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Summary of a Computer Modeling Study to Understand the Performance Properties of Fully Permeable Pavements

November 2010

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SUMMARY OF A COMPUTER MODELING STUDY TO UNDERSTAND THE PERFORMANCE PROPERTIES OF FULLY PERMEABLE PAVEMENTS

TECHNICAL MEMORANDUM

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November 30, 2010

California Department of Transportation

Division of Environmental Analysis

Storm Water Program

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15. Abstract
This technical memo presents a summary of the methods and results from a computer modeling study, undertaken to understand the performance under loading of fully permeable pavements. Input data for the models was obtained from the comprehensive laboratory investigation undertaken as part of the study and from California Department of Transportation databases. The results presented in this tech memo will be used to prepare pavement designs for fully permeable pavement pilot studies in California and to identify under what conditions they are appropriate to use. The preliminary pavement designs will be presented in a separate report.

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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 technical memorandum summarizes Task 2.

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 Tech Memo

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 under heavy traffic. The main purpose of this technical memorandum is to summarize the methods and results from the computer modeling study of open-graded asphalt, open-graded concrete and pervious concrete slab pavement performance under heavy truck loading. The results of the study will be used to produce preliminary structural designs for fully permeable pavement pilot studies and identify conditions if and under which fully permeable pavements can be used on Caltrans highways and facilities.

This technical memorandum is organized as follows:

1. Introduction to the study
2. Experimental designs
3. Example results
4. Summary and future work

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 the development of fully permeable pavement designs for use in areas that carry heavy truck traffic 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 *(1)* 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) *(2)*, American Concrete Pavement Association *(3)*, and Interlocking Concrete Pavement Institute *(4)* 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.

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 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 *(5)*. 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 Task 4.

The results of test sections should be used for validation and, if necessary, recalibration of the structural designs developed as part of this project. More detailed LCCA and LCA should be performed after construction, evaluation and performance validation of accelerated pavement test sections using the Heavy Vehicle Simulator (HVS) and field test sections, which will provide more realistic initial cost information and improved maintenance and rehabilitation cost estimates.

Chapter 3. Experimental Designs and Procedures

3.1 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 3.1. 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.

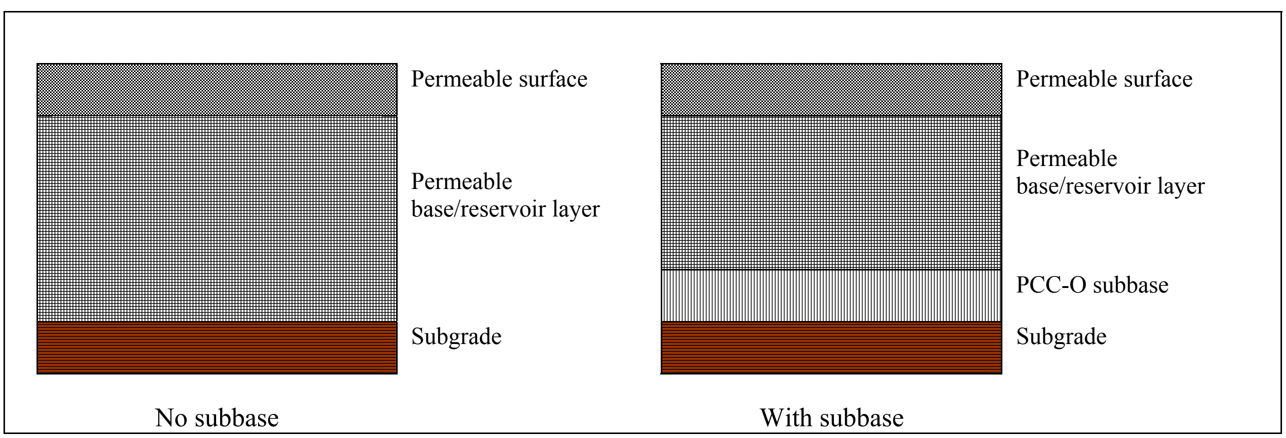

Figure 3.1: Pavement structures analyzed.

3.2 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 3.1. 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 3.2.

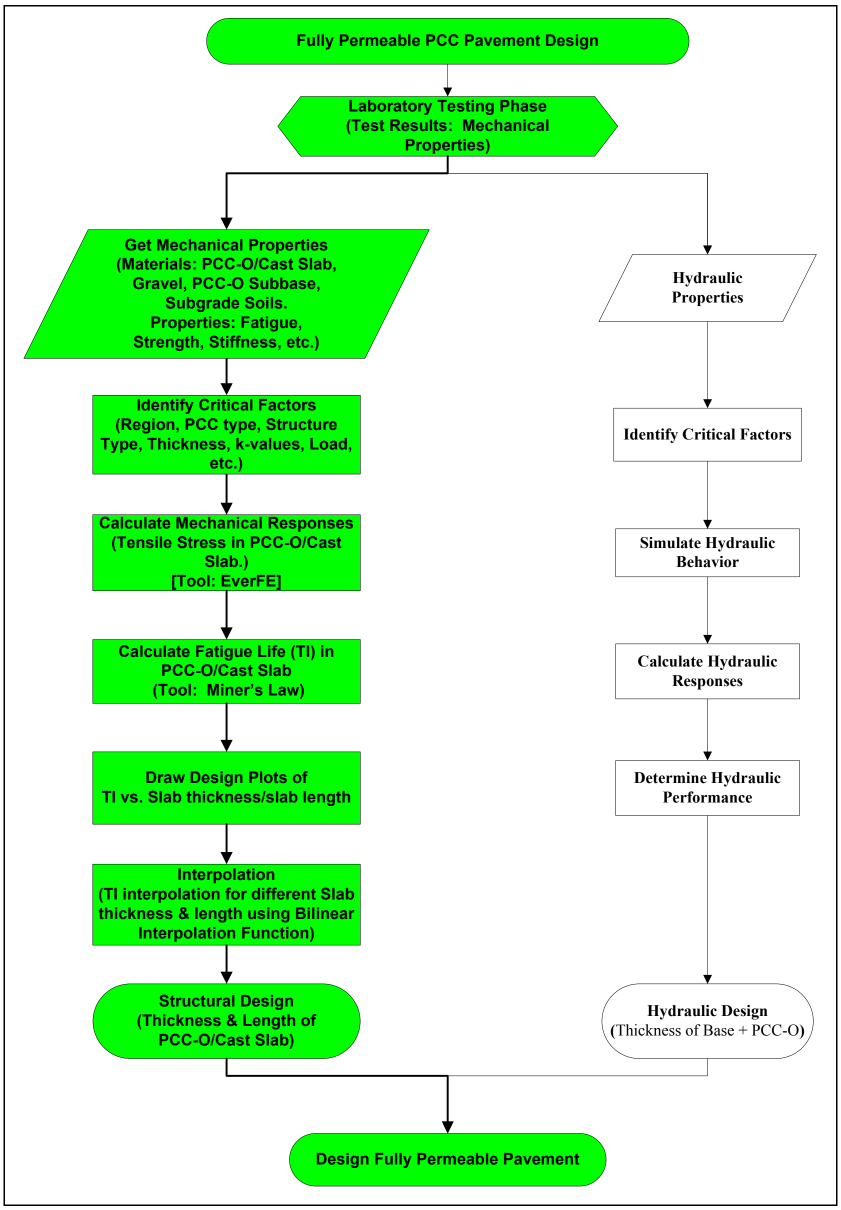

Figure 3.2: Analysis process for developing structural designs for fully permeable PCC pavements

Table 3.1: Summary of Experimental Design for Performance Modeling of PCC

Layer	Label	Material (M)	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 *(5)*. 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 3.3. 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 3.3). 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.

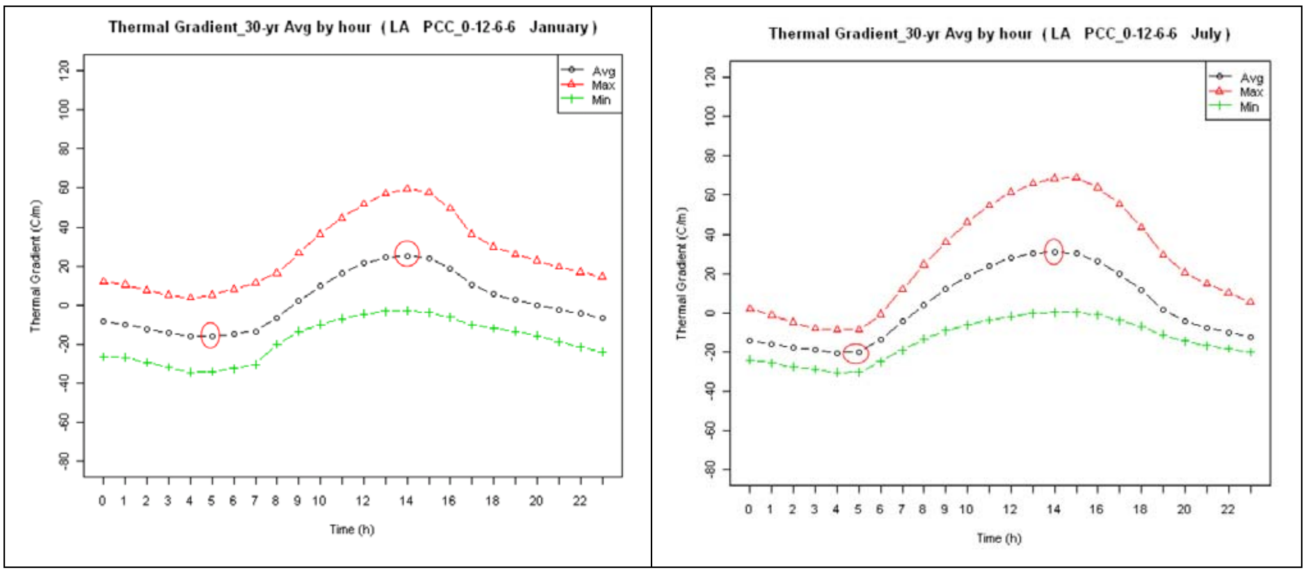

Figure 3.3: Example thermal gradient calculation for PCC pavements.

