVs. These NPVs were then multiplied by the annual volume of runoff from the one-mile pavement section example in the Sacramento area (see Table 7.2) to obtain the total NPVs, also shown in Table 7.4 (last column). It is clear from Table 7.4 that there is a significant difference in the life-cycle costs of the different technologies over the design life of a pavement. Table 7.5 provides a summary of the highest and lowest NPVs for the three design scenarios over a 40-year analysis period. It should be noted that certain treatment BMPs may not be feasible in certain locations (e.g., there may not be sufficient space to construct a specific BMP technology), and local costs may differ from those used in these example comparisons.

Fully Permeable Pavement

The three pavement design scenarios included in the structural analysis part of this project, namely open-graded asphalt, open-graded concrete, and jointed plain concrete with holes cast into it were each costed separately (Table 7.6). The costs of removing any existing stormwater drainage infrastructure were not considered. The highest and lowest NPVs for each scenario were then extracted from the cost analysis for comparison with conventional asphalt pavement with a BMP, as shown in Table 7.7. The type of pavement used in Table 7.3 through Table 7.5 were not stated because of the lack of historical cost data for the different kinds of pavement structure, and were intended to only provide a reasonable range for comparison with the conventional pavements with a currently available BMP technology. The costs in Table 7.6 and Table 7.7 indicate that there is not a significant difference in the life-cycle costs of the three different surfacings, and that choice of surfacing may be driven by operational issues rather than cost issues.

7.2.5 Comparison of Life-Cycle Costs

A comparison of the life-cycle cost estimates of currently available BMPs installed adjacent to existing pavements (Table 7.4) with those of fully permeable pavements (Table 7.6) indicate that the fully permeable pavement appears to be more cost effective than currently available BMPs in most instances for both the shoulder retrofit and maintenance yard/parking lot scenarios (Figure 7.1). Fully permeable shoulders draining single lanes were on the order of two-thirds the cost of the lowest cost currently available BMP; fully permeable shoulders draining three lanes were on the order of half the cost; while fully permeable maintenance yards/parking lots were of a similar cost when lowest costs were compared, assuming that the fully permeable system is replaced after 10 years in all instances. If highest costs are compared, fully permeable pavement systems are significantly more cost-effective than currently available BMP technologies. It must be emphasized again that these cost comparisons are intended as examples for order of magnitude comparison only, that costs will vary depending on a number of factors (e.g., depth of excavation required, thickness of aggregate reservoir, haul distance for reservoir aggregate, haul distance for disposal of excess excavated material, contractor establishment costs, contractor experience, traffic control, traffic delays, etc.) and that the findings will need to be validated in full-scale field experiments. A project-specific LCCA should be performed for each project to ensure that appropriate technologies are compared.

Table 7.3: Currently Available BMP Cost per Cubic Meter of Water Treated

BMP Type	Average Construction Cost		Construction Cost per m^3 Water		Annual O and M Cost (2007$)	Annual O and M Cost per m^3 Water (2007$)
	1999$	2007$	1999$	2007$		
Wet Basin	448,412	557,726	1,731	2,153	21,206	40
Multi-chambered Treatment Train	275,616	342,806	1,875	2,332	7,147	14
Oil-Water Separator	128,305	159,583	1,970	2,450	No data	No Data
Delaware Sand Filter	230,145	286,250	1,912	2,378	2,497	5
Storm-Filter	305,355	379,795	1,572	1,955	No data	No Data
Austin Sand Filter - Concrete	242,799	301,989	1,447	1,800	2,553	5
Biofiltration Swale	57,818	71,913	752	935	4,124	8
Biofiltration Strip	63,037	78,404	748	930	671	1
Infiltration Trench	146,154	181,784	733	912	1,982	4
Extended Detention Basin	172,737	214,847	590	734	4,999	9
Infiltration Basin	155,110	192,923	369	459	3,728	7
Drain Inlet Insert	370	460	10	12	No data	No Data
Austin Sand Filter - Earthen	No data	No data	No data	543	3,129	6
Traction Sand Trap	No data	No data	No data	1,860	1,823	3
Gross Solids Removal Device	No data	No data	No data	760	4,963	9

Table 7.4: NPV of Currently Available BMPs per Cubic Meter of Water Treated (in 2007$)

BMP Type	Number of Construction Events in Analysis Period[1]	Analysis for Life of One Design Period (20-Year Design[1])			Analysis for 40-Year Period
		Initial Construction[2] ($)	Annual O and M Cost[2] ($)	NPV in the Year of Construction[2] ($)	Initial Construction[2] ($)
Wet Basin	2	2,153	40	2,714	3,952
Multi-chambered Treatment Train	2	2,332	14	2,528	3,682
Delaware Sand Filter	2	2,378	5	2,444	3,560
Austin Sand Filter - Concrete	2	1,800	5	1,867	2,719
Biofiltration Swale	2	935	8	1,044	1,521
Biofiltration Strip	2	930	1	948	1,381
Infiltration Trench	2	912	4	964	1,404
Extended Detention Basin	2	734	9	866	1,261
Infiltration Basin	2	459	7	557	812
Austin Sand Filter - Earthen	2	543	6	625	911
Traction Sand Trap	2	1,860	3	1,899	2,766
Gross Solids Removal Device	2	760	9	892	1,299
Oil-Water Separator	2	2,450	No data	No data	No data
Storm-Filter	2	1,955	No data	No data	No data
Drain Inlet Insert	2	12	No data	No data	No data

[1] Assumed that BMPs are reconstructed after 20 years [2] All costs are based on unit volume (m^3) of water treated annually.

Table 7.5: Summary of Currently Available BMP NPV Costs for Total Runoff (Sacramento Example)

(Conventional HMA pavement with highest and lowest cost treatment BMP over 40-year analysis period)

Application	Traffic Index	Pavement (x $1,000)	High BMP (x $1,000)	Low BMP (x $1,000)	High Total (x $1,000)	Low Total (x $1,000)
BMP draining 1 lane	N/A	Existing	18,321	3,764	-	-
BMP draining 3 lanes	N/A	Existing	34,728	7,134	-	-
Maintenance yard or rest stop	7	1,110	16,995	3,491	18,105	4,601
	11	1,720	16,995	3,491	18,715	5,211

Notes
1. These cost values are Net Present Values (NPV) in life-cycle cost calculation.
2. The calculation of pavement cost is based on a 4% discount rate and recommended cost and schedules of M&R of pavements in Caltrans LCCA manual.
3. BMP is assumed to have a 20-year design life.

Table 7.6: NPV of Fully Permeable Pavement for Total Runoff (Sacramento Example)

Application	Traffic Index	Surface Type	Subbase Structure	Surface Thickness (mm)	Granular Base (mm)	Subbase (mm)	Initial Construction (x $1,000)	Remove & Replace (x $1,000)	Annual Maintenance (x $1,000)	10-Year, 0% (x $1,000)	10-Year, 4% (x $1,000)	20-Year, 0% (x $1,000)	20-Year, 4% (x $1,000)
Highway shoulder retrofit, 1 lane	7	RHMA-O	PCC-O	200	530	150	1,323	577	2	3,139	2,198	1,986	1,631
			No subbase	200	680	0	1,146	577	2	2,962	2,021	1,809	1,454
		PCC-O	PCC-O	250	530	150	1,496	801	2	3,986	2,694	2,383	1,906
			No subbase	250	680	0	1,319	801	2	3,809	2,518	2,207	1,729
		Cast PCC	PCC-O	420	530	150	2,500	0	2	2,586	2,544	2,586	2,544
			No subbase	420	680	0	2,323	0	2	2,409	2,367	2,409	2,367
	11	RHMA-O	PCC-O	260	530	150	1,417	683	2	3,552	2,445	2,186	1,773
			No subbase	305	680	0	1,310	763	2	3,685	2,453	2,159	1,702
		PCC-O	PCC-O	270	530	150	1,533	846	2	4,157	2,796	2,465	1,963
			No subbase	270	680	0	1,356	846	2	3,980	2,619	2,288	1,786
		Cast PCC	PCC-O	460	530	150	2,523	0	2	2,609	2,567	2,609	2,567
			No subbase	460	680	0	2,346	0	2	2,432	2,390	2,432	2,390
Highway shoulder retrofit, 3 lane	7	RHMA-O	PCC-O	200	1,000	150	1,519	577	2	3,335	2,394	2,182	1,827
			No subbase	200	1,150	0	1,338	577	2	3,153	2,212	2,000	1,645
		PCC-O	PCC-O	250	1,000	150	1,691	801	2	4,181	2,889	2,578	2,101
			No subbase	250	1,150	0	1,509	801	2	3,999	2,708	2,396	1,919
		Cast PCC	PCC-O	420	1,000	150	2,694	0	2	2,779	2,738	2,779	2,738
			No subbase	420	1,150	0	2,512	0	2	2,598	2,556	2,598	2,556
	11	RHMA-O	PCC-O	260	1,000	150	1,613	683	2	3,748	2,641	2,382	1,969
			No subbase	305	1,150	0	1,501	763	2	3,877	2,644	2,350	1,893
		PCC-O	PCC-O	270	1,000	150	1,728	846	2	4,352	2,991	2,660	2,158
			No subbase	270	1,150	0	1,546	846	2	4,170	2,809	2,478	1,976
		Cast PCC	PCC-O	460	1,000	150	2,717	0	2	2,803	2,761	2,803	2,761
			No subbase	460	1,150	0	2,535	0	2	2,621	2,579	2,621	2,579

Application	Traffic Index	Surface Type	Subbase Structure	Surface Thickness (mm)	Granular Base (mm)	Subbase (mm)	Initial Construction (x $1,000)	Remove & Replace (x $1,000)	Annual Maintenance (x $1,000)	10-Year, 0% (x $1,000)	10-Year, 4% (x $1,000)	20-Year, 0% (x $1,000)	20-Year, 4% (x $1,000)
Maintenance yard, rest stop, or parking lot	7	RHMA-O	PCC-O	200	530	150	1,593	635	4	3,664	2,593	2,394	1,968
			No subbase	200	680	0	1,277	635	4	3,348	2,277	2,077	1,652
		PCC-O	PCC-O	250	530	150	1,694	826	4	4,338	2,969	2,686	2,156
			No subbase	250	680	0	1,377	826	4	4,022	2,653	2,369	1,840
		Cast PCC	PCC-O	420	530	150	3,398	0	4	3,564	3,483	3,564	3,483
			No subbase	420	680	0	3,082	0	4	3,247	3,167	3,247	3,167
		HMA[2]	No subbase	120	370	0	609			1,721	1,110		
	11	RHMA-O	PCC-O	260	530	150	1,747	808	4	4,338	2,996	2,721	2,201
			No subbase	305	680	0	1,546	938	4	4,526	2,982	2,649	2,059
		PCC-O	PCC-O	270	530	150	1,742	1,194	4	5,488	3,546	3,101	2,371
			No subbase	270	680	0	1,425	1,194	4	5,171	3,229	2,784	2,055
		Cast PCC	PCC-O	460	530	150	3,435	0	4	3,600	3,520	3,600	3,520
			No subbase	460	680	0	3,119	0	4	3,284	3,204	3,284	3,204
		HMA[2]	No subbase	160	560	0	829			2332	1,720		

Notes
1. The cost values are Net Present Values (NPV) in life-cycle cost calculation.
2. The cost and schedule for maintenance and replacement are from the Caltrans LCCA manual, which are not listed here. They are not necessarily 10-year or 20-year based design life.
3. 10 years and 20 years are the surface layer replacement period.