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) *(6)*. 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 3.2. The value of each factor was determined based on the statistical analysis of statewide traffic information from the UCPRC/Caltrans Weigh-in-Motion database *(6)*. 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 3.2: Load Spectrum Factors for PCC Structures

Seasonal Factor		Day/Night Factor		Axle Type Factor		ESAL Factor	
Winter	Summer	Day	Night	Single	Tandem	Single	Tandem
0.5	0.5	0.45	0.55	0.2	0.8	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

The various factors listed in Table 3.2 are explained as follows:

- Seasonal Factor. UCPRC WIM data study *(6)* 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 6 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 *(6)*. 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 *(6)*. This factor converts the ESALs in the Traffic Index into total axle repetitions. (See Figure 35 in Reference 6 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 *(7)* 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) *(10)*. 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 *(8)*, 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 3.1) 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. Structural designs for test sections and pilot studies will be developed from these results.

The Miner's Law equation is shown in Equation 3.1.

$$D = \sum_i \frac{n_i}{N_i} \tag{3.1}$$

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,

$$n_i = ESAL \times F_{seasonal} \times F_{day/night} \times F_{axletype} \times 1/F_{ESAL} \times F_{LB} \quad (3.2)$$

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 Fig 35 for years 1991 to 2000).
F_{LB} = Load bin factor.

Based on the laboratory fatigue testing results from this project (Figure 3.4)*(5)*, the Zero-Maintenance fatigue equation *(9)* was used to calculate the allowable repetitions under i^{th} condition (combination of factors shown in Equation 3.2) as follows (Equation 3.3):

$$N_i = 10^{17.61(1-\sigma_i/MR)} \quad (3.3)$$

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, and MR=2.6 MPa; for cast slabs considering stress concentration based on finite element analysis).

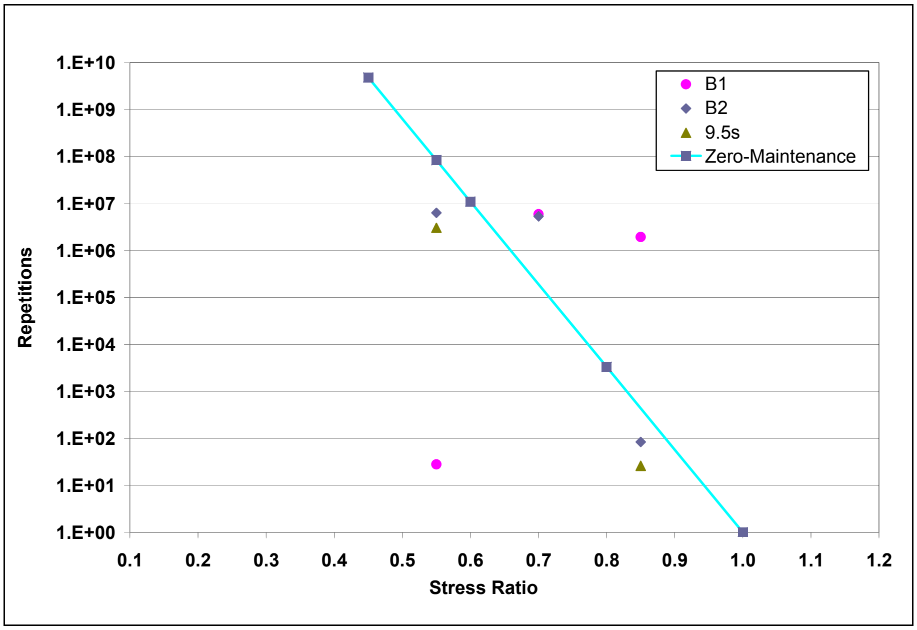

Figure 3.4: Fatigue life of open-graded concrete pavement (PCC-O).

3.3 Hot Mix Asphalt Surfacing

The factorial for performance modeling of permeable hot mix asphalt wearing courses is summarized in Table 3.3. A total of 15,552 different cases were run. The analysis process is summarized in Figure 3.5. 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.

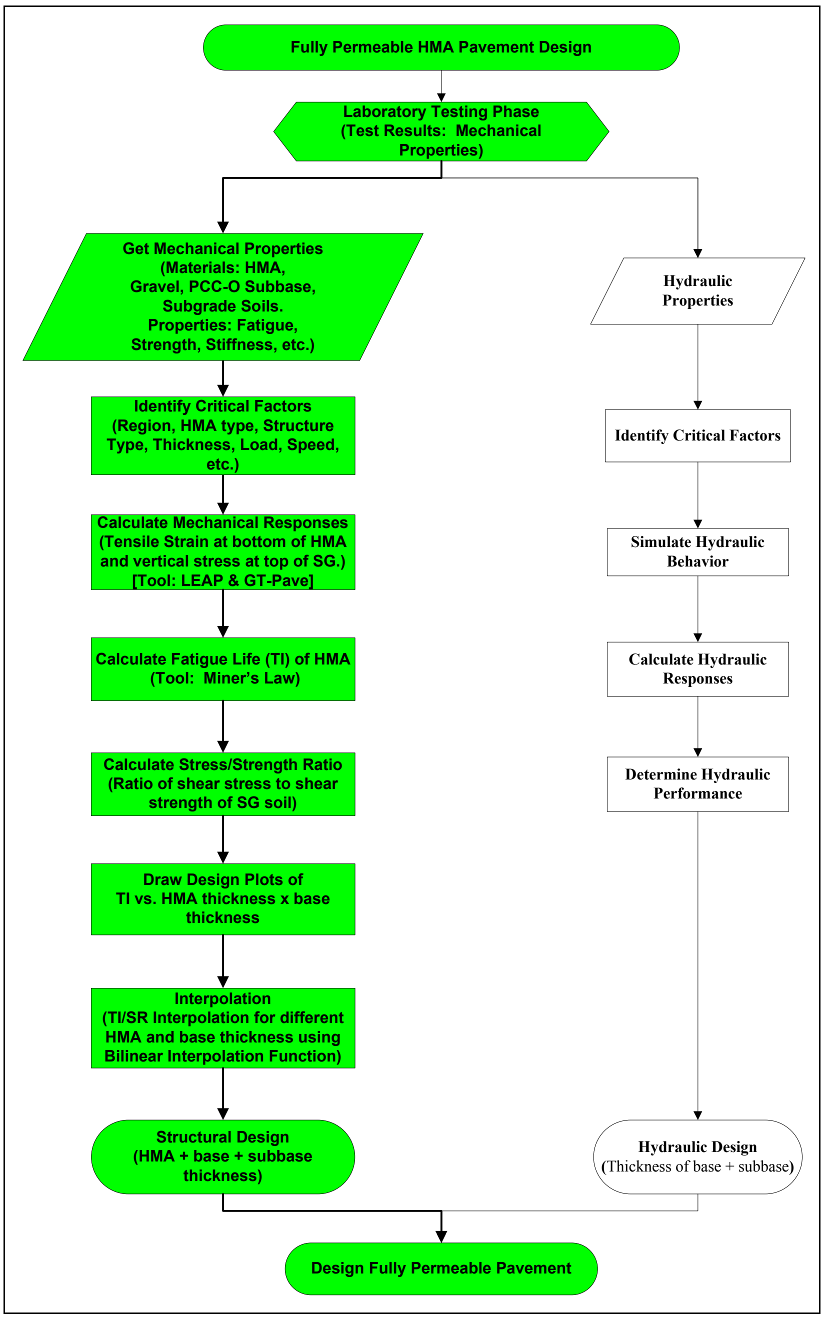

Figure 3.5: Analysis process for developing structural designs for fully permeable HMA pavements.

Table 3.3: 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 *(5)*. 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 Figure 3.6. 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 *(6)*.

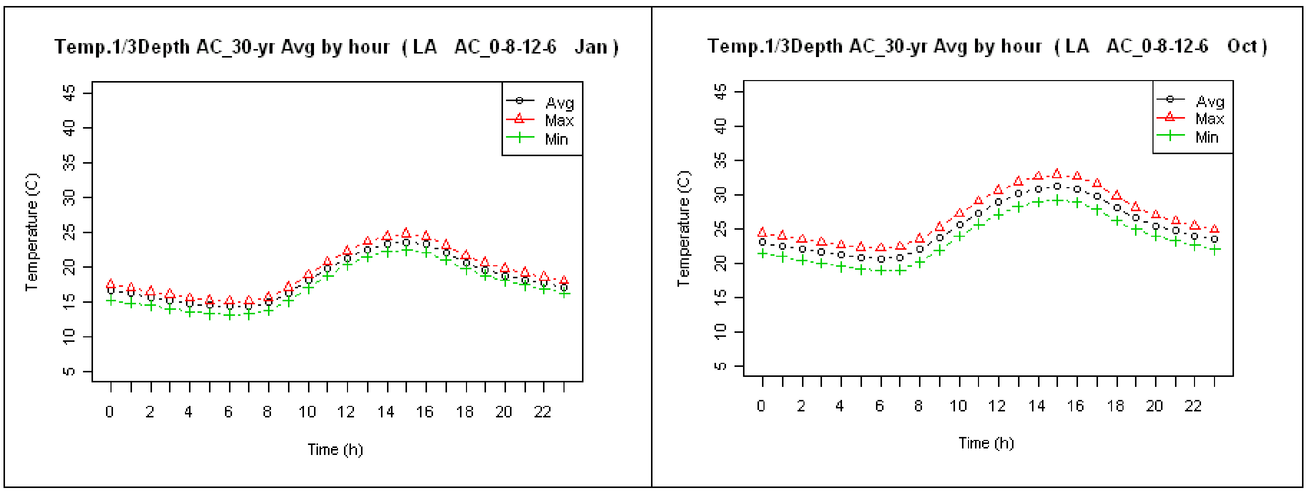

Figure 3.6: Example one-third depth temperatures for hot mix asphalt pavements.

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.

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 *(5)*. The loading frequency at one third thickness of the hot mix asphalt layer was calculated using Equation 3.4. 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 3.4.

$$freq = \frac{1}{t} = \frac{1}{L/v} = \frac{v}{L} = \frac{v}{D + 2 \times Th/3} \quad (3.4)$$

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

Table 3.4: 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

Note:

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: $\ln(aT) = A \cdot \left(1 - \exp\left(-\frac{T - Tref}{B}\right)\right)$

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 *(11)*.

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 3.7). 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 *(12)*. A range of values for different structural factors were selected for the structural response values of the granular base stiffness (Table 3.5). Figure 3.8 and Figure 3.9 show examples of the *GT-Pave* output for the stiffness of the granular base, with and without the cemented subbase. The Uzan model *(13)* was used to consider the non-linear behavior of the granular base using *GT-Pave*. The procedure proposed by Tutumluer and Thompson *(14)* was used to obtain cross-anisotropic parameters of the granular base for *GT-Pave* (Table 3.6). 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 3.5.

$$M_R = K_1 (\frac{\theta}{p_0})^{K_2} (\frac{\sigma_d}{p_0})^{K_3} \tag{3.5}$$

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.

Table 3.5: 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 3.6)		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 3.6: 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

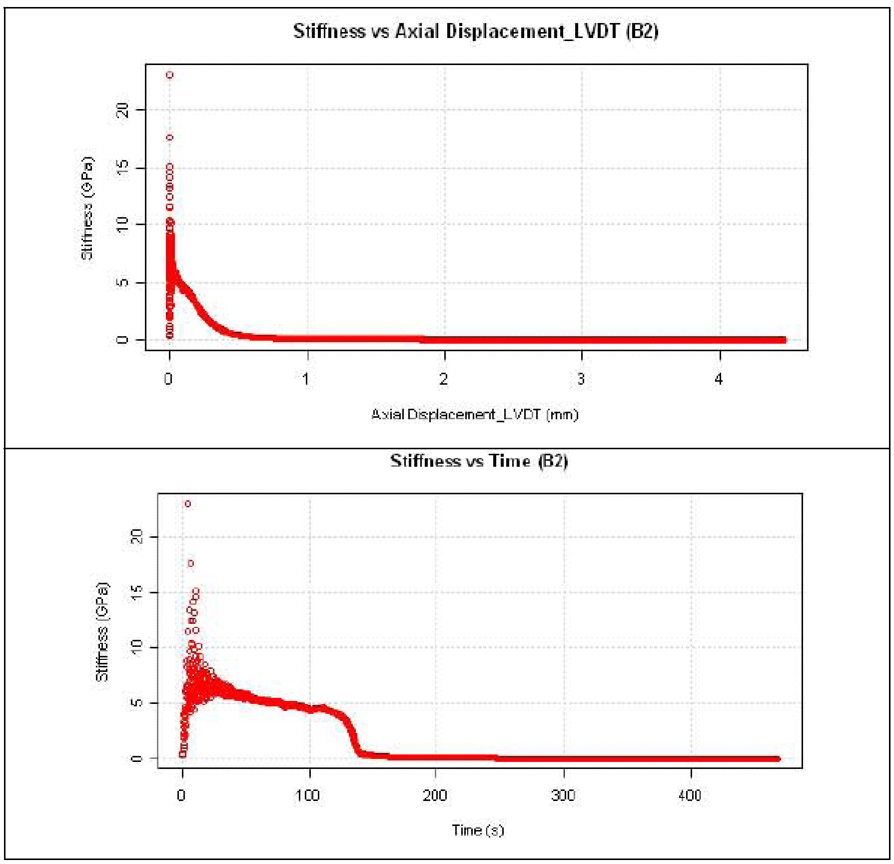

Figure 3.7: Example stiffness test results of PCC-O subbase material (B2 grading).
(Figure shows stiffness time from flexural strength test)

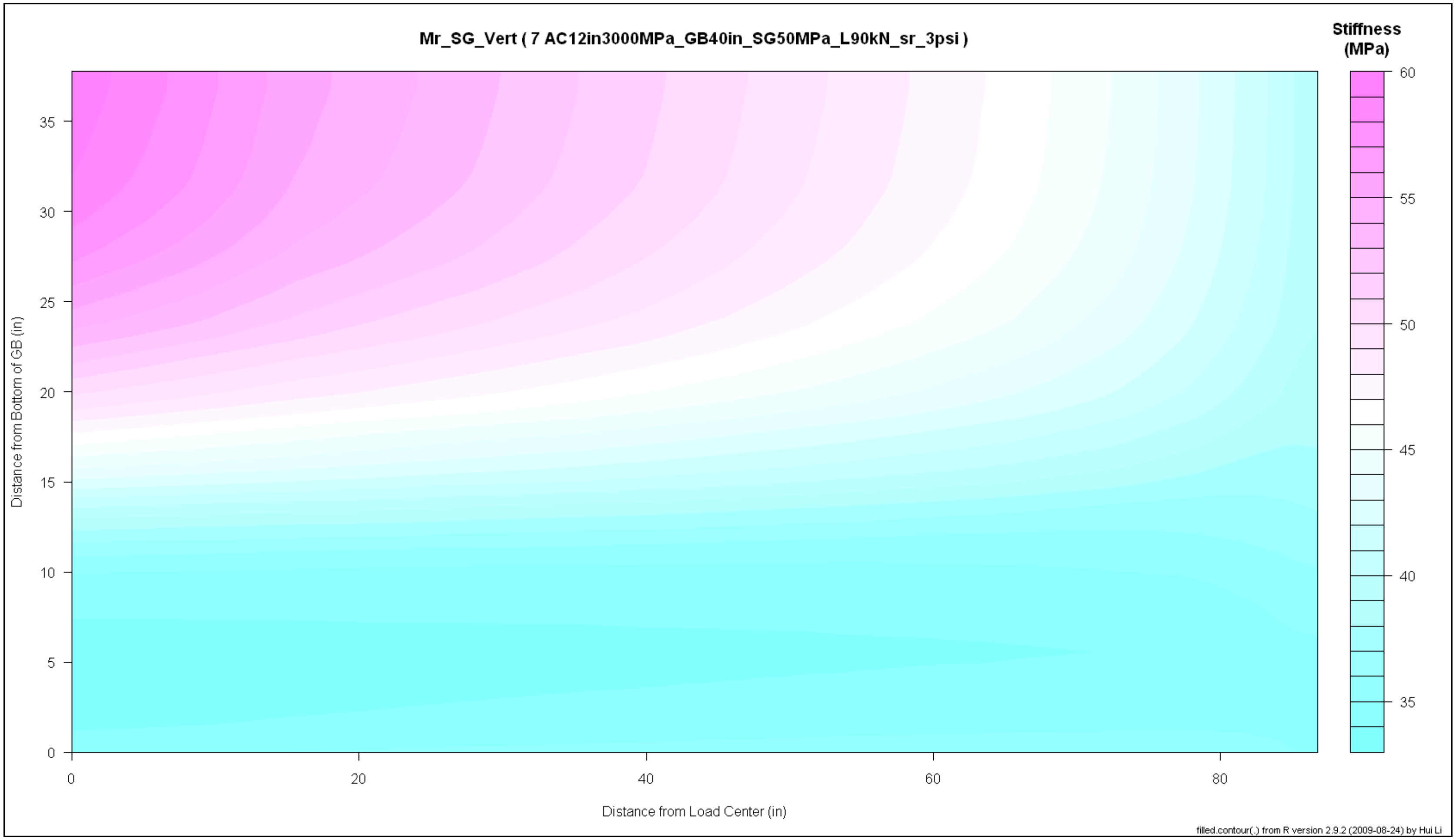

Figure 3.8: Stiffness of Granular Base from *GT-Pave* (without subbase)