Table 7.7: Summary of Fully Permeable Pavement NPV Costs for Total Runoff (Sacramento Example)

(Fully permeable pavement with highest and lowest cost over 40-Year Design)

Application	Traffic Index	Cost	10-Year Replacement (x $1,000)		20-Year Replacement (x $1,000)	
Highway shoulder retrofit, 1 lane	7	High	PCC-O	2,694	Cast PCC	2,544
		Low	RHMA-O	2,021	RHMA-O	1,454
	11	High	PCC-O	2,796	Cast PCC	2,567
		Low	Cast PCC	2,390	RHMA-O	1,702
Highway shoulder retrofit, 3 lane	7	High	PCC-O	2,889	Cast PCC	2,738
		Low	RHMA-O	2,212	RHMA-O	1,645
	11	High	PCC-O	2,991	Cast PCC	2,761
		Low	Cast PCC	2,579	RHMA-O	1,893
Maintenance yard or rest stop	7	High	Cast PCC	3,483	Cast PCC	3,483
		Low	RHMA-O	2,277	RHMA-O	1,652
	11	High	PCC-O	3,546	Cast PCC	3,520
		Low	RHMA-O	2,982	PCC-O	2,055

Notes
1. These cost values are Net Present Values (NPV) in life-cycle cost calculation.
2. The calculation of pavement is based on a 4% discount rate
3. All cast PCC concrete pavements in this table have a 40-year life. 10-year and 20-year replacement are only for RHMA-O and PCC-O.
4. Conventional HMA is not included.

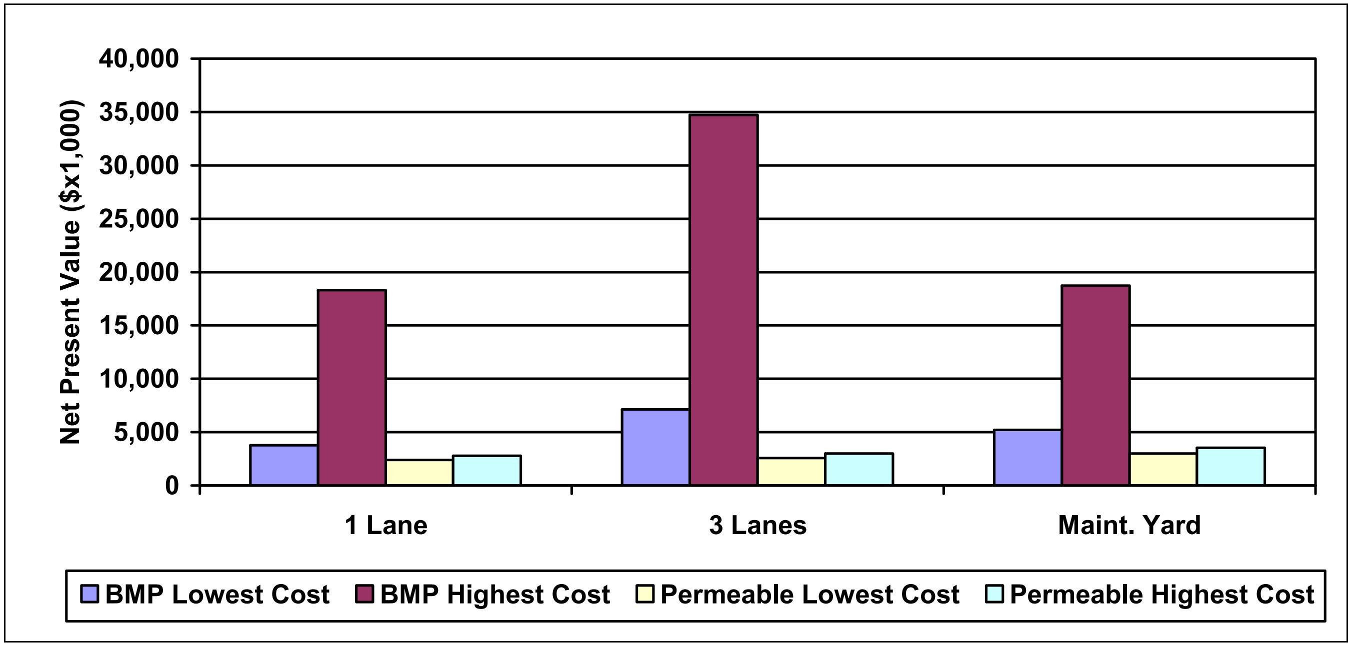


Figure 7.1: NPV comparison for BMP and Fully Permeable Pavement (Low and High Cost Options).
(for TI 11, 40 year analysis, BMP is replaced every 20 years, permeable pavement is replaced every 10years)

7.3 Framework for Environmental Life-Cycle Assessment

7.3.1 Introduction

Life-cycle assessment (LCA) is an approach for assessing the life-cycle of a product from cradle to grave, and investigates and evaluates all the inputs and outputs from raw material production to the final end-of-life phase of the product. It provides a comprehensive and defendable means of evaluating the total environmental impacts of a product. LCA is a separate process from LCCA and uses different analysis approaches and inputs.

Although the International Organization for Standardization (ISO) has established a series of standards for conducting LCA, applying these general guidelines to long-life infrastructure such as pavements is constrained by the lack of current knowledge and the definition of system boundaries. Although several LCA studies have been undertaken on pavement projects, there is a general lack of consistency in the methodology followed and in how the system boundaries are defined. Other inconsistencies include poor identification of pavement life-cycle phases, unclear functional units, and poor interpretation of inventory. Consequently, the findings are debatable and, like other forms of environmental and cost analysis, can be influenced by the way that the input values are used and interpreted. Decisions made based on the outputs of such analyses can lead to unanticipated longer-term consequences. Therefore, this study strives to improve current knowledge and make recommendations towards dealing with some of the controversial inputs and system boundary definitions relevant to fully permeable pavements. Similar problems are encountered with assessing BMP devices and to date, no documented LCAs have been undertaken on treatment BMPs. Consequently, only a pavement-oriented LCA framework has been developed in this study. Furthermore, since many of these problems are still under discussion, no quantified results will be given here.

The life-cycle assessment discussed in this report follows the guidelines described in ISO 14044 – *Environmental Management – Life-cycle Assessment – Requirement and Guidelines (39)*. The basic stages of performing an LCA include goal and scope definition, life-cycle inventory, impact assessment, and interpretation (Figure 7.2). Since the interpretation stage is essentially an analysis procedure to draw conclusions, make recommendations, or assist decision-making, it is integrated into the description of all other stages.

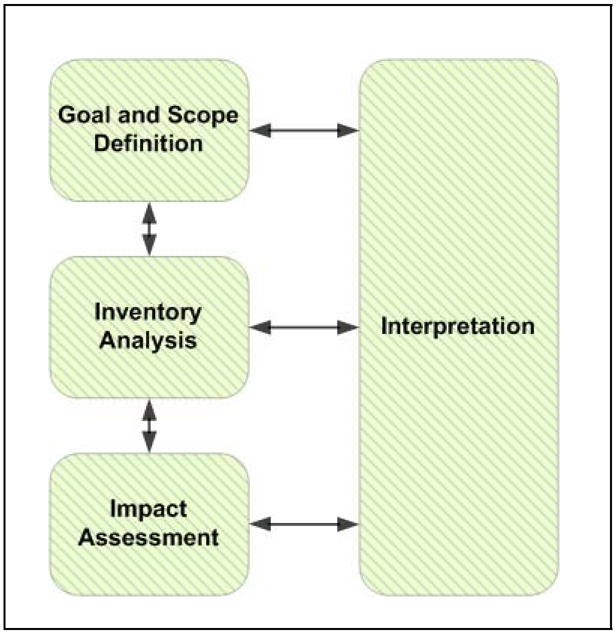


Figure 7.2: Stages for life-cycle assessment.

7.3.2 Goal and Scope Definition

Goal

Goal definition is the first stage in performing an LCA study. Defining the goal of a pavement LCA includes identifying its purpose and audience. For pavement LCA, this purpose could be characterizing a group of projects, where the result is to be used for policy or decision-making, or it could be identifying the benefit from a specific project. If the goal of the LCA is a framework that can be used across multiple projects, datasets reflecting average temporal and spatial information may need to be used. Conversely, in a project-specific LCA, site-specific and project-specific information should be used (when available) to develop local results. This type of resolution will be particularly important at the impact assessment stage.

Scope

Scope includes functional unit, analysis period, and life-cycle phases with their system boundaries.

- **Functional Unit**. This is the reference unit representing a quantified performance of a product. It is the foundation of comparison between different construction methods. For pavements, it should address both the "reference unit" and "quantified performance" components. Defining a physical dimension is the general method used to represent the "reference unit" component. It includes length, width, and number of lanes for a highway system. The physical dimension needs to reflect the scale of a real-world project because certain activities can only be modeled at the scale of a practical project (e.g., mobilization of equipment or traffic analysis). A length of between 0.3 mi (0.5 km) and 60 mi (100 km) is a typical project dimension in highway construction.
- **Performance**. The performance of a pavement is combined with many parameters and thus it is difficult to develop a single indicator for performance. Functional design life, truck traffic, climate,

subgrade, and criteria for functional performance should be included as parameters in any study to quantify performance.

- **Analysis Period**. This refers to the time horizon used to inventory the inputs and outputs related with the functional unit. Since each initial construction will often have a different functional design life, and may be followed by a series of maintenance and rehabilitation activities, setting the analysis period correctly presents a challenge in quantifying the total effects in a life-cycle of a pavement. Some proposed methods to determine the analysis period include:
  - Using 1.5 times the longest functional design life among all alternatives. This method comes from the analysis period in LCCA. Adopting this method may result in greater compatibility between the LCCA and LCA results, and allow integrated analyses.
  - Selecting the minimal activity required for next major rehabilitation. This method serves to make a "fair" comparison between two rehabilitation activities with different design lives. Within the same period for each alternative, activities with a shorter design life will be penalized by a higher construction frequency.
  - Annualizing/amortizing construction events. This method also creates a "fair" comparison between alternatives by allocating one construction into the design life.
- **System Boundaries.** The life-cycle phases of pavement include material production, construction, use, maintenance and rehabilitation, and end-of-life phase. A framework showing this process is presented in Figure 7.3.
  - <u>Material production.</u> In the material production phase, the inputs and outputs from the production process of all the materials (such as quarrying, or mixing, and the transport of materials) should be included. The allocation of impacts during asphalt production is, however, difficult since asphalt is a by-product of oil refining, and correctly allocating the energy consumption and pollutant emission to asphalt presents a challenge.
  - <u>Construction, maintenance, and rehabilitation.</u> Since maintenance and rehabilitation is essentially a construction process, it will have essentially the same system boundaries as the construction phase. In these phases, the inputs and outputs from transporting the materials and equipment and equipment usage are included. Important factors include the transport of water and water use during construction, which are often omitted in many studies. The additional fuel consumption and emission from vehicles affected by construction is also taken into consideration. Other energy use includes lighting during night construction and building the roadway lighting system.
  - <u>Use.</u> The factors considered in the use phase include increasing vehicle operating costs as the pavement deteriorates, heat island effect from solar reflection and evaporative cooling, non-greenhouse gas climate change effects, including radiated heat forcing from pavement surfaces, carbonation of cement (CO_2 absorption), and water pollution from leachate and runoff. The most significant part in this phase is thought to be the extra fuel use due to increased rolling resistance as the pavement deteriorates. However, there is currently no state-of-art model to simulate this problem and consequently it is difficult to quantify the effect.
  - <u>End-of-life phase.</u> In end-of-life phase, demolition and recycling are considered. For demolition, the emissions and fuel use during the hauling of demolished material are included. However, recycling imposes a critical problem regarding the allocation of net input/output between the system that generates the "waste" and the system that recycles the "waste." Currently there are a number of methods for doing this, but only two that are commonly used. One method assumes that each construction event is responsible for the materials it uses. This implies that the construction event that uses virgin material is assigned all the environmental burdens for consuming that virgin material. Thus, all subsequent construction events that use recycled materials are only responsible for the recycling process and transport of the recycled materials. The other method allocates half the burden of

producing and disposing of virgin materials to the first construction event and half to the final construction event, which uses recycled forms of the virgin material.

7.3.3 Life-Cycle Inventory

The *life-cycle inventory* stage involves data collection and modeling of the product based on the life-cycle phases and system boundaries identified in the previous stage. It includes all the inputs and outputs related to the product and its environment, within the boundary and based on the functional units defined in the first stage. However, currently a life-cycle inventory which meets the goal defined at the first stage (policy-level or project-level) is still under investigation. Some common categories of inventory include:

- **Energy Consumption.** Energy consumption should include all the energy used during the life-cycle, including feedstock energy and combusted energy. Feedstock energy is the embodied energy in a material which is usually utilized until combusted. Feedstock energy must be recorded because it can often be utilized when the material is burned for energy. In pavement, asphalt binder has very high feedstock energy; however, it is rarely burned for energy.
- **Greenhouse Gas Emissions.** This category quantifies the climate change effect in the impact assessment stage. Major greenhouse gas emissions, including CO_2, CH_4, and N_2O, need to be recorded. In addition, NO_X, particulates and other pollutants that are emerging as critical climate change factors should also be included as the scientific consensus develops on their effects/global warming potential.
- **Material Flows**, including fossil/non-renewable resource flows, and water flow.
- **Air Pollutants**, including NO_X, VOC (Volatile Organic Compounds), PM_{10}, $PM_{2.5}$, SO_2, CO, and lead.
- **Water Pollutants and Solid Waste Flows**, including toxics or hazardous waste.