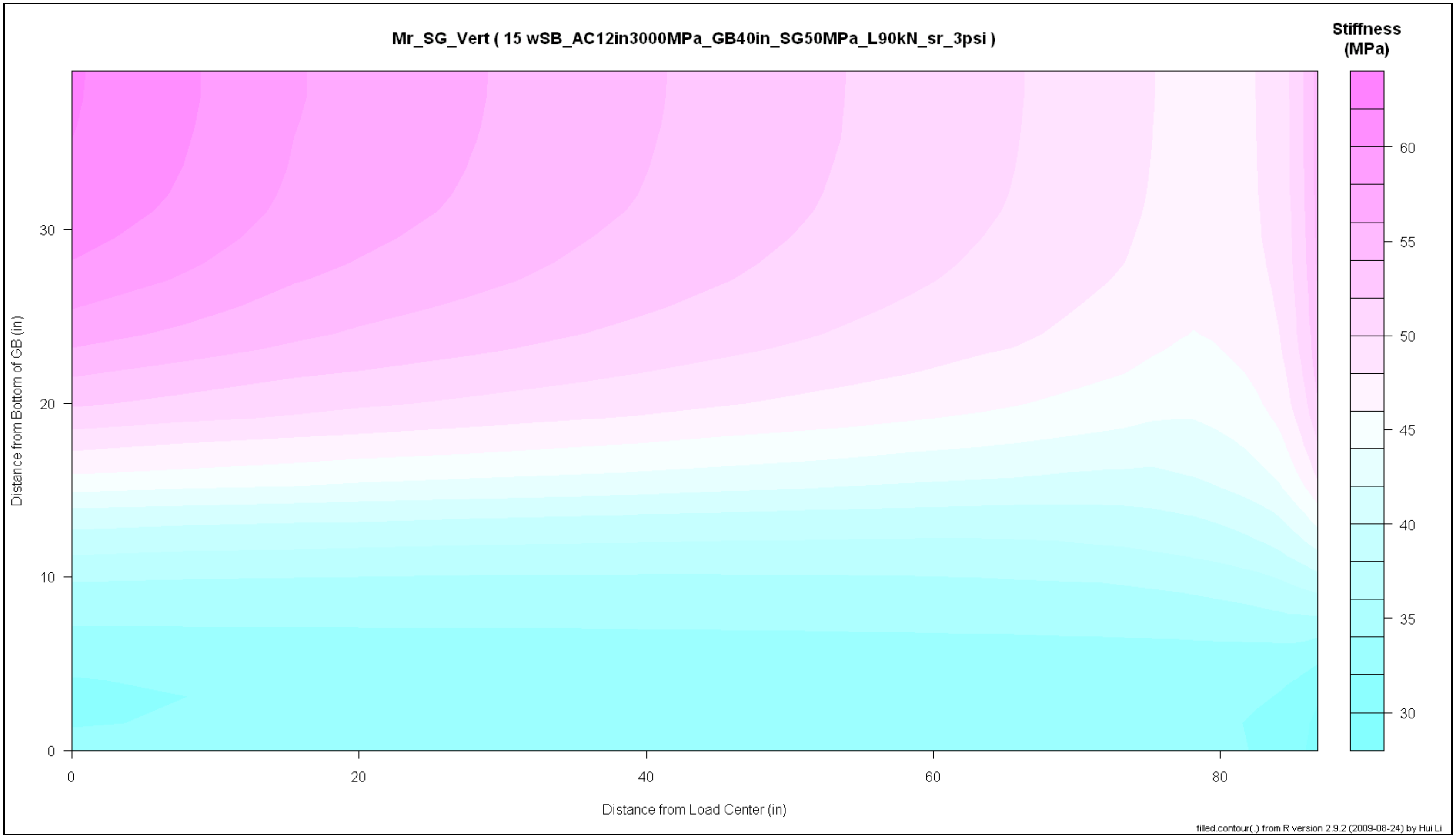

Figure 3.9: Stiffness of Granular Base from *GT-Pave* (with subbase)

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 3.7. The value for each factor was determined based on the statistical analysis of statewide traffic information from the UCPRC/Caltrans Weigh-in-Motion database *(6)*. 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 3.7: 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 3.1 and 3.2) 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 3.10. 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 3.1) 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 *(15)* 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). Continued permanent deformation of the subgrade after initial densification under traffic is unlikely when the stress/strength ratio (SR) is less than 0.3 *(11)*, 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 times the shear strength but greater than 0.3.

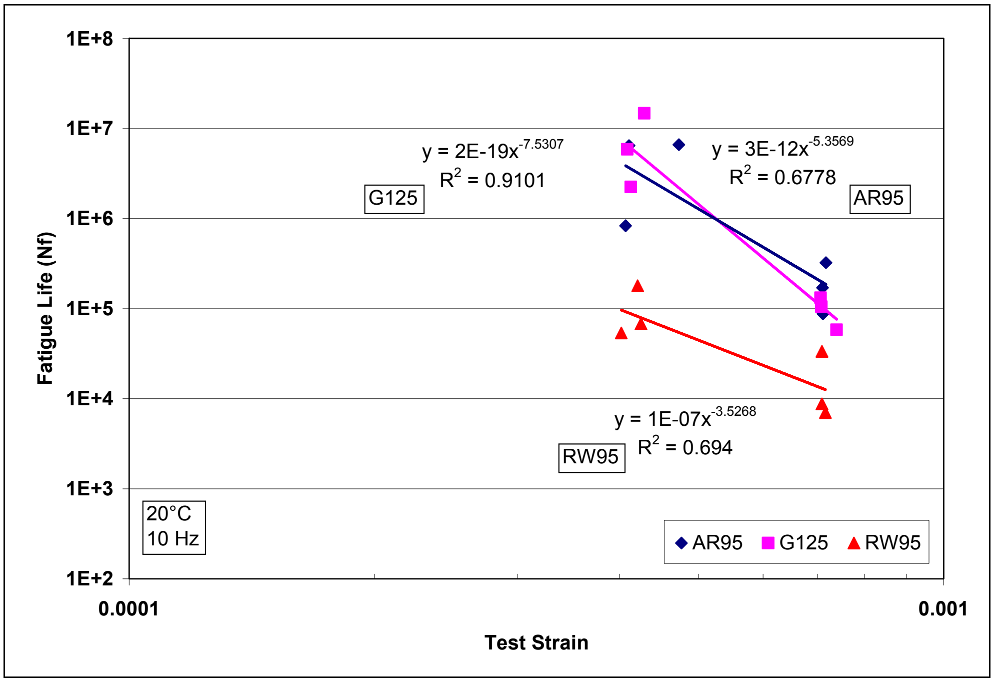

Figure 3.10: Summary of HMA-O fatigue life equations.

Results from these calculations were plotted to assess the influence of pavement layer combinations on the subgrade stress/strength ratio. 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. Structural designs for test sections and pilot studies will be developed from these results and discussed in the final report.

Chapter 4. Example Results

4.1 Portland Cement Concrete Surfaced Fully Permeable Pavement

Example predictions of design life (traffic index) 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

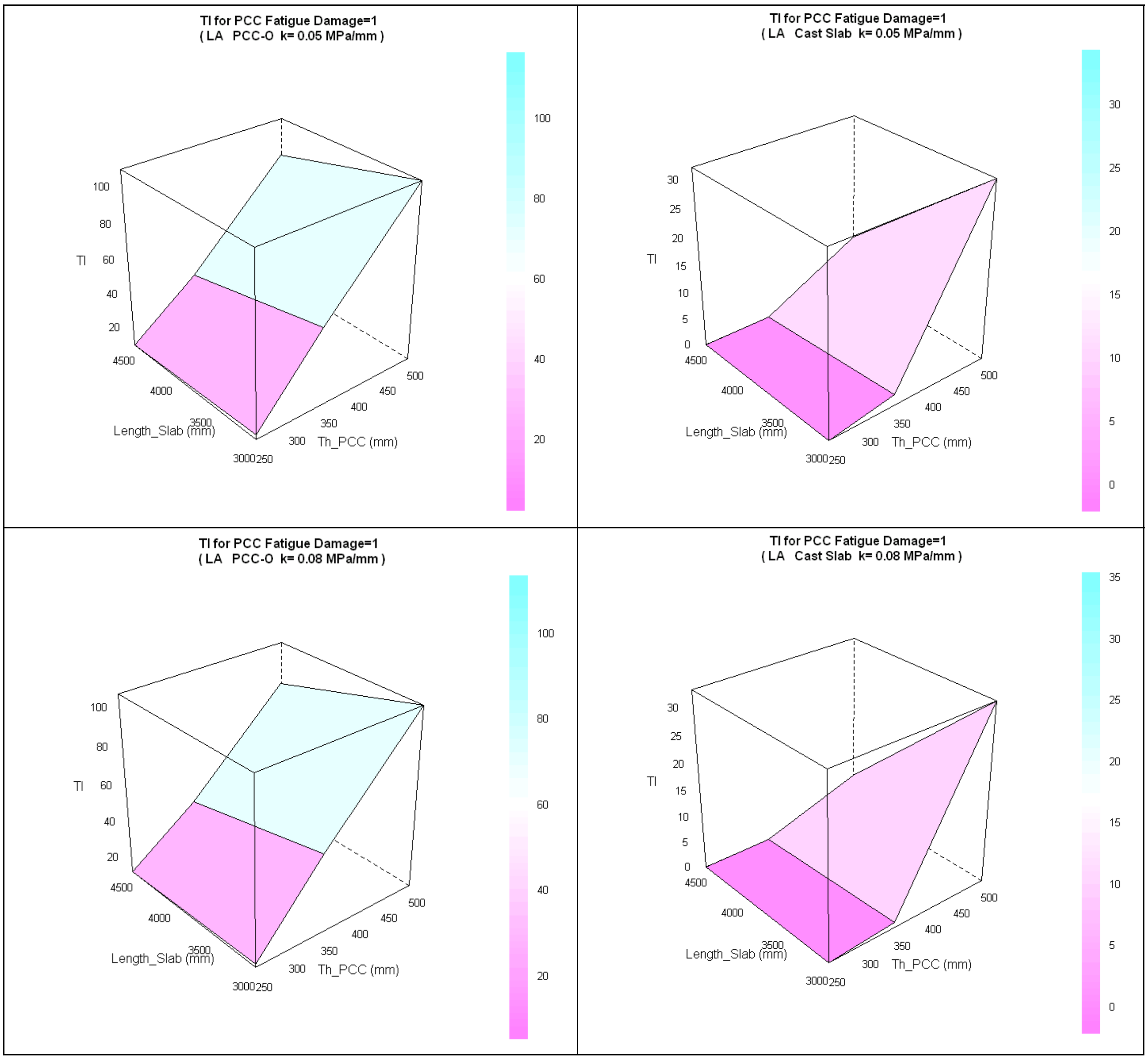

Figure 4.1 and Figure 4.2. These three dimensional surface plots show traffic index on the y-axis, slab length on the x1-axis and PCC thickness on the x2-axis. Note that different scales are used in the plots.