7.3.4 Impact Assessment

The *impact assessment* stage provides comprehensive information to help assess the product's inventory results. The first step in this stage is to assign the appropriate inventory results to the selected impact categories, such as global warming, ozone depletion, etc. Then, the results that fall into the same category are characterized and calculated by a category indicator, such as Global Warming Potential (GWP), Ozone Depletion Potential (ODOP), etc. Usually a reference substance with a standard impact is set for each impact category, and all other substances are converted based on its impact over the reference level. For example, in global warming, CO_2 is set as the reference substance, and all other greenhouse gases will be converted to CO_2-equivalents based on their impact on global warming relative to CO_2. The final step is valuation, which integrates across impact categories using weights or other approaches enabling decision-makers to assimilate and consider the full range of relevant outcomes. However, because this step contains very high uncertainty and variability, and the second step is usually based on scientifically reliable research, many studies stop at the second step as a "mid-point" assessment. Some common impact categories include:

- **Climate Change.** The inventory of greenhouse gases should be tracked and reported in CO_2-equivalents or a similarly well-understood climate change indicator – preferably one that accounts for the timing of emissions. The source of method and time horizon used to calculate CO_2-equivalents must be reported in the analysis.
- **Resource Depletion.** This translates the inventory of material flows into categories of consumption, such as non-renewable use or abiotic resource use.
- **Other impact categories**, such as effects on human health, or environmental impact categories such as ozone depletion potential or acidification potential.

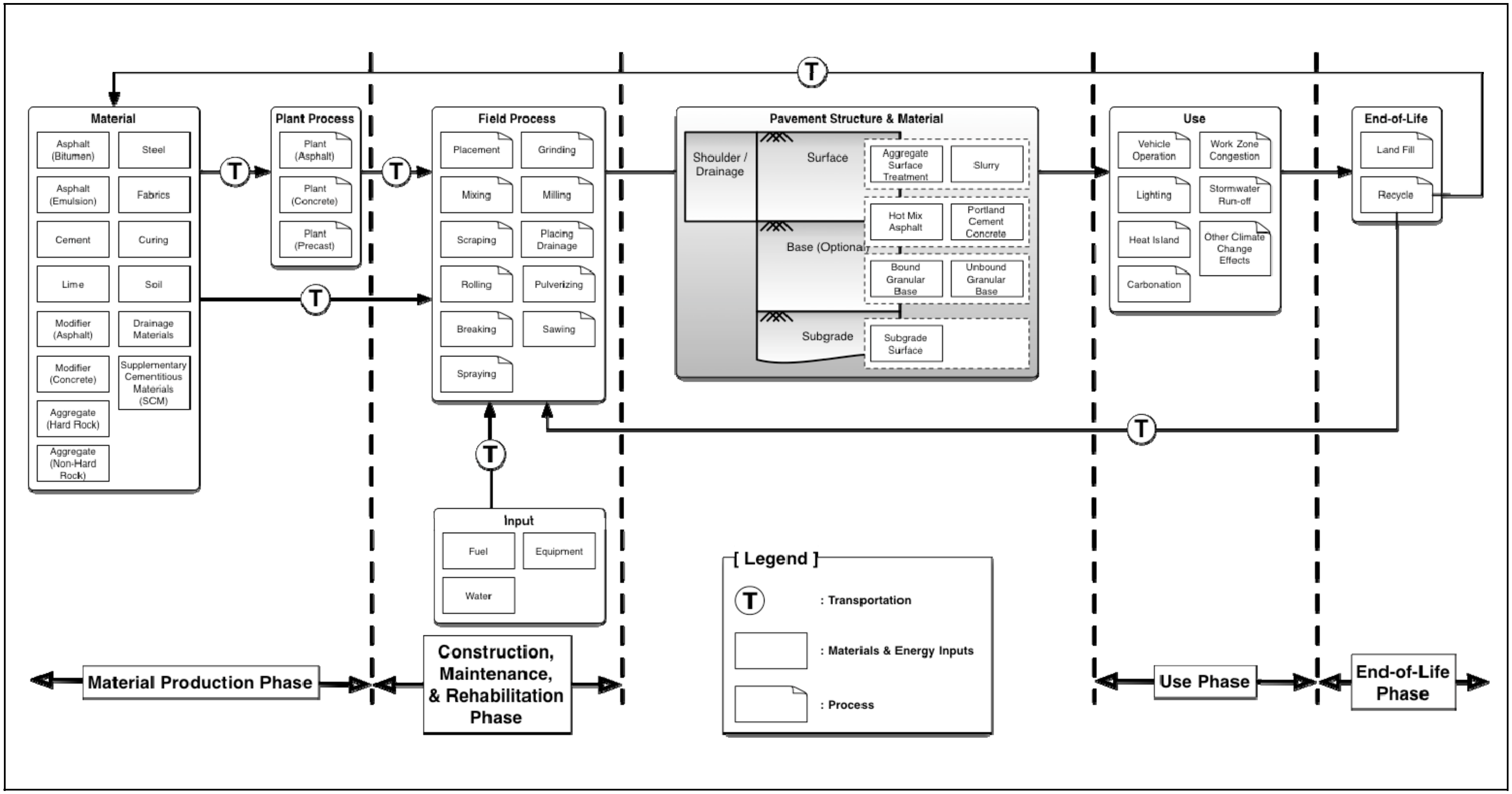


Figure 7.3: Proposed framework for pavement LCA.

Chapter 8 Summary, Conclusions and Recommendations

8.1 Summary

This final report summarizes the following testing, calculations, and analyses performed for this project:

- Review of available information regarding fully permeable pavements;
- Laboratory testing to characterize materials for fully permeable pavements, including subgrade, permeable granular base, open-graded hot-mix asphalt (HMA-O), open-graded portland cement concrete (PCC-O), and PCC slabs with cast-in holes;
- Mechanistic-empirical computer modeling for structural designs for three types of surface material (HMA-O, PCC-O, and cast slabs) considering different traffic loading based on typical California highway traffic, different traffic speeds, several typical California climate regions, and materials properties developed from the laboratory testing;
- Development of a preliminary design method and preliminary design tables considering both hydraulic and structural performance, with hydraulic performance information sourced from a companion project;
- Examples of the use of the preliminary design method and tables;
- Example life-cycle cost analyses comparing fully permeable pavement with other best management practices (BMPs), and
- A suggested framework for environmental life-cycle assessment.

The results included in this report complete all of the objectives for this project. Note that the deliverable from this research is a **preliminary** design procedure and an **example** set of catalogue-type design tables that can be used to design fully permeable pavement **pilot and experimental test sections** in California. Recommendations towards the implementation of fully permeable pavements as a stormwater best management practice in California and preparation of guidelines for the design, construction and maintenance of these pavements will only be possible after an evaluation of performance and maintenance requirements in full-scale field experiments and pilot studies.

8.2 Conclusions

Key findings from the laboratory testing phase include:

- The results of tests on two different subgrade soils (clay and silt) common in the Central Valley of California and much of the rest of the most populated areas of the state indicate that both soil types will offer very little support to a pavement structure, and that the stiffness and associated strength of the materials will decrease significantly as moisture content increases. The fully permeable pavement structures constructed on these materials discussed in this project have been developed to compensate for this poor bearing capacity, with thicker base and surfacing layers, and the optional inclusion of a PCC subbase.
- Saturated hydraulic conductivity (permeability) of the two soil types was dependent on construction compaction, as expected. The reduction in permeability with increasing compaction

was not as significant for the silt as it was for the clay. The permeability of the clay decreased from 10^{-2} cm/s (natural, uncompacted in situ soil) to 10^{-5}cm/s (100 percent of laboratory determined maximum dry density) over the range of compacted densities tested.

- The results of tests on four different commercially available permeable base-course aggregates indicate that these materials will probably provide sufficient support for typical traffic loads and speeds in parking lots, basic access streets and driveways, and on highway shoulders, while serving as a reservoir layer for the pavement structure. Although three of the four materials tested had smaller maximum aggregate sizes than those typically recommended in the literature, the permeabilities and reservoir capacities were still adequate for California rainfall events.
- For open-graded hot-mix asphalt materials (HMA-O), test results indicate that the aggregate particle size distribution in the mix, and the binder type will be the two most critical factors in selecting appropriate mixes. Sufficient permeability for anticipated needs in California was obtained on a range of mixes tested. Adequate resistance to rutting of the surface material appears to be mostly a problem for the HMA-O (RW95 in this report) with conventional binder and the RHMA-O (AR95 in this report) mix with rubberized binder, based on shear modulus. The AR95 and Georgia (G125 in this report) mixes had better rutting resistance in the Hamburg Wheel Tracking test (which also considers moisture sensitivity), in particular the G125 mix containing polymers and fibers. Some moisture sensitivity was evident, but this can be overcome by the use of appropriate anti-strip mechanisms. Most of the mixes of interest had adequate durability (resistance to raveling) compared to the dense-graded control. Flexural stiffness and fatigue cracking resistance of the various mixes were tested for use in the structural design calculations.
- The results from tests on open-graded portland cement concrete (PCC-O) indicate a clear relationship between aggregate grading, cement content, water-to-cement ratio, and strength and permeability. All specimens tested exceeded the anticipated permeability requirements, indicating that aggregate gradings and cement contents can be adjusted to increase the strength of the material while still retaining adequate water flow through the pavement. The water-to-cement ratio appears to be critical in ensuring good constructability and subsequent performance of the pavement. Although no durability testing was carried out, the mixes are likely to have some susceptibility to raveling under traffic. Coefficient of thermal expansion of the various mixes was assumed to be $1.2(10^{-5})$/°F ($6.5[10^{-6}]$/°C) for the design calculations included in this report.
- The results from tests on the slabs cast with holes using conventional PCC showed reduced flexural strength compared with conventional PCC slabs without holes, as expected. A 70 percent strength ratio is recommended for use in design for the drainage pattern used in this study. Based on a finite element analysis, weakening of the permeable beams is mostly caused by a reduction in crack resistance cross section, while the effect of stress concentration can be ignored. Permeable concrete pavements with similar surface void ratio (3.1 percent in this study) can be designed the same way as regular non-permeable concrete pavements. The effect of the vertical drainage holes can be accommodated by reducing the modulus of rupture value. This reduction can be estimated by calculating the reduction in crack-resisting cross section normal to the direction of maximum principle stress induced by truck traffic. An additional 10 percent reduction in design modulus of rupture is recommended to account for the lower homogeneity caused by the existence of the drainage holes.

Key findings from the computer modeling of structural capacity and development of structural designs phase include:

- The use of mechanistic-empirical pavement design equations developed in this project was effective in estimating required structural thicknesses for fully permeable pavements to carry slow moving (up to 25 mph [40 km/h]) truck traffic. Thousands of finite element calculations to find critical stresses in fully permeable concrete pavements (PCC-O and cast permeable concrete), and tens of thousands of layer elastic theory calculations to find critical stresses and strains in fully permeable asphalt pavements were performed in order to estimate thicknesses required for structural capacity. Statewide truck axle load spectra from Caltrans weigh-in-motion (WIM) measurements (captured in a UCPRC database) were used to select representative axle loads. Representative pavement temperatures were selected from a database of *Enhanced Integrated Climate Model (EICM)* calculations to estimate asphalt stiffnesses and temperature gradients in concrete slabs.