4.2 Hot Mix Asphalt Surface Fully Permeable Pavement

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) are shown in Figure 4.3 through Figure 4.8. In Figure 4.3 through Figure 4.6, three dimensional surface plots are used, with stress ratio on the y-axis, hot mix asphalt thickness on the x1-axis and aggregate base thickness on the x2-axis. Figure 4.9 and Figure 4.10 show example plots of the fatigue design life of the same pavements. Three dimensional surface plots are used, with fatigue design life on the y-axis, hot mix asphalt thickness on the x1-axis and granular base thickness on the x2-axis.

Note that an automatic scaling function was used in the analysis and consequently the plots have different scales.

4.3 Implications for Pavement Design of Fully Permeable Pavements

The results indicate that sufficient structural strength can be obtained with appropriate and reasonable pavement designs for fully permeable portland cement concrete and hot mix asphalt pavements. A methodology for selecting an appropriate pavement design for a given set of circumstances, as well as example cost estimates will be discussed in the final report. Although functional performance in terms of permeability was considered in the designs, functional performance in terms of raveling and clogging can only be quantified in full-scale experiments. Recommendations for full-scale experiments will also be provided in the final report.

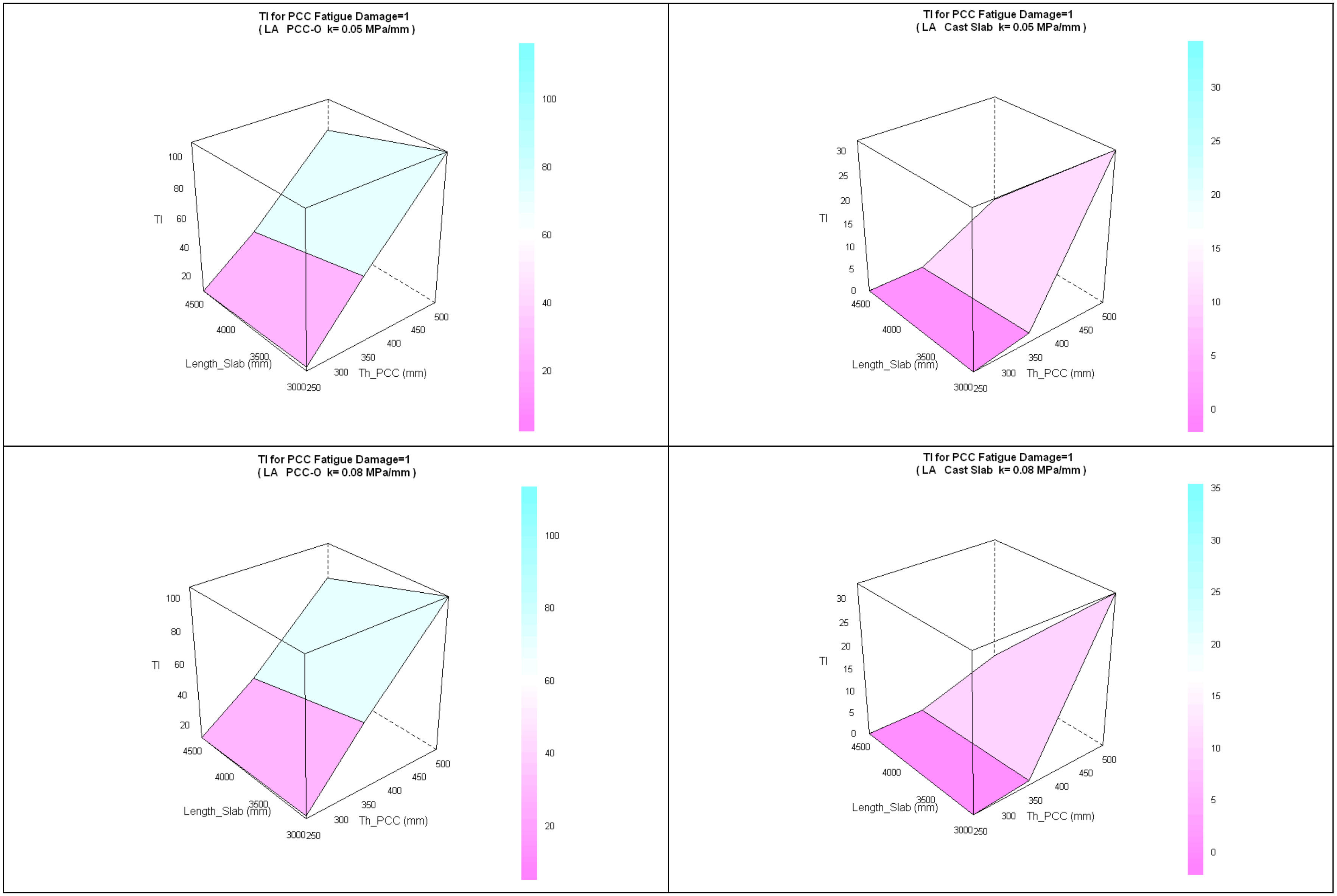

Figure 4.1: Example design life for PCC-O & cast PCC in Los Angeles County (3-D Surface Plots).

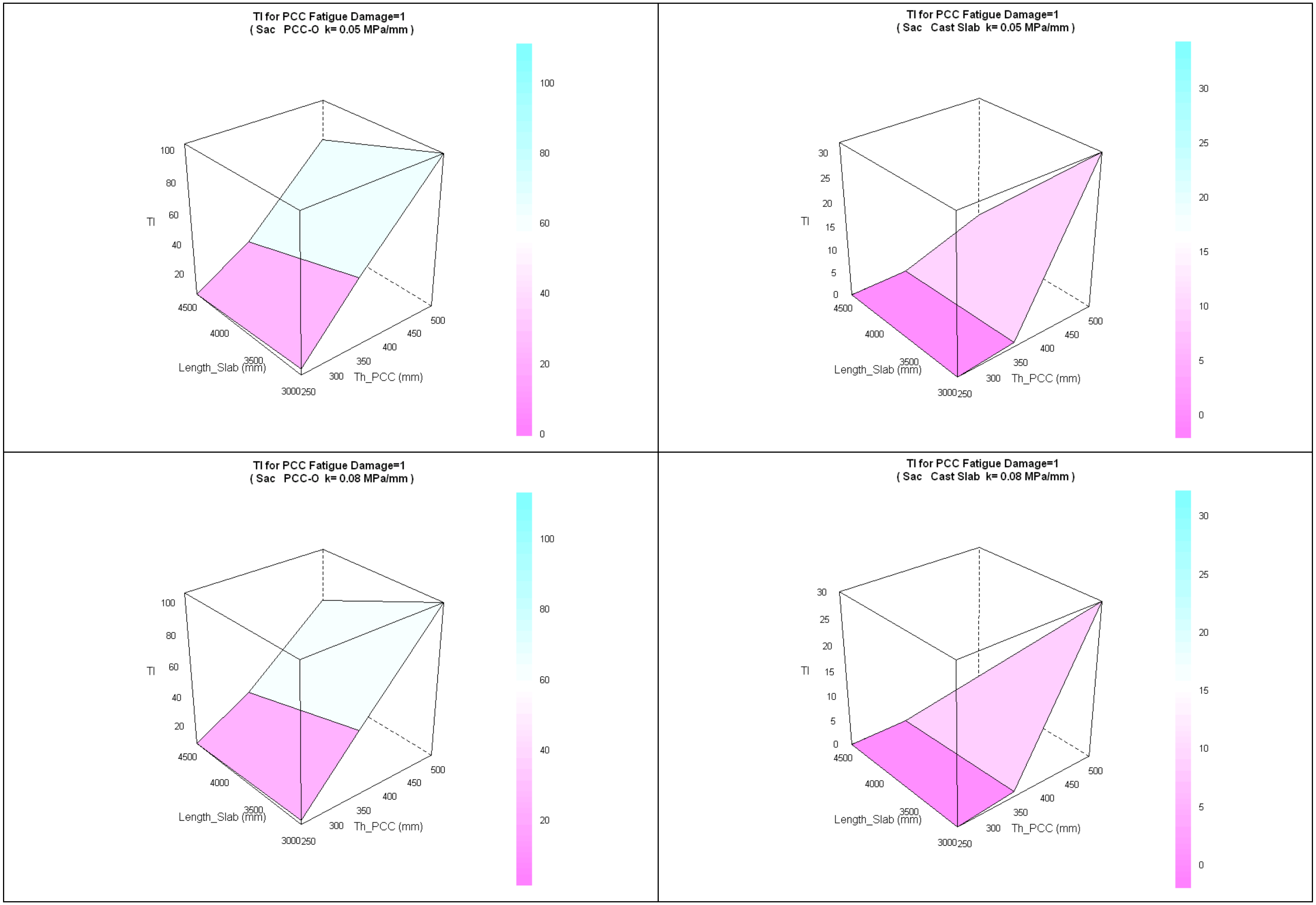

Figure 4.2: Example design life for PCC-O & cast PCC in Sacramento County.

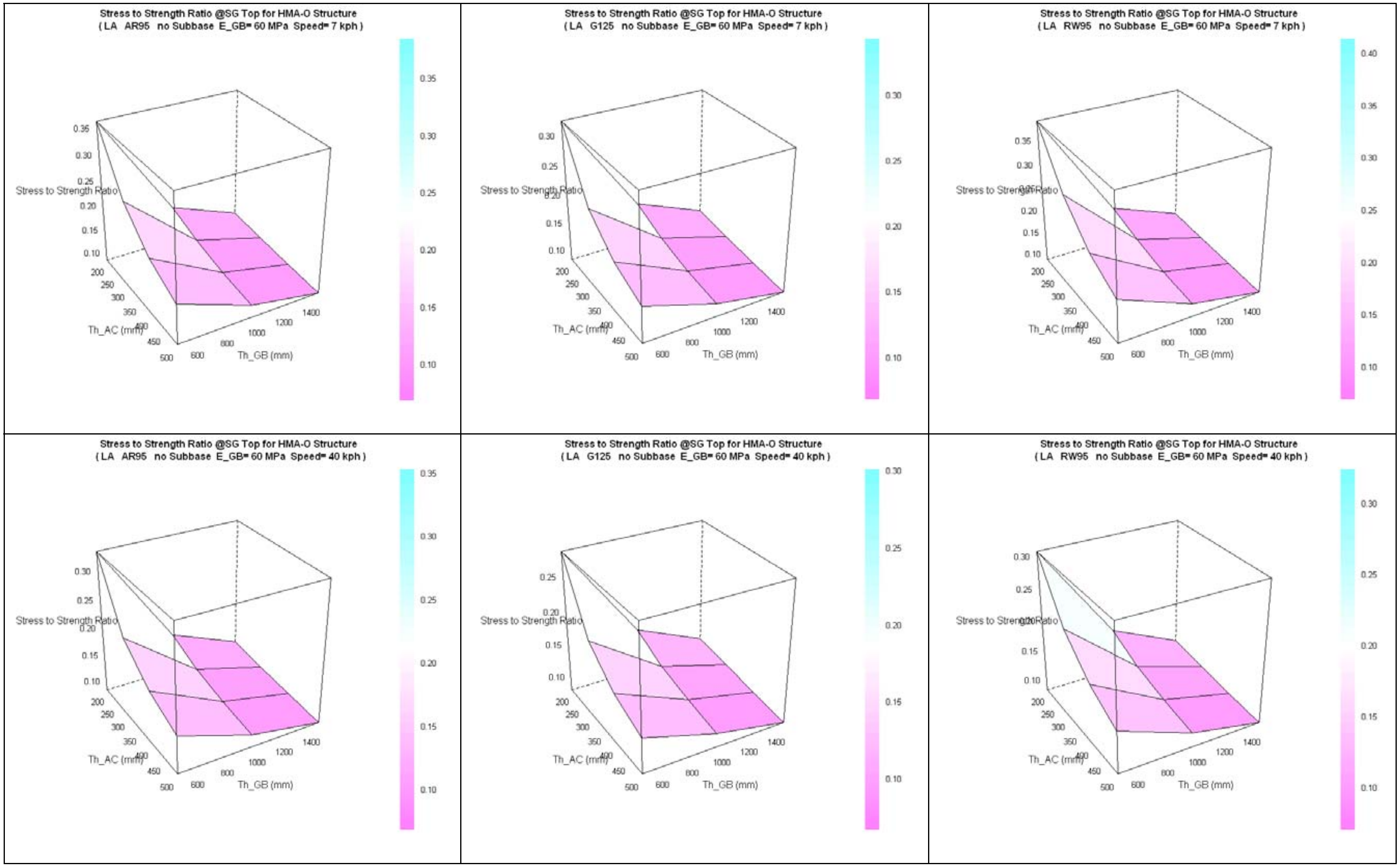

Figure 4.3: Example subgrade stress/strength ratio for HMA-O in Los Angeles County #1.

(AR95, G125, RW95 HMA mixes, no PCC-O subbase, speeds of 7 km/h and 40 km/h)

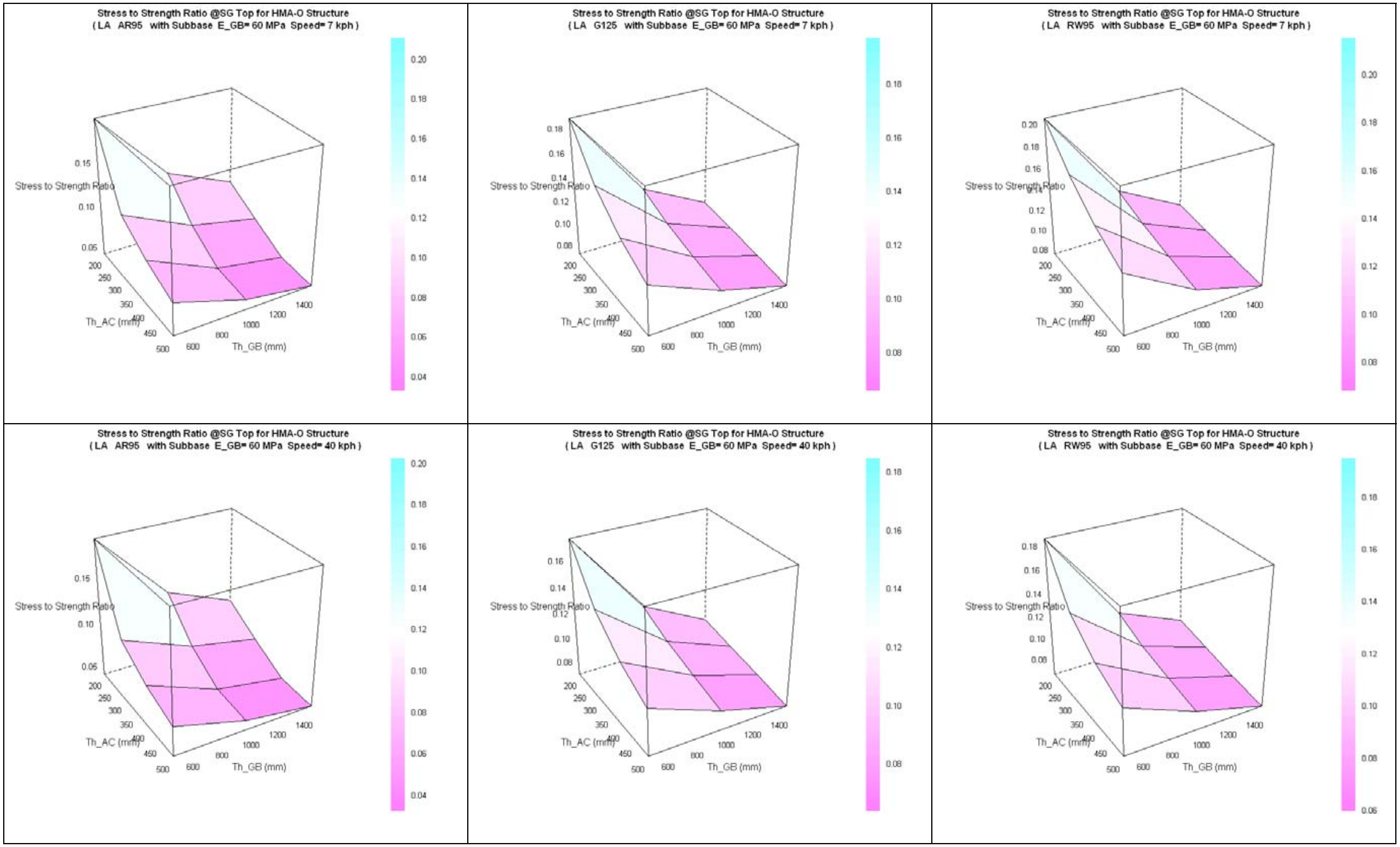

Figure 4.4: Example subgrade stress/strength ratio for HMA-O in Los Angeles County #2.