- The results of stress calculations in concrete and strain calculations in asphalt were used to estimate the required thicknesses for preventing fatigue cracking. Nonlinear layer elastic theory calculations were used to estimate the stiffness of the granular base, which were then used to estimate shear stress-to-strength ratios in the subgrade. Together, these results were used to develop structural design tables that can be used with hydraulic design calculations from the companion project to determine required layer thicknesses. The pavement structures were considered feasible, with all pavement structures less than 5 ft (1.5 m) in total thickness, and most concrete slabs less than 1.5 ft (0.46 m) thick for the heaviest traffic. The use of the PCC-O subbase offers considerably greater protection against the risk of subgrade rutting for asphalt pavements.
- Preliminary design tables for pilot studies were developed considering structural and hydraulic performance for the design input variables:
  - Subgrade permeability,
  - Truck traffic level in terms of Traffic Index,
  - Two temperature climate regions (Sacramento and Los Angeles),
  - Two traffic speeds (4 mph [7 km/h] and 24 mph [40 km/h]),
  - Three design storms (2, 50, and 100 years) for three climate regions, and
  - Various numbers of adjacent impermeable lanes.
- Design cross sections developed for shoulder retrofit of highways as well as low-speed trafficked areas such as parking lots and maintenance yards were reviewed by construction and maintenance experts and were considered to be feasible to construct and maintain.

Key findings from life-cycle analyses include:

- Example life-cycle cost analysis (LCCA) comparisons with conventional stormwater best management practices (BMPs) for the Sacramento region indicated that fully permeable pavements should cost less than conventional BMPs over a 40-year life-cycle. LCCA should be undertaken on a project-by-project basis because alternatives and costs for different types of fully permeable pavement will vary by region and over time.
- A framework for environmental life-cycle analysis (LCA) was reviewed; however, it was found that insufficient data were available at this time to complete an example LCA for fully permeable pavements.

8.3 Preliminary Recommendations for Design, Construction and Maintenance of Pilot Sections

8.3.1 Design

Recommendations regarding design and specifications for fully permeable pavement test sections, based on the findings of this project, include:

- Life-cycle cost analyses should be performed for all projects and the results used to develop criteria for the selection of pavement type and materials. The LCCA comparison results will depend on materials costs at the time, contractor experience, and project-specific conditions (climate region, traffic level, subgrade conditions, etc.).

- ASTM specifications for granular materials recommended in the NAPA and ACPA manuals should **not** be used, unless those materials are locally available, and are found to be the most cost-effective. Instead, it is recommended that locally available materials such as those considered in this study be considered and costed.
- A subgrade compaction of between 90 and 92 percent (i.e., target 91% ± 1% tolerance) of laboratory determined maximum density, following Caltrans Test Method 216, is recommended. Compaction in the field should be performed dry of optimum water content. Variability of compaction within the tolerance, the sensitivity of the permeability to variations in compaction, and the relationship between laboratory and field determined densities should be closely monitored in full-scale experiments. Any post-construction consolidation of the reservoir layers and subgrade under trafficking should also be closely monitored.
- PCC-O mixes similar to those recommended in this project should be specified, with smaller maximum aggregate sizes and greater cement contents permissible, as long as they provide a minimum permeability of 1.5 cm/s, which satisfies permeability requirements for California rain events and includes a factor for clogging over time. Minimum flexural strengths on the order of 325 psi (2.25 MPa) and/or minimum splitting tensile strengths of 290 psi (2.0 MPa) are recommended for use with the structural design tables included in this report. The use of the splitting tensile strength for mix design was found convenient and cost-effective and is recommended over flexural or compressive strength testing, provided that replicate specimens are tested and variation in test results is appropriately assessed.
- The Georgia DOT (G125 in this project) open-graded asphalt mix should be considered first for higher Traffic Index designs, followed by the RHMA-O (AR95 in this report) for lower Traffic Index designs. The HMA-O mix (RW95 in this report) will likely have a higher risk of raveling, rutting, and cracking.
- The design cross sections for shoulder retrofit shown in Figure 6.1 and Figure 6.2 are recommended as starting points for producing a design that maintains adequate drainage, structural integrity of the traveled lanes, and constructability.
- The use of appropriate Caltrans-specified geotextiles is recommended for use as a filter layer between the subgrade and granular base or subgrade and PCC-O subbase. Appropriate drainage systems with outlets are recommended between the traveled lanes pavement and the impermeable membrane for shoulder retrofit projects. The use of an appropriate Caltrans-specified impermeable membrane fabric is recommended for separation of the permeable shoulder from trafficked lanes.
- The number of permitted overflows will need to be determined by Caltrans for each project. This will influence the thickness of the gravel base/reservoir layer and will depend on storm intensity, duration and frequency.

8.3.2 Construction and Maintenance of Pilot Sections

Recommendations regarding construction and maintenance for fully permeable pavement pilot sections, based on the findings of this project, include:

- Permeability tests on the subgrade should be performed at the design depth of the top of the subgrade in the completed structure, and as many permeability tests as possible should be performed across the project to ascertain that sufficient permeability is available for the fully permeable pavement to function effectively. Many subgrades are non-uniform in permeability both laterally and with depth because of the nature of sediment deposition.
- For permeable concrete pavements it is recommended that all of the curing and sawing (or other appropriate crack initiation process) recommendations included in the American Concrete

Pavement Association (ACPA) guide be followed. Joints in the shoulder should match the joints in the pavement.

- Construction traffic should be kept to a minimum on the subgrade after compaction is completed in order to help preserve permeability and prevent rutting.
- Conventional street sweeping equipment should **not** be used on fully permeable pavement because it tends to break organic materials (leaves, seeds, etc.) into smaller particles that will likely clog the surface of the pavement and reduce its permeability. Instead, it is recommended that low-pressure cleaning/vacuuming equipment be used annually to clean the pavement surface.

8.4 Recommendations for Future Work

8.4.1 Accelerated Pavement Testing and Pilot Studies

It is recommended that the preliminary design method and cross sections to meet hydraulic and structural performance requirements developed in this project be used for the appropriate design of test sections for accelerated pavement testing (with Heavy Vehicle Simulator [HVS]) and pilot study field validation for both hydraulic and structural design considerations. The actual designs for those sections (following the procedure discussed in Chapter 6) will depend on the subgrade soil permeability, climate, and design truck traffic levels. The pavements should be instrumented to monitor stresses, strains, deflections, temperatures, thermal gradients, moisture content, and water quality. In PCC-O test sections, optimal mix designs and the use of proprietary additives should be discussed with readymix suppliers. Distresses such as raveling, clogging, brooming, and other issues that will impact on the maintenance of these pavements should also be monitored.

8.4.2 Life-Cycle Considerations

More detailed LCCA and LCA should be performed after construction, evaluation, and performance validation of HVS and field test sections, which will provide more realistic initial cost information and improved maintenance and rehabilitation cost estimates.

8.4.3 Other Pavement Type Consideration

It is recommended that this study be extended through another project to consider permeable interlocking concrete blocks instead of cast concrete as an alternative to asphalt- and concrete-surfaced pavement. It is recommended that an LCCA be performed as part of that study to provide example information for comparison with the pavement types considered in this project.

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Appendix A: HMA-O Frequency Sweep Test Results

Table A.1: Summary of Frequency Sweep Test Results: AR95 (RHMA-O)

AR95-1A2 (AV = 18.4%; 10°C)						AR95-5A1 (AV = 19.8%; 10°C)						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degree)	E* (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degree)	E* (MPa)	
15.16	0.1812	0.000104	9.88	15.32	1737	15.16	0.1991	0.000104	9.56	15.91	1909	1823
10.01	0.1770	0.000104	0.83	14.55	1702	10.01	0.1934	0.000104	9.52	15.47	1866	1784
5.01	0.1644	0.000104	0.78	16.08	1577	5.00	0.1781	0.000104	9.47	16.17	1704	1641
2.00	0.1343	0.000099	0.88	15.62	1350	2.00	0.1456	0.000099	9.43	16.66	1465	1407
1.00	0.1178	0.000097	10.04	17.29	121	1.00	0.1288	0.000099	9.36	16.49	1295	1252
0.50	0.1050	0.000100	10.02	17.28	1053	0.50	0.1125	0.000099	9.33	18.77	1136	1095
0.20	0.0884	0.000099	9.98	19.61	893	0.20	0.0931	0.000099	9.30	19.06	944	918
0.10	0.0764	0.000098	9.89	18.60	776	0.10	0.0803	0.000098	9.23	20.79	820	798
0.05	0.0669	0.000098	9.78	22.40	684	0.05	0.0696	0.000097	9.38	21.03	715	699
0.02	0.0554	0.000098	9.91	20.22	568	0.02	0.0572	0.000097	9.38	22.76	588	578
0.01	0.0496	0.000098	9.90	22.56	505	0.01	0.0198	0.000097	9.36	24.22	513	509
AR95-4B2 (AV = 19.5%; 20°C)						**AR95-5A2 (AV = 19.8%; 20°C)**						**Avg. E* (MPa)**
Freq. (Hz)	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degree)**	**E* (MPa)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degree)**	**E* (MPa)**	
15.16	0.1013	0.000106	19.72	23.96	951	15.15	0.1173	0.000109	19.79	22.36	1080	1015
9.99	0.0982	0.000107	19.74	22.84	914	10.01	0.1112	0.000105	19.66	20.27	1061	987
5.00	0.0865	0.000106	19.85	23.84	815	5.00	0.0994	0.000106	19.61	20.63	938	876
2.00	0.0674	0.000102	19.79	23.17	664	2.00	0.0790	0.000102	19.66	20.91	776	720
1.00	0.0556	0.000099	19.57	24.22	562	1.00	0.0637	0.000099	19.79	22.40	644	603
0.50	0.0454	0.000098	19.57	24.36	465	0.50	0.0547	0.000098	19.76	23.54	557	511
0.20	0.0347	0.000096	19.65	24.65	360	0.20	0.0428	0.000098	19.63	25.08	436	398
0.10	0.0277	0.000096	19.81	28.58	289	0.10	0.0355	0.000098	19.66	23.57	363	326
0.05	0.0231	0.000094	19.64	28.27	246	0.05	0.0289	0.000097	19.64	29.06	298	272
0.02	0.0189	0.000093	19.70	33.38	204	0.02	0.0223	0.000096	19.70	30.68	232	218
0.01	0.0156	0.000093	19.71	36.04	167	0.01	0.0188	0.000097	19.68	33.86	194	180
AR95-1A1 (AV = 18.7%; 30°C)						**AR95-6B2 (AV = 20.4%; 30°C)**						**Avg. E* (MPa)**
Freq. (Hz)	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degree)**	**E* (MPa)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degree)**	**E* (MPa)**	
15.14	0.1047	0.000209	29.63	33.45	500	15.13	0.1052	0.000207	29.62	34.34	509	504
10.00	0.1055	0.000208	29.73	28.92	506	9.99	0.1042	0.000210	29.67	31.16	496	501
5.01	0.0939	0.000205	29.72	26.88	458	5.00	0.0912	0.000206	29.55	29.09	443	450
2.00	0.0718	0.000197	29.80	28.63	364	2.00	0.0702	0.000197	29.57	29.27	356	360
1.00	0.0600	0.000195	29.73	29.50	308	1.00	0.0572	0.000195	29.60	30.49	294	301
0.50	0.0493	0.000199	29.80	27.76	248	0.50	0.0483	0.000199	29.78	31.49	243	246
0.20	0.0380	0.000199	29.81	30.14	191	0.20	0.0364	0.000197	29.65	32.42	185	188
0.10	0.0330	0.000198	29.69	35.42	167	0.10	0.0294	0.000198	29.58	30.76	149	158
0.05	0.0266	0.000198	29.68	35.92	135	0.05	0.0251	0.000197	29.63	32.04	128	131
0.02	0.0215	0.000198	29.67	32.08	109	0.02	0.0189	0.000196	29.66	36.95	96	103
0.01	0.0175	0.000197	29.69	35.03	89							89

Table A.2: Summary of Frequency Sweep Test Results: G125

G125-5A2 (AV = 17.0%; 10°C)						G125-4B1 (AV = 16.8%; 20°C)						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degree)	E* (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degree)	E* (MPa)	
15.17	0.2572	0.000058	10.57	13.15	4423	15.14	0.2619	0.000066	10.48	12.26	3972	4198
10.00	0.4398	0.000102	10.53	13.30	4292	10.00	0.4020	0.000104	10.44	13.05	3865	4078
5.00	0.4032	0.000103	10.46	13.75	3921	5.00	0.3649	0.000103	10.37	13.68	3545	3733
2.00	0.3345	0.000098	10.42	15.07	3417	2.00	0.3071	0.000099	10.34	14.78	3095	3256
1.00	0.2986	0.000097	10.35	15.79	3064	1.00	0.2691	0.000097	10.28	16.08	2764	2914
0.50	0.2729	0.000101	10.33	16.48	2713	0.50	0.2436	0.000100	10.26	15.93	2448	2580
0.20	0.2292	0.000099	10.28	17.58	2306	0.20	0.2041	0.000099	10.21	17.78	2071	2188
0.10	0.1971	0.000097	10.21	18.91	2022	0.10	0.1776	0.000098	10.15	18.31	1817	1920
0.05	0.1734	0.000098	10.09	19.98	1767	0.05	0.1558	0.000098	10.05	19.44	1595	1681
0.02	0.1438	0.000098	9.94	21.56	1463	0.02	0.1281	0.000098	9.88	22.23	1309	1386
0.01	0.1269	0.000099	9.86	22.86	1286	0.01	0.1134	0.000098	9.88	24.83	1153	1220
G125-4B1 (AV = 16.8%; 20°C)						G125-4B2 (AV = 16.8%; 20°C)						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degree)	E* (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degree)	E* (MPa)	
15.16	0.2249	0.000083	19.87	17.14	2722	15.16	0.2032	0.000070	19.49	15.32	2890	2806
10.00	0.2666	0.000104	19.89	18.54	2563	10.01	0.2776	0.000102	19.50	18.23	2725	2644
5.00	0.2380	0.000104	19.73	18.90	2282	5.00	0.2513	0.000103	19.53	18.68	2437	2359
2.00	0.1894	0.000100	19.71	20.14	1893	2.00	0.2051	0.000102	19.54	19.82	2018	1956
1.00	0.1591	0.000098	19.79	21.92	1628	1.00	0.1728	0.000100	19.56	21.49	1726	1677
0.50	0.1370	0.000100	19.79	23.44	1366	0.50	0.1462	0.000100	19.56	23.57	1461	1413
0.20	0.1073	0.000098	19.65	24.38	1095	0.20	0.1146	0.000099	19.58	23.89	1153	1124
0.10	0.0886	0.000098	19.62	24.83	904	0.10	0.0935	0.000099	19.60	24.01	947	925
0.05	0.0723	0.000097	19.81	30.00	745	0.05	0.0784	0.000098	19.65	28.21	802	773
0.02	0.0556	0.000097	19.73	30.21	574	0.02	0.0595	0.000097	19.73	28.15	612	593
0.01	0.0450	0.000096	19.72	31.99	467	0.01	0.0473	0.000097	19.73	30.57	486	477
G125-6B2 (AV = 18.9%; 30°C)						G125-4B2 (AV = 16.8%; 30°C)						Avg. E* (MPa)
Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degree)	E* (MPa)	Freq. (Hz)	Stress (MPa)	Strain	Temp. (°C)	Phase Angle (Degree)	E* (MPa)	
15.15	0.2507	0.000213	29.67	30.87	1175	15.15	0.2826	0.000203	29.61	28.73	1391	1283
10.00	0.2252	0.000208	29.73	29.37	1084	10.01	0.2643	0.000207	29.55	28.13	1279	1181
5.00	0.1869	0.000205	29.68	29.88	911	5.00	0.2218	0.000206	29.53	28.64	1078	994
2.00	0.1380	0.000198	29.75	31.30	697	2.00	0.1669	0.000198	29.66	30.43	842	770
1.00	0.1107	0.000199	29.58	33.35	557	1.00	0.1340	0.000197	29.56	31.60	679	618
0.50	0.0889	0.000201	29.69	35.10	443	0.50	0.1093	0.000203	29.67	32.79	539	491
0.20	0.0633	0.000199	29.69	36.38	318	0.20	0.0804	0.000200	29.66	34.05	402	360
0.10	0.0502	0.000199	29.63	37.71	253	0.10	0.0641	0.000199	29.59	37.80	321	287
0.05	0.0396	0.000198	29.62	37.74	200	0.05	0.0507	0.000199	29.63	37.05	255	227
0.02	0.0300	0.000197	29.63	38.73	152	0.02	0.0381	0.000199	29.61	39.49	192	172
0.01	0.0242	0.000198	29.64	44.91	122	0.01	0.0314	0.000199	29.64	36.60	158	140

Table A.3: Summary of Frequency Sweep Test Results: RW95 (HMA-O)

RW95-4B2 (AV = 19.3%; 10°C)						RW95-5A2 (AV = 22.8%; 10°C)						Avg. E* (MPa)
Freq. (Hz)	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degree)**	**E* (MPa)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degree)**	**E* (MPa)**	
15.27	0.2542	0.000049	9.85	12.24	5168	15.16	0.2758	0.000082	9.80	15.47	3376	4272
10.00	0.5224	0.000104	9.89	12.52	5027	9.99	0.3371	0.000103	9.87	15.31	3276	4152
5.00	0.4675	0.000102	9.99	13.74	4605	5.00	0.3034	0.000103	9.82	17.07	2948	3776
2.00	0.3890	0.000098	9.95	16.47	3971	2.00	0.2456	0.000099	9.79	19.16	2480	3225
1.00	0.3416	0.000098	9.97	18.18	3483	1.00	0.2071	0.000098	9.93	21.84	2123	2803
0.50	0.2996	0.000101	10.03	21.27	2972	0.50	0.1797	0.000100	9.92	23.55	1801	2387
0.20	0.2382	0.000100	10.00	23.99	2394	0.20	0.1393	0.000099	9.83	28.06	1401	1898
0.10	0.1937	0.000099	9.84	26.86	1962	0.10	0.1088	0.000097	9.90	28.34	1118	1540
0.05	0.1553	0.000098	9.95	34.56	1580	0.05	0.0872	0.000098	9.85	35.05	892	1236
0.02	0.1107	0.000099	9.94	39.81	1121	0.02	0.0614	0.000097	9.93	37.11	634	877
0.01	0.0814	0.000098	9.91	43.31	828	0.01	0.0449	0.000098	9.87	44.80	459	644
RW95-3A1 (AV = 18.6%; 20°C)						**RW95-4B2 (AV = 19.3%; 20°C)**						**Avg. E* (MPa)**
Freq. (Hz)	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degree)**	**E* (MPa)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degree)**	**E* (MPa)**	
15.14	0.3064	0.000108	20.80	27.54	2845	15.18	0.1390	0.000045	19.54	23.37	3115	2980
9.99	0.2862	0.000109	20.82	27.18	2628	9.98	0.3021	0.000105	19.63	23.81	2880	2754
5.00	0.2390	0.000108	20.79	28.96	2216	5.00	0.2542	0.000104	19.77	26.06	2440	2328
1.99	0.1742	0.000105	20.32	31.66	1653	2.00	0.1849	0.000099	19.74	31.26	1859	1756
1.00	0.1333	0.000103	20.40	35.64	1296	1.00	0.1444	0.000099	19.55	35.33	1454	1375
0.50	0.0999	0.000101	20.60	40.15	990	0.50	0.1030	0.000094	19.55	36.45	1101	1046
0.20	0.0653	0.000099	20.72	45.58	657	0.20	0.0715	0.000098	19.61	46.84	731	694
0.10	0.0471	0.000099	20.61	44.53	476	0.10	0.0495	0.000099	19.76	49.90	503	489
0.05	0.0302	0.000099	20.50	50.95	306	0.05	0.0343	0.000097	19.67	58.22	355	330
0.02	0.0179	0.000095	20.46	52.55	189	0.02	0.0199	0.000096	19.70	54.72	207	198
0.01	0.0147	0.000104	20.60	44.62	142	0.01	0.0131	0.000096	19.69	68.28	136	139
RW95-5A1 (AV = 22.0%; 30°C)						**RW95-3A1 (AV = 18.6%; 30°C)**						**Avg. E* (MPa)**
Freq. (Hz)	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degree)**	**E* (MPa)**	**Freq. (Hz)**	**Stress (MPa)**	**Strain**	**Temp. (°C)**	**Phase Angle (Degree)**	**E* (MPa)**	
15.15	0.1212	0.000210	29.83	50.84	576	15.15	0.2207	0.000204	29.64	44.27	1084	830
10.01	0.1092	0.000210	29.61	46.98	520	9.99	0.1930	0.000206	29.52	44.45	938	729
5.01	0.0827	0.000206	29.61	46.46	401	5.00	0.1427	0.000205	29.53	47.33	696	548
2.00	0.0523	0.000199	29.59	48.29	262	2.00	0.0880	0.000197	29.58	51.36	446	354
1.00	0.0378	0.000197	29.57	53.28	192	1.00	0.0608	0.000198	29.53	56.33	307	250
0.50	0.0261	0.000200	29.61	52.78	131	0.50	0.0398	0.000200	29.63	54.51	199	165
0.20	0.0156	0.000199	29.70	49.55	78	0.20	0.0237	0.000199	29.67	55.97	119	99
0.10	0.0119	0.000199	29.69	45.26	60	0.10	0.0146	0.000199	29.68	60.55	74	67
0.05	0.0075	0.000198	29.63	53.72	38							38

Appendix B: Preliminary Hydraulic Design Tables

Table B.1: Preliminary Granular Base Thickness based on Hydraulic Performance Simulations

Subgrade soil permeability (cm/s)[1]	Storm design (years) (Full storm duration)	Rainfall region											
		Sacramento (Sac)				Riverside (LA)				Eureka			
		Thickness of Granular Base + PCC-O Subbase (mm)				Thickness of Granular Base + PCC-O Subbase (mm)				Thickness of Granular Base + PCC-O Subbase (mm)			
		Number of highway lanes[2]				Number of highway lanes[2]				Number of highway lanes[2]			
		2	3	4	5	2	3	4	5	2	3	4	5
1.00E-05	2	270	450	600	700	270	400	480	680	600	900	1270	1570
1.00E-04		130	180	250	420	130	150	320	400	350	650	850	1200
1.00E-03		130	130	130	130	130	130	130	130	130	130	130	150
1.00E-05	50	480	700	1050	1250	580	860	1180	1600	800	1270	1720	2150
1.00E-04		190	420	680	950	360	700	950	1350	500	850	1300	1770
1.00E-03		130	130	130	130	130	130	130	230	130	130	220	500
1.00E-05	100	600	800	1150	1430	680	1050	1300	1800	1150	1720	2300	2900
1.00E-04		210	500	750	1070	400	850	1200	1450	830	1300	1890	2500
1.00E-03		130	130	130	150	130	130	150	320	130	220	650	950

[1] Note that draw down times will vary significantly and are dependent primarily on subgrade soil permeabilities, but also on other factors such as number of lanes drained, storm recurrence interval, etc as well. Draw down times could vary between one hour for subgrades with a permeability of 1.00E-03 to several months for subgrades with a permeability of 1.00E-05 and higher. Refer to Reference 4 for discussion on the calculation of drain down times.

[2] The number of highway lanes must include the shoulder. Shoulder width is 10 ft. (3.0 m).