(AR95, G125, RW95 HMA mixes, with PCC-O subbase, speeds of 7 km/h and 40 km/h)

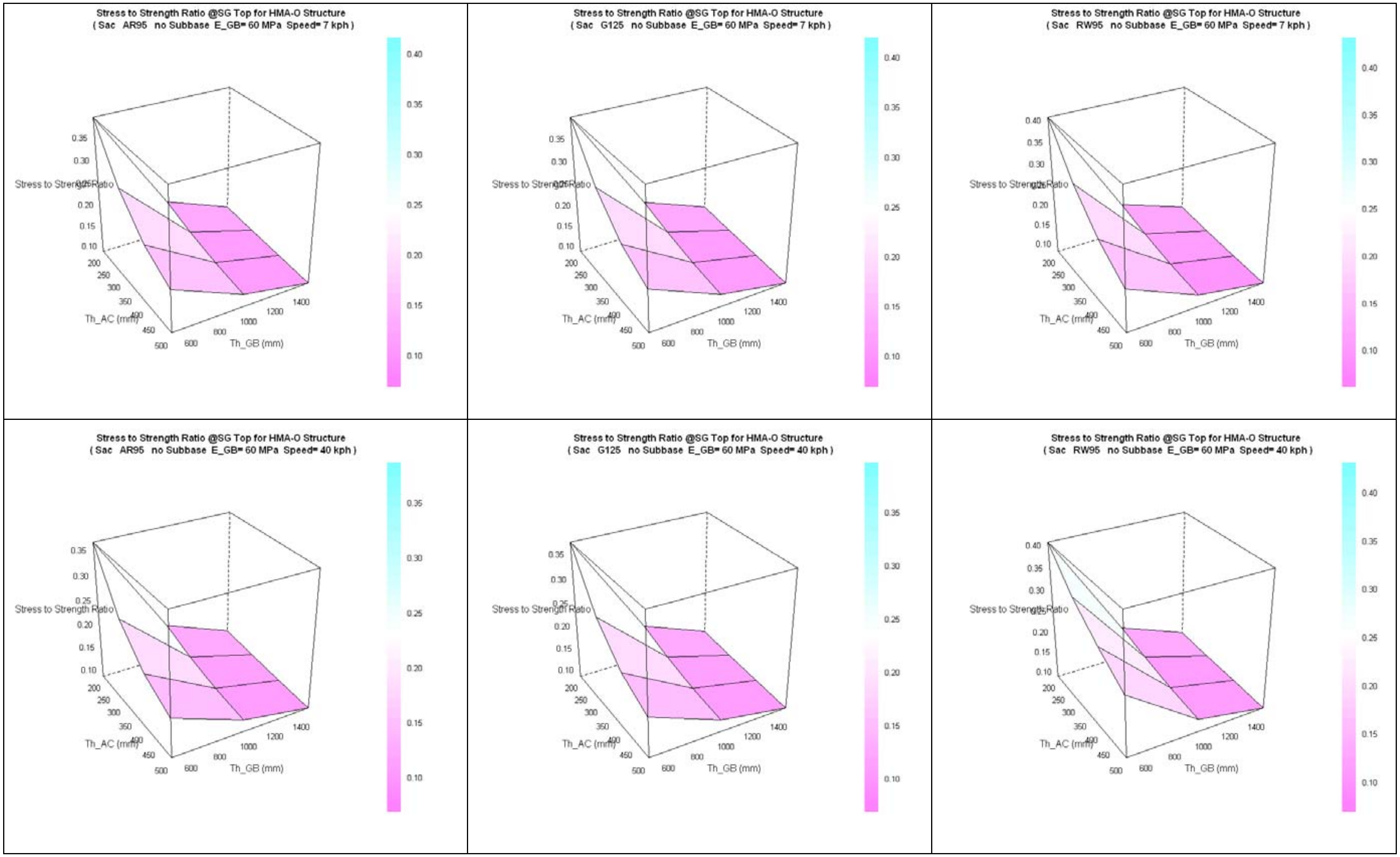

Figure 4.5: Example subgrade stress/strength ratio for HMA-O in Sacramento County #1.

(AR95, G125, RW95 HMA mixes, no PCC-O subbase, speeds of 7 km/h and 40 km/h)

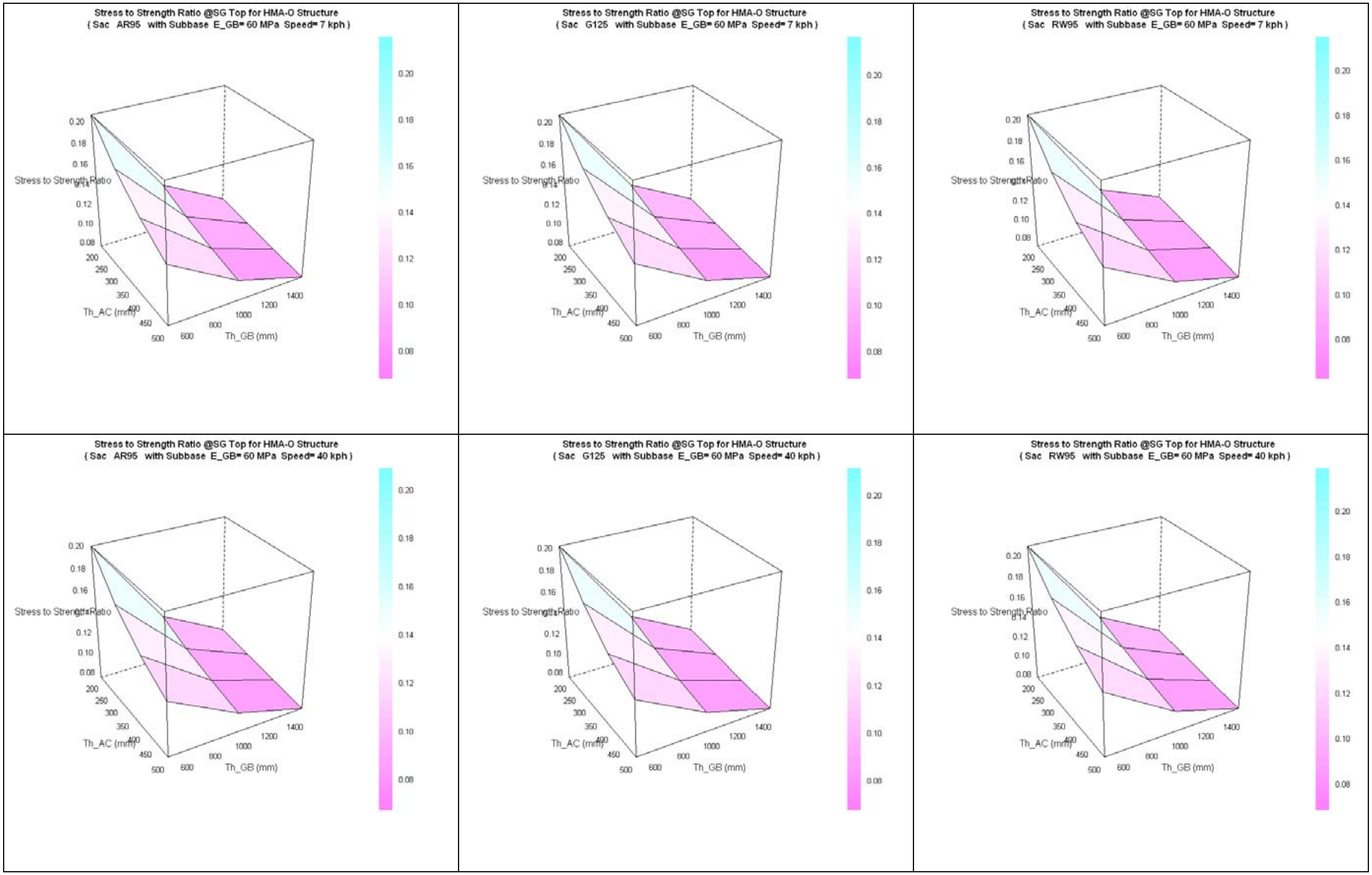

Figure 4.6: Example subgrade stress/strength ratio for HMA-O in Sacramento County #2.

(AR95, G125, RW95 HMA mixes, with PCC-O subbase, speeds of 7 km/h and 40 km/h)

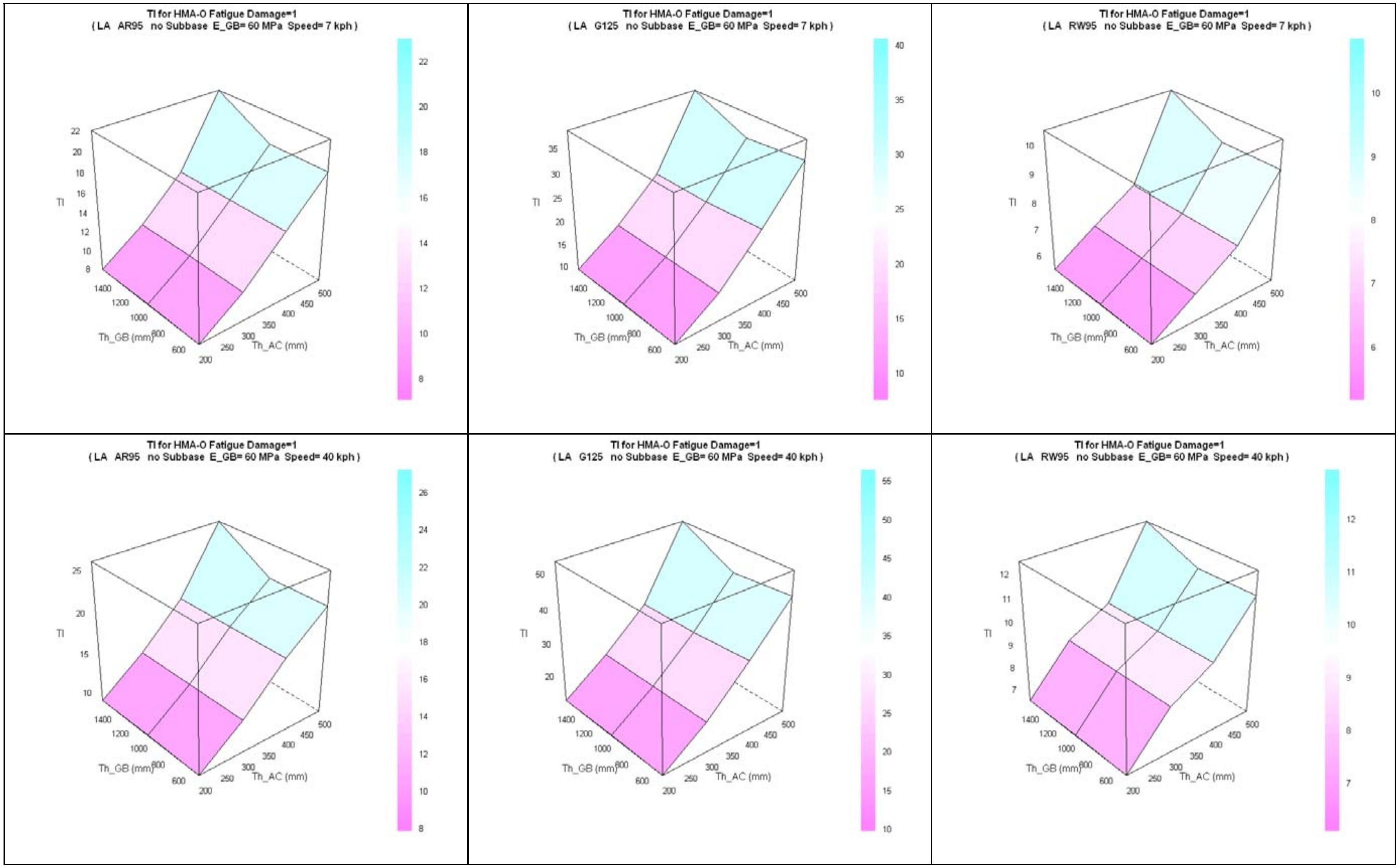

Figure 4.7: Example fatigue design life for HMA-O in Los Angeles County #1.