Appendix C: Preliminary Structural Design Tables for PCC-O Surfaces

Table C.1: Preliminary TI for PCC Fatigue Damage=1, Los Angeles County (PCC-O, k= 0.05 MPa/mm)

PCC Layer Thickness (mm)	Slab Length (mm)															
	3000	3100	3200	3300	3400	3500	3600	3700	3800	3900	4000	4100	4200	4300	4400	4500
250	12.0	12.0	11.5	11.5	11.0	11.0	11.0	10.5	10.5	10.0	10.0	10.0	9.5	9.5	9.0	9.0
260	16.0	16.0	15.5	15.0	15.0	14.5	14.5	14.0	14.0	13.5	13.0	13.0	12.5	12.5	12.0	11.5
270					18.5	18.5	18.0	17.5	17.0	16.5	16.5	16.0	15.5	15.0	15.0	14.5
280													18.5	18.0	17.5	17.0
290																
300																
310																
320																
330																
340																
350																
360																
370																
380																
390																
400																
410																
420																
430																
440																
450																
460																
470																
480																
490																
500																

Note: Slab Width = 3.5 m

Table C.2: Preliminary TI for PCC Fatigue Damage=1, Los Angeles County (PCC-O, k= 0.08 MPa/mm)

PCC Layer Thickness (mm)	Slab Length (mm)															
	3000	3100	3200	3300	3400	3500	3600	3700	3800	3900	4000	4100	4200	4300	4400	4500
250	13.5	13.5	13.0	13.0	13.0	13.0	12.5	12.5	12.5	12.5	12.0	12.0	12.0	12.0	11.5	11.5
260	17.5	17.5	17.0	17.0	16.5	16.5	16.0	16.0	15.5	15.5	15.0	15.0	14.5	14.5	14.0	14.0
270										18.5	18.0	18.0	17.5	17.0	17.0	16.5
280																
290																
300																
310																
320																
330																
340																
350																
360																
370																
380																
390																
400																
410																
420																
430																
440																
450																
460																
470																
480																
490																
500																

Note: Slab Width = 3.5 m

Table C.3: Preliminary TI for PCC Fatigue Damage=1, Sacramento County (PCC-O, k= 0.05 MPa/mm)

PCC Layer Thickness (mm)	Slab Length (mm)															
	3000	3100	3200	3300	3400	3500	3600	3700	3800	3900	4000	4100	4200	4300	4400	4500
250	10.0	9.5	9.5	9.0	9.0	8.5	8.5	8.0	8.0	7.5	7.5	7.0	7.0	6.5	6.5	6.0
260	14.0	13.5	13.0	13.0	12.5	12.0	11.5	11.0	11.0	10.5	10.0	9.5	9.5	9.0	8.5	8.0
270	18.0	17.5	17.0	16.5	16.0	15.5	15.0	14.5	14.0	13.5	13.0	12.5	12.0	11.0	10.5	10.0
280							18.0	17.5	17.0	16.0	15.5	15.0	14.0	13.5	13.0	12.5
290											18.5	17.5	16.5	16.0	15.0	14.5
300														18.5	17.5	16.5
310																18.5
320																
330																
340																
350																
360																
370																
380																
390																
400																
410																
420																
430																
440																
450																
460																
470																
480																
490																
500																

Note: Slab Width = 3.5 m

Table C.4: Preliminary TI for PCC Fatigue Damage=1, Sacramento County (PCC-O, k= 0.08 MPa/mm)

PCC Layer Thickness (mm)	Slab Length (mm)															
	3000	3100	3200	3300	3400	3500	3600	3700	3800	3900	4000	4100	4200	4300	4400	4500
250	11.0	11.0	10.5	10.5	10.0	10.0	10.0	9.5	9.5	9.0	9.0	9.0	8.5	8.5	8.0	8.0
260	15.0	14.5	14.0	14.0	13.5	13.5	13.0	12.5	12.5	12.0	11.5	11.5	11.0	10.5	10.5	10.0
270		18.5	18.0	17.5	17.0	16.5	16.0	15.5	15.0	14.5	14.5	14.0	13.5	13.0	12.5	12.0
280								18.5	18.0	17.5	17.0	16.5	15.5	15.0	14.5	14.0
290													18.0	17.5	16.5	16.0
300																18.0
310																
320																
330																
340																
350																
360																
370																
380																
390																
400																
410																
420																
430																
440																
450																
460																
470																
480																
490																
500																

Note: Slab Width = 3.5 m

Appendix D: Preliminary Structural Design Tables for Cast PCC Surfaces

Table D.1: Preliminary TI for PCC Fatigue Damage=1, Los Angeles County
(Cast Slab, k= 0.05 MPa/mm)

PCC Layer Thickness (mm)	Slab Length (mm)															
	3000	3100	3200	3300	3400	3500	3600	3700	3800	3900	4000	4100	4200	4300	4400	4500
250	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
260	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
270	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
280	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
290	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0
300	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0
310	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0
320	1.5	1.5	1.0	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0
330	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0
340	2.0	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.0	0.0	0.0
350	2.0	2.0	1.5	1.5	1.5	1.5	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.0	0.0
360	4.0	4.0	3.5	3.5	3.0	3.0	2.5	2.5	2.0	2.0	1.5	1.5	1.5	1.0	1.0	0.5
370	6.0	5.5	5.5	5.0	4.5	4.5	4.0	4.0	3.5	3.0	3.0	2.5	2.0	2.0	1.5	1.0
380	8.0	7.5	7.0	7.0	6.5	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0	2.5	2.0	2.0
390	10.0	9.5	9.0	8.5	8.0	7.5	7.0	6.5	6.0	5.5	5.0	4.5	4.0	3.5	3.0	2.5
400	12.0	11.5	11.0	10.0	9.5	9.0	8.5	8.0	7.0	6.5	6.0	5.5	5.0	4.0	3.5	3.0
410	14.0	13.5	12.5	12.0	11.0	10.5	10.0	9.0	8.5	8.0	7.0	6.5	5.5	5.0	4.5	3.5
420	16.0	15.0	14.5	13.5	13.0	12.0	11.5	10.5	9.5	9.0	8.0	7.5	6.5	6.0	5.0	4.0
430	18.0	17.0	16.0	15.5	14.5	13.5	12.5	12.0	11.0	10.0	9.0	8.5	7.5	6.5	5.5	5.0
440			18.0	17.0	16.0	15.0	14.0	13.0	12.0	11.0	10.5	9.5	8.5	7.5	6.5	5.5
450					17.5	16.5	15.5	14.5	13.5	12.5	11.5	10.5	9.0	8.0	7.0	6.0
460						18.0	17.0	16.0	14.5	13.5	12.5	11.0	10.0	9.0	8.0	6.5
470							18.5	17.0	16.0	14.5	13.5	12.0	11.0	9.5	8.5	7.0
480								18.5	17.0	16.0	14.5	13.0	12.0	10.5	9.0	8.0
490									18.5	17.0	15.5	14.0	12.5	11.5	10.0	8.5
500										18.0	16.5	15.0	13.5	12.0	10.5	9.0

Note: Slab Width = 3.5 m

**Table D.2: Preliminary TI for PCC Fatigue Damage=1, Los Angeles County
(Cast Slab, k= 0.08 MPa/mm)**

PCC Layer Thickness (mm)	Slab Length (mm)															
	3000	3100	3200	3300	3400	3500	3600	3700	3800	3900	4000	4100	4200	4300	4400	4500
250	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
260	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
270	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
280	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
290	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
300	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
310	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
320	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0
330	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0
340	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0
350	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0
360	3.0	3.0	3.0	2.5	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.0	1.0	1.0	0.5	0.5
370	5.5	5.0	4.5	4.5	4.0	4.0	3.5	3.0	3.0	2.5	2.5	2.0	1.5	1.5	1.0	1.0
380	7.5	7.0	6.5	6.0	5.5	5.5	5.0	4.5	4.0	3.5	3.5	3.0	2.5	2.0	1.5	1.0
390	9.5	9.0	8.5	8.0	7.5	7.0	6.5	6.0	5.5	5.0	4.0	3.5	3.0	2.5	2.0	1.5
400	11.5	11.0	10.5	9.5	9.0	8.5	8.0	7.0	6.5	6.0	5.0	4.5	4.0	3.5	2.5	2.0
410	14.0	13.0	12.5	11.5	11.0	10.0	9.0	8.5	7.5	7.0	6.0	5.5	4.5	4.0	3.0	2.5
420	16.0	15.0	14.0	13.5	12.5	11.5	10.5	10.0	9.0	8.0	7.0	6.5	5.5	4.5	3.5	3.0
430	18.0	17.0	16.0	15.0	14.0	13.0	12.0	11.0	10.0	9.0	8.0	7.0	6.0	5.0	4.0	3.0
440			18.0	17.0	16.0	14.5	13.5	12.5	11.5	10.0	9.0	8.0	7.0	6.0	4.5	3.5
450				18.5	17.5	16.0	15.0	14.0	12.5	11.5	10.0	9.0	7.5	6.5	5.0	4.0
460						18.0	16.5	15.0	14.0	12.5	11.0	10.0	8.5	7.0	5.5	4.5
470							18.0	16.5	15.0	13.5	12.0	10.5	9.0	7.5	6.5	5.0
480								18.0	16.0	14.5	13.0	11.5	10.0	8.5	7.0	5.0
490									17.5	15.5	14.0	12.5	10.5	9.0	7.5	5.5
500									18.5	17.0	15.0	13.0	11.5	9.5	8.0	6.0

Note: Slab Width = 3.5 m

Table D.3: Preliminary TI for PCC Fatigue Damage=1, Sacramento County
(Cast Slab, k= 0.05 MPa/mm)

PCC Layer Thickness (mm)	Slab Length (mm)															
	3000	3100	3200	3300	3400	3500	3600	3700	3800	3900	4000	4100	4200	4300	4400	4500
250	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
260	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
270	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
280	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
290	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
300	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
310	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
320	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0
330	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0
340	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0
350	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0
360	3.0	3.0	2.5	2.5	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.0	1.0	1.0	0.5	0.5
370	5.0	5.0	4.5	4.5	4.0	3.5	3.5	3.0	3.0	2.5	2.0	2.0	1.5	1.5	1.0	1.0
380	7.0	7.0	6.5	6.0	5.5	5.0	5.0	4.5	4.0	3.5	3.0	3.0	2.5	2.0	1.5	1.0
390	9.5	9.0	8.0	7.5	7.0	6.5	6.0	5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5
400	11.5	10.5	10.0	9.5	9.0	8.0	7.5	7.0	6.5	5.5	5.0	4.5	4.0	3.0	2.5	2.0
410	13.5	12.5	12.0	11.0	10.5	9.5	9.0	8.5	7.5	7.0	6.0	5.5	4.5	4.0	3.0	2.5
420	15.5	14.5	14.0	13.0	12.0	11.0	10.5	9.5	8.5	8.0	7.0	6.0	5.5	4.5	3.5	3.0
430	17.5	16.5	15.5	14.5	13.5	13.0	12.0	11.0	10.0	9.0	8.0	7.0	6.0	5.0	4.0	3.0
440		18.5	17.5	16.5	15.5	14.5	13.0	12.0	11.0	10.0	9.0	8.0	7.0	5.5	4.5	3.5
450				18.0	17.0	16.0	14.5	13.5	12.0	11.0	10.0	8.5	7.5	6.5	5.0	4.0
460					18.5	17.5	16.0	14.5	13.5	12.0	11.0	9.5	8.5	7.0	5.5	4.5
470							17.5	16.0	14.5	13.0	12.0	10.5	9.0	7.5	6.0	5.0
480								17.5	16.0	14.5	13.0	11.0	9.5	8.0	6.5	5.0
490								18.5	17.0	15.5	13.5	12.0	10.5	9.0	7.0	5.5
500									18.0	16.5	14.5	13.0	11.0	9.5	7.5	6.0

Note: Slab Width = 3.5 m

**Table D.4: Preliminary TI for PCC Fatigue Damage=1, Sacramento County
(Cast Slab, k= 0.08 MPa/mm)**

PCC Layer Thickness (mm)	Slab Length (mm)															
	3000	3100	3200	3300	3400	3500	3600	3700	3800	3900	4000	4100	4200	4300	4400	4500
250	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
260	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
270	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
280	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
290	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
300	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
310	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
320	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0
330	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0
340	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0
350	1.0	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0
360	3.0	3.0	2.5	2.5	2.0	2.0	2.0	1.5	1.5	1.5	1.0	1.0	0.5	0.5	0.5	0.0
370	5.0	4.5	4.5	4.0	3.5	3.5	3.0	3.0	2.5	2.0	2.0	1.5	1.5	1.0	0.5	0.5
380	7.0	6.5	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0	2.5	2.5	2.0	1.5	1.0	0.5
390	8.5	8.0	7.5	7.0	6.5	6.0	5.5	5.0	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
400	10.5	10.0	9.5	8.5	8.0	7.5	7.0	6.0	5.5	5.0	4.0	3.5	3.0	2.5	1.5	1.0
410	12.5	12.0	11.0	10.5	9.5	9.0	8.0	7.5	6.5	6.0	5.0	4.0	3.5	2.5	2.0	1.0
420	14.5	13.5	13.0	12.0	11.0	10.0	9.5	8.5	7.5	6.5	6.0	5.0	4.0	3.0	2.5	1.5
430	16.5	15.5	14.5	13.5	12.5	11.5	10.5	9.5	8.5	7.5	6.5	5.5	4.5	3.5	2.5	1.5
440	18.5	17.5	16.0	15.0	14.0	13.0	12.0	10.5	9.5	8.5	7.5	6.0	5.0	4.0	3.0	2.0
450			18.0	16.5	15.5	14.0	13.0	12.0	10.5	9.5	8.0	7.0	5.5	4.5	3.0	2.0
460				18.5	17.0	15.5	14.0	13.0	11.5	10.0	9.0	7.5	6.0	5.0	3.5	2.0
470					18.5	17.0	15.5	14.0	12.5	11.0	9.5	8.0	7.0	5.5	4.0	2.5
480						18.5	16.5	15.0	13.5	12.0	10.5	9.0	7.5	5.5	4.0	2.5
490							18.0	16.5	14.5	13.0	11.0	9.5	8.0	6.0	4.5	3.0
500								17.5	15.5	14.0	12.0	10.0	8.5	6.5	5.0	3.0

Note: Slab Width = 3.5 m

Appendix E: Preliminary Structural Design Tables for RHMA-O Surfaces with no Subbase

Table E.1: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County (RHMA-O, no Subbase, E_GB= 60 MPa, Speed= 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
215	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
230	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
245	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
260	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
275	10.5	10.5	10.5	10.0	10.5	10.5	10.5	10.0	10.5	10.5	10.5	10.5	10.5	10.0	10.5	10.5	10.5	10.0	10.5	10.5	10.5
290	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
305	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
320	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
335	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
350	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
365	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
380	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
395	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
410	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
425	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.5	16.5	16.5	16.5	16.5	16.5	17.0
440	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	17.0	17.0	17.0	17.0	17.5	17.5	17.5	17.5	18.0
455	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.5	17.5	17.5	18.0	18.0	18.0	18.5	18.5	18.5	
470	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.5	18.5						
485	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5									
500																					

Table E.2: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County (RHMA-O, no Subbase, E_GB= 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table E.3: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County (RHMA-O, no Subbase, E_GB= 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
215	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
230	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
245	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
260	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
275	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
290	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
305	13.5	13.5	13.5	13.0	13.5	13.5	13.5	13.0	13.5	13.5	13.5	13.5	13.5	13.0	13.5	13.5	13.5	13.0	13.5	13.5	13.5
320	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
335	15.0	15.0	14.5	14.5	15.0	15.0	15.0	14.5	14.5	15.0	15.0	15.0	14.5	14.5	15.0	15.0	15.0	14.5	14.5	15.0	15.0
350	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
365	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
380	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
395	17.5	18.0	18.0	18.0	18.0	17.5	18.0	18.0	18.0	18.0	17.5	18.0	18.0	18.0	18.0	17.5	18.0	18.0	18.0	18.0	17.5
410	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5		
425																					
440																					
455																					
470																					
485																					
500																					

Table E.4: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County (RHMA-O, no Subbase, E_GB= 60 MPa, Speed = 40 km/h)

		Granular Base (GB) Layer Thickness (mm)																				
		500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
HMA Layer Thickness (mm)	200	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	215	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	230	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
	500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table E.5: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County (RHMA-O, no Subbase, E_GB = 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
215	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
230	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
245	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
260	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
275	9.5	9.5	9.5	9.0	9.5	9.5	9.5	9.0	9.5	9.5	9.5	9.5	9.5	9.0	9.5	9.5	9.5	9.0	9.5	9.5	9.5
290	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
305	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
320	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
335	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
350	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
365	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
380	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
395	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
410	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
425	14.0	14.0	14.0	13.5	14.0	14.0	14.0	13.5	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.5	14.5	14.5	14.5
440	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.5	14.5	14.5	14.5	15.0	15.0	15.0	15.0	15.5	15.5
455	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	15.0	15.0	15.0	15.5	15.5	15.5	16.0	16.0	16.0	16.5
470	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.5	15.5	15.5	16.0	16.0	16.5	16.5	17.0	17.0	17.0
485	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	16.0	16.0	16.5	16.5	17.0	17.0	17.5	17.5	18.0	18.0
500	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.5	16.5	17.0	17.0	17.5	18.0	18.0	18.5	18.5	

Table E.6: Preliminary Stress-to-Strength Ratio at Top of Subgrade for AC Structure, Sacramento County (RHMA-O, no Subbase, E_GB = 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	Y	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table E.7: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County (RHMA-O, no Subbase, E_GB = 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
215	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
230	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
245	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
260	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
275	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5
290	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.0	11.0	11.0	11.0	11.0	11.0	10.5
305	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	11.5	11.5	11.5	11.5	11.5	11.0
320	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.0	12.0	12.0	12.0	12.0	12.0
335	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	12.5	12.5	12.5	12.5	12.5	12.5
350	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.0	13.0	13.0	13.0	13.0
365	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	13.5	13.5	13.5	13.5	13.5
380	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.0	14.0	14.0
395	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
410	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
425	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.5	16.5	16.5	16.5	16.5	16.5	17.0
440	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	17.0	17.0	17.0	17.0	17.5	17.5	17.5	17.5	18.0
455	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.5	17.5	17.5	18.0	18.0	18.0	18.5	18.5	18.5	
470	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.5	18.5						
485	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5									
500																					

Table E.8: Preliminary Stress-to-Strength Ratio at Top of Subgrade for AC Structure, Sacramento County (RHMA-O, no Subbase, E_GB = 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Appendix F: Preliminary Structural Design Tables for RHMA-O Surfaces with Subbase

Table F.1: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County
(RHMA-O, with Subbase, E_GB= 60 MPa, Speed= 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
215	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
230	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
245	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
260	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
275	12.0	12.0	12.0	11.5	12.0	12.0	12.0	11.5	12.0	12.0	12.0	12.0	12.0	11.5	12.0	12.0	12.0	11.5	12.0	12.0	12.0
290	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
305	13.5	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
320	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
335	15.0	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
350	15.5	15.5	15.5	15.5	15.5	15.5	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
365	16.5	16.0	16.0	16.0	16.0	16.0	16.0	16.0	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
380	17.0	17.0	17.0	17.0	16.5	16.5	16.5	16.5	16.5	16.5	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
395	17.5	17.5	17.5	17.5	17.5	17.5	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
410	18.5	18.5	18.5	18.0	18.0	18.0	18.0	18.0	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5
425							18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5
440																					
455																					
470																					
485																					
500																					

Table E.2: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County (RHMA-O, with Subbase, E_GB= 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table F.3: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County (RHMA-O, with Subbase, E_GB= 60 MPa, Speed = 40 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	9.0	9.0	9.0	8.5	8.5	8.5	8.5	8.5	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
215	10.0	9.5	9.5	9.5	9.5	9.5	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
230	10.5	10.5	10.5	10.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
245	11.5	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
260	12.0	12.0	12.0	12.0	12.0	12.0	12.0	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
275	13.0	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
290	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
305	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.0
320	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
335	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
350	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	16.5	16.5	16.5	16.5	16.5
365	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5
380												18.5	18.5	18.5	18.5	18.5	18.5	18.0	18.0	18.0	18.0
395																					
410																					
425																					
440																					
455																					
470																					
485																					
500																					

Table F.4: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County (RHMA-O, with Subbase, E_GB= 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table F.5: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County (RHMA-O, with Subbase, E_GB = 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	7.0	7.0	7.0	6.5	6.5	6.5	6.5	6.5	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
215	7.5	7.0	7.0	7.0	7.0	7.0	7.0	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
230	7.5	7.5	7.5	7.5	7.5	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
245	8.0	8.0	8.0	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
260	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
275	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
290	9.0	9.0	9.0	9.0	9.0	9.0	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
305	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
320	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
335	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
350	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
365	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
380	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
395	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
410	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
425	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.5	13.5	13.5	13.5
440	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.0	13.0	13.5	13.5	13.5	13.5	14.0	14.0	14.0	14.0	14.5	14.5
455	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	13.5	13.5	14.0	14.0	14.0	14.5	14.5	14.5	15.0	15.0	15.0	15.5
470	15.0	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.0	14.0	14.0	14.5	14.5	14.5	15.0	15.0	15.5	15.5	16.0	16.0	16.0
485	15.5	15.5	15.0	15.0	15.0	15.0	15.0	15.0	14.5	14.5	14.5	15.0	15.0	15.5	15.5	16.0	16.0	16.5	16.5	17.0	17.0
500	16.0	16.0	16.0	15.5	15.5	15.5	15.5	15.5	15.0	15.0	15.0	15.5	15.5	16.0	16.0	16.5	17.0	17.0	17.5	17.5	18.0

Table F.6: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Sacramento County (RHMA-O, with Subbase, E_GB = 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table F.7: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County (RHMA-O, with Subbase, E_GB = 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	8.0	8.0	8.0	7.5	7.5	7.5	7.5	7.5	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
215	8.5	8.5	8.5	8.0	8.0	8.0	8.0	8.0	8.0	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
230	9.0	9.0	9.0	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
245	9.5	9.5	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
260	10.0	10.0	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
275	10.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
290	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
305	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
320	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
335	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
350	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
365	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
380	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
395	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
410	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
425	15.5	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.5	15.5	15.5	15.5	15.5	15.5	16.0
440	16.0	16.0	16.0	16.0	16.0	16.0	16.0	15.5	15.5	15.5	15.5	15.5	16.0	16.0	16.0	16.0	16.5	16.5	16.5	16.5	17.0
455	17.0	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.0	16.5	16.5	16.5	17.0	17.0	17.0	17.5	17.5	17.5	18.0
470	17.5	17.5	17.5	17.5	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.5	17.5	18.0	18.0	18.5	18.5	18.5	
485	18.5	18.0	18.0	18.0	18.0	18.0	17.5	17.5	17.5	17.5	17.5	17.5	18.0	18.0	18.5	18.5					
500				18.5	18.5	18.5	18.5	18.5	18.0	18.0	18.0	18.5	18.5								

Table F.8: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Sacramento County (RHMA-O, with Subbase, E_GB = 60 MPa, Speed = 40 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Appendix G: Preliminary Structural Design Tables for G125 HMA-O Surfaces, no Subbase

Table G.1: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County
(G125 HMA-O, no Subbase, E_GB= 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
215	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
230	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
245	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
260	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
275	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
290	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
305	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
320	17.5	17.5	17.5	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
335	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5
350																					
365																					
380																					
395																					
410																					
425																					
440																					
455																					
470																					
485																					
500																					

Table G.2: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County (G125 HMA-O, no Subbase, E_GB= 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table G.3: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County (G125 HMA-O, no Subbase, E_GB= 60 MPa, Speed = 40 km/h)

		Granular Base (GB) Layer Thickness (mm)																				
		500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
HMA Layer Thickness (mm)	200	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
	215	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
	230	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
	245	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
	260	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
	275																					
	290																					
	305																					
	320																					
	335																					
	350																					
	365																					
	380																					
	395																					
	410																					
	425																					
	440																					
	455																					
	470																					
	485																					
	500																					

Table G.4: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County (G125 HMA-O, no Subbase, E_GB = 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table G.5: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County
(G125 HMA-O, no Subbase, E_GB = 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
215	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
230	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
245	8.0	8.0	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
260	8.5	8.5	8.5	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
275	9.0	9.0	9.0	9.0	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
290	9.5	9.5	9.5	9.5	9.0	9.0	9.0	9.0	9.0	9.0	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
305	10.0	10.0	10.0	10.0	10.0	9.5	9.5	9.5	9.5	9.5	9.0	9.5	9.5	9.5	9.5	9.0	9.5	9.5	9.5	9.5	9.0
320	11.0	10.5	10.5	10.5	10.5	10.5	10.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
335	11.5	11.5	11.5	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	10.5	11.0	11.0	11.0	11.0	11.0	10.5	11.0	11.0
350	12.0	12.0	12.0	12.0	12.0	12.0	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5
365	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.0	12.5	12.5	12.5	12.0	12.5	12.5	12.5
380	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
395	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	13.5	13.5	14.0	13.5	14.0	13.5	14.0	13.5	14.0	13.5	13.5
410	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
425	15.5	15.5	15.5	15.0	15.5	15.5	15.5	15.0	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	16.0
440	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.5	16.5	16.5	16.5	16.5	16.5	17.0
455	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.5	17.5	17.5	17.5	17.5	18.0
470	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	18.0	18.0	18.0	18.0	18.5	18.5	18.5		
485	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5								
500																					

Table G.6: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Sacramento County (G125 HMA-O, no Subbase, E_GB = 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	Y	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

**Table G.7: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County
(G125 HMA-O, no Subbase, E_GB = 60 MPa, Speed = 40 km/h)**

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
215	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
230	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
245	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
260	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
275	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
290	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
305	11.5	11.0	11.5	11.0	11.5	11.5	11.5	11.0	11.5	11.0	11.5	11.0	11.5	11.0	11.5	11.5	11.5	11.0	11.5	11.0	11.5
320	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
335	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
350	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
365	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
380	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
395	16.0	16.0	16.0	15.5	16.0	16.0	16.0	15.5	16.0	16.0	16.0	16.0	16.0	15.5	16.0	16.0	16.0	15.5	16.0	16.0	16.0
410	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
425	18.0	18.0	18.0	17.5	18.0	18.0	18.0	17.5	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.5	18.5	18.5	18.5
440																					
455																					
470																					
485																					
500																					

Table G.8: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Sacramento County (G125 HMA-O, no Subbase, E_GB = 60 MPa, Speed = 40 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Appendix H: Preliminary Structural Design Tables for G125 HMA-O Surfaces, with Subbase

Table H.1: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County (G125 HMA-O, with Subbase, E_GB= 60 MPa, Speed 7 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
215	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
230	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
245	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
260	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
275	15.5	15.0	15.0	15.0	15.0	15.0	15.0	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
290	16.5	16.0	16.0	16.0	16.0	16.0	16.0	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
305	17.5	17.5	17.0	17.0	17.0	17.0	17.0	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
320	18.5	18.5	18.5	18.5	18.5	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5
335																					
350																					
365																					
380																					
395																					
410																					
425																					
440																					
455																					
470																					
485																					
500																					

**Table H.2: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County
(G125 HMA-O, with Subbase, E_GB= 60 MPa, Speed = 7 km/h)**

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table H.3: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County (G125 HMA-O, with Subbase, E_GB= 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	13.0	13.0	13.0	12.5	12.5	12.5	12.5	12.5	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
215	14.5	14.5	14.0	14.0	14.0	14.0	14.0	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
230	15.5	15.5	15.5	15.5	15.5	15.0	15.0	15.0	15.0	15.0	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
245	17.0	17.0	17.0	17.0	16.5	16.5	16.5	16.5	16.5	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
260	18.5	18.5	18.0	18.0	18.0	18.0	18.0	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5
275																					
290																					
305																					
320																					
335																					
350																					
365																					
380																					
395																					
410																					
425																					
440																					
455																					
470																					
485																					
500																					

Table H.4: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County (G125 HMA-O, with Subbase, E_GB = 60 MPa, Speed = 40 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table H.5: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County
(G125 HMA-O, with Subbase, E_GB = 60 MPa, Speed = 7 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
215	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
230	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
245	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
260	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
275	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	8.5	8.5	8.5	8.5	8.5	8.5	8.5
290	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.0	9.0	9.0	9.0	9.0	9.0	8.5
305	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	9.5	9.5	9.5	9.5	9.5	9.0
320	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	10.5	10.5	10.5	10.5	10.5	10.5	10.0	10.0	10.0	10.0
335	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
350	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	11.5	11.5	11.5	11.5	11.5
365	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
380	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
395	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	13.5
410	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
425	15.5	15.5	15.5	15.0	15.5	15.5	15.5	15.0	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	16.0
440	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.5	16.5	16.5	16.5	16.5	16.5	17.0
455	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.5	17.5	17.5	17.5	17.5	18.0
470	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5	18.0	18.0	18.0	18.0	18.5	18.5	18.5		
485	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5								
500																					

**Table H.6: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Sacramento County
(G125 HMA-O, with Subbase, E_GB = 60 MPa, Speed = 7 km/h)**

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table H.7: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County
(G125 HMA-O, with Subbase, E_GB = 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
215	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
230	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
245	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
260	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
275	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
290	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
305	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.0	11.5	11.0	11.5	11.5	11.5	11.0	11.5	11.0	11.5
320	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
335	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
350	14.0	14.0	14.0	14.0	14.0	14.0	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
365	15.0	15.0	15.0	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5	14.5
380	16.0	15.5	15.5	15.5	15.5	15.5	15.5	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
395	16.5	16.5	16.5	16.5	16.5	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	15.5	16.0	16.0	16.0	15.5	16.0	16.0	16.0
410	17.5	17.5	17.5	17.5	17.0	17.0	17.0	17.0	17.0	17.0	16.5	16.5	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
425	18.5	18.5	18.5	18.5	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.5	18.5	18.5	18.5
440																					
455																					
470																					
485																					
500																					

Table H.8: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Sacramento County (G125 HMA-O, with Subbase, E_GB = 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Appendix I: Preliminary Structural Design Tables for HMA-O Surfaces, no Subbase

Table I.1: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County
(HMA-O, no Subbase, E_GB = 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
215	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
230	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
245	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
260	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
275	6.5	6.5	6.5	6.0	6.5	6.5	6.5	6.0	6.5	6.5	6.5	6.5	6.5	6.0	6.5	6.5	6.5	6.0	6.5	6.5	6.5
290	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
305	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
320	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
335	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
350	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
365	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
380	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
395	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
410	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	8.0	8.0	8.0	8.0	8.0	8.0
425	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.5
440	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
455	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
470	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.5	9.5	9.5	9.5	9.5	9.5
485	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.5	9.5	9.5	9.5	9.5	9.5	10.0	10.0	10.0	10.0
500	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	10.0	10.0	10.0	10.0	10.0	10.5	10.5	10.5

Table I.2: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County (HMA-O, no Subbase, E_GB = 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	Y	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table I.3: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County
(HMA-O, no Subbase, E_GB = 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
215	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
230	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
245	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
260	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
275	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
290	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
305	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
320	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
335	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
350	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
365	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
380	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
395	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
410	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	10.0	10.0	10.0	10.0	10.0	10.0
425	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.5
440	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
455	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
470	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.5	11.5	11.5	11.5	11.5	11.5
485	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.5	11.5	11.5	11.5	11.5	11.5	12.0	12.0	12.0	12.0
500	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	12.0	12.0	12.0	12.0	12.0	12.5	12.5	12.5

Table I.4: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County (HMA-O, no Subbase, E_GB = 60 MPa, Speed = 40 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table I.5: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County (HMA-O, no Subbase, E_GB = 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
215	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
230	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
245	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
260	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
275	6.0	6.0	6.0	5.5	6.0	6.0	6.0	5.5	6.0	6.0	6.0	6.0	6.0	5.5	6.0	6.0	6.0	5.5	6.0	6.0	6.0
290	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
305	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
320	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
335	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
350	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
365	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
380	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
395	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
410	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
425	7.5	7.5	7.5	7.0	7.5	7.5	7.5	7.0	7.5	7.5	7.5	7.5	7.5	7.0	7.5	7.5	7.5	7.0	7.5	7.5	7.5
440	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
455	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
470	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
485	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
500	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0

Table I.6: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Sacramento County (HMA-O, no Subbase, E_GB = 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	Y	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	Y	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table I.7: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County
(HMA-O, no Subbase, E_GB = 60 MPa, Speed = 40 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
215	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
230	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
245	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
260	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
275	3.5	3.5	3.5	3.0	3.5	3.5	3.5	3.0	3.5	3.5	3.5	3.5	3.5	3.0	3.5	3.5	3.5	3.0	3.5	3.5	3.5
290	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
305	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
320	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
335	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
350	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
365	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
380	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
395	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
410	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
425	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
440	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
455	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
470	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
485	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
500	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0

Table I.8: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Sacramento County (HMA-O, no Subbase, E_GB = 60 MPa, Speed = 40 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	Y	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	Y	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	Y	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	Y	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	Y	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	Y	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	Y	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Appendix J: Preliminary Structural Design Tables for HMA-O Surfaces, with Subbase

Table J.1: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County
(HMA-O, with Subbase, E_GB = 60 MPa, Speed = 7 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
215	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
230	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
245	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
260	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
275	6.5	6.5	6.5	6.0	6.5	6.5	6.5	6.0	6.5	6.5	6.5	6.5	6.5	6.0	6.5	6.5	6.5	6.0	6.5	6.5	6.5
290	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
305	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
320	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
335	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
350	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
365	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
380	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
395	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
410	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	8.0	8.0	8.0	8.0	8.0	8.0
425	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.5
440	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
455	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
470	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.5	9.5	9.5	9.5	9.5	9.5
485	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.5	9.5	9.5	9.5	9.5	9.5	10.0	10.0	10.0	10.0
500	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	10.0	10.0	10.0	10.0	10.0	10.5	10.5	10.5

**Table J.2: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County
(HMA-O, with Subbase, E_GB = 60 MPa, Speed = 7 km/h)**

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table J.3: Preliminary TI for HMA-O Fatigue Damage=1, Los Angeles County (HMA-O, with Subbase, E_GB = 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
215	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
230	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
245	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
260	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
275	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
290	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
305	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
320	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
335	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
350	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
365	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
380	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
395	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
410	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
425	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.5	10.5	10.5	10.5	10.5	10.5
440	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	11.0	11.0	11.0	11.0	11.0
455	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	11.0	11.0	11.0	11.0	11.5	11.5	11.5	11.5	11.5
470	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.5	11.5	11.5	11.5	12.0	12.0	12.0	12.5
485	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.5	11.5	11.5	12.0	12.0	12.0	12.5	12.5	12.5	13.0
500	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	11.5	12.0	12.0	12.5	12.5	12.5	13.0	13.0	13.5	13.5

Table J.4: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Los Angeles County (HMA-O, with Subbase, E_GB = 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table J.5: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County
(HMA-O, with Subbase, E_GB = 60 MPa, Speed = 7 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
215	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
230	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
245	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
260	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
275	6.0	6.0	6.0	5.5	6.0	6.0	6.0	5.5	6.0	6.0	6.0	6.0	6.0	5.5	6.0	6.0	6.0	5.5	6.0	6.0	6.0
290	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
305	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
320	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
335	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
350	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
365	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
380	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
395	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
410	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
425	7.5	7.5	7.5	7.0	7.5	7.5	7.5	7.0	7.5	7.5	7.5	7.5	7.5	7.0	7.5	7.5	7.5	7.0	7.5	7.5	7.5
440	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
455	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
470	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
485	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
500	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0

Table J.6: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Sacramento County (HMA-O, with Subbase, E_GB = 60 MPa, Speed = 7 km/h)

	Granular Base (GB) Layer Thickness (mm)																				
HMA Layer Thickness (mm)	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7

Table J.7: Preliminary TI for HMA-O Fatigue Damage=1, Sacramento County (HMA-O, with Subbase, E_GB = 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
215	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
230	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
245	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
260	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
275	6.0	6.0	6.0	5.5	6.0	6.0	6.0	5.5	6.0	6.0	6.0	6.0	6.0	5.5	6.0	6.0	6.0	5.5	6.0	6.0	6.0
290	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
305	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
320	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
335	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
350	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
365	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
380	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
395	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
410	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
425	7.5	7.5	7.5	7.0	7.5	7.5	7.5	7.0	7.5	7.5	7.5	7.5	7.5	7.0	7.5	7.5	7.5	7.0	7.5	7.5	7.5
440	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
455	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
470	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
485	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
500	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0

Table J.8: Preliminary Stress-to-Strength Ratio at Top of Subgrade, Sacramento County (HMA-O, with Subbase, E_GB = 60 MPa, Speed = 40 km/h)

HMA Layer Thickness (mm)	Granular Base (GB) Layer Thickness (mm)																				
	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1350	1400	1450	1500
200	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
215	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
230	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
245	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
260	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
275	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
290	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
305	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
320	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
335	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
350	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
365	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
380	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
395	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
410	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
425	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
440	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
455	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
470	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
485	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
500	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

Note: G--Stress-to-Strength Ratio <0.3; Y--0.3=<Stress-to-Strength Ratio <=0.7; R--Stress-to-Strength Ratio >0.7