(AR95, G125, RW95 HMA mixes, no PCC-O subbase, speeds of 7 km/h and 40 km/h)

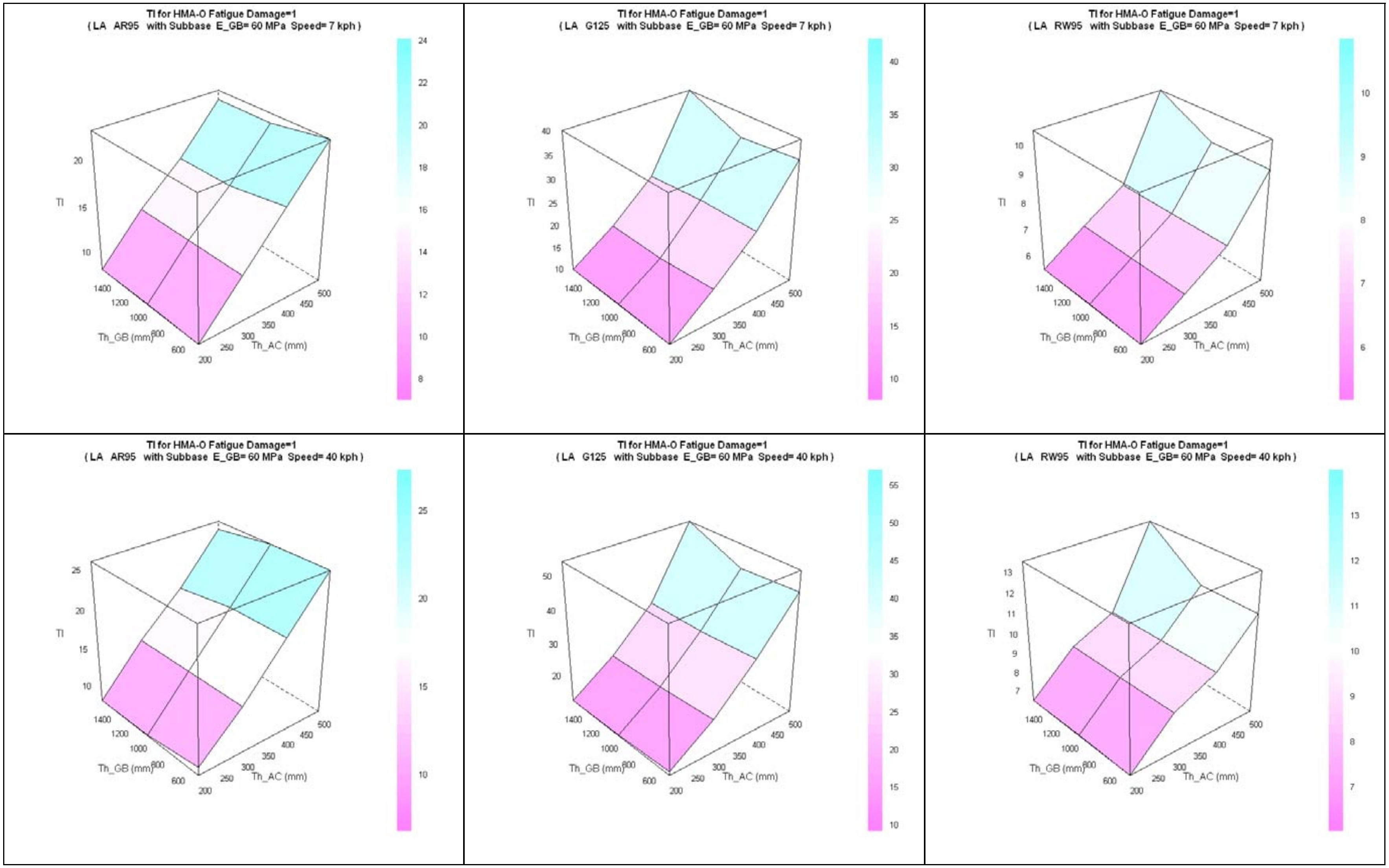

Figure 4.8: Example fatigue design life for HMA-O in Los Angeles County #2.
(AR95, G125, RW95 HMA mixes, with PCC-O subbase, speeds of 7 km/h and 40 km/h)

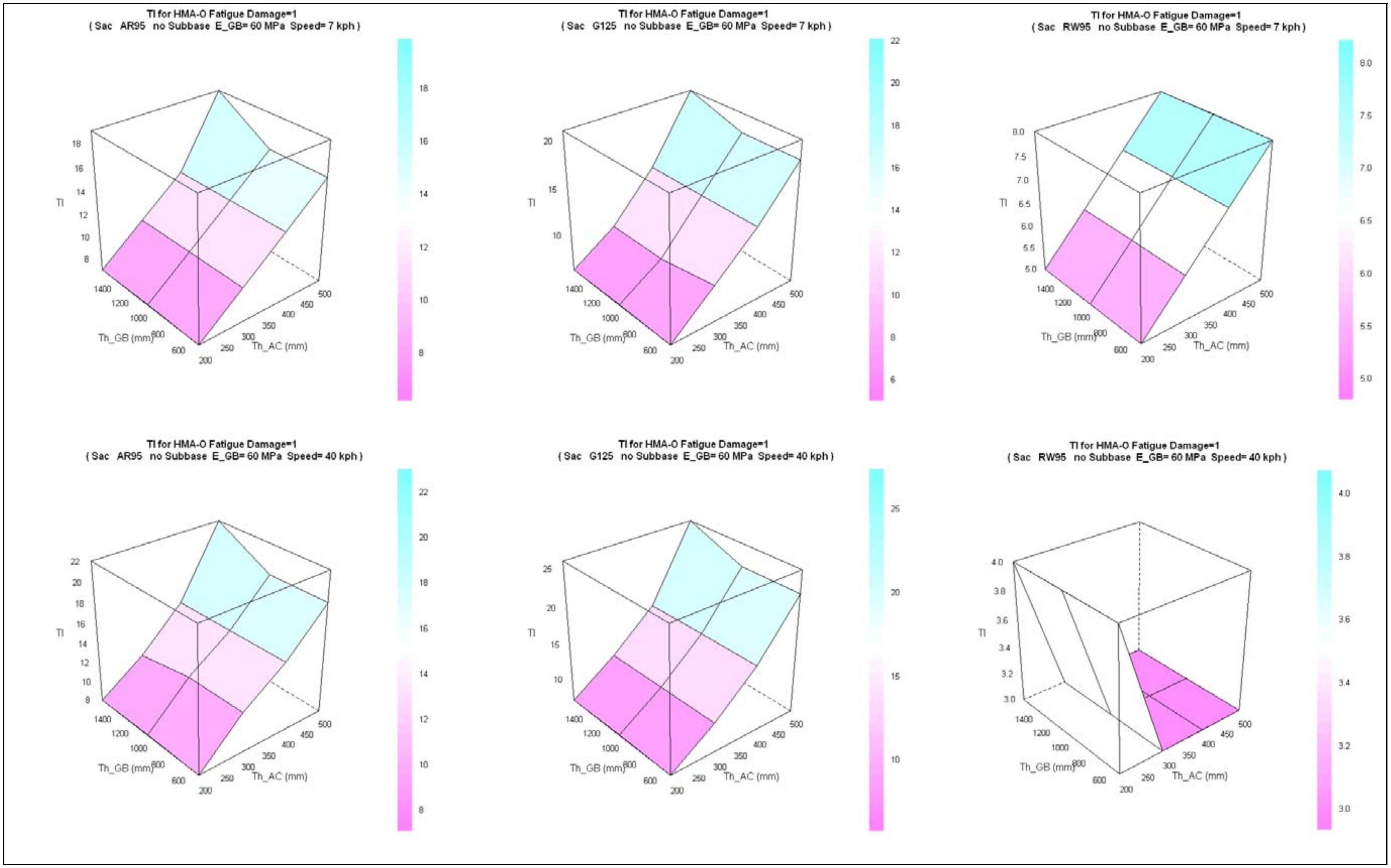

Figure 4.9: Example fatigue design life for HMA-O in Sacramento County #1.
(AR95, G125, RW95 HMA mixes, no PCC-O subbase, speeds of 7 km/h and 40 km/h)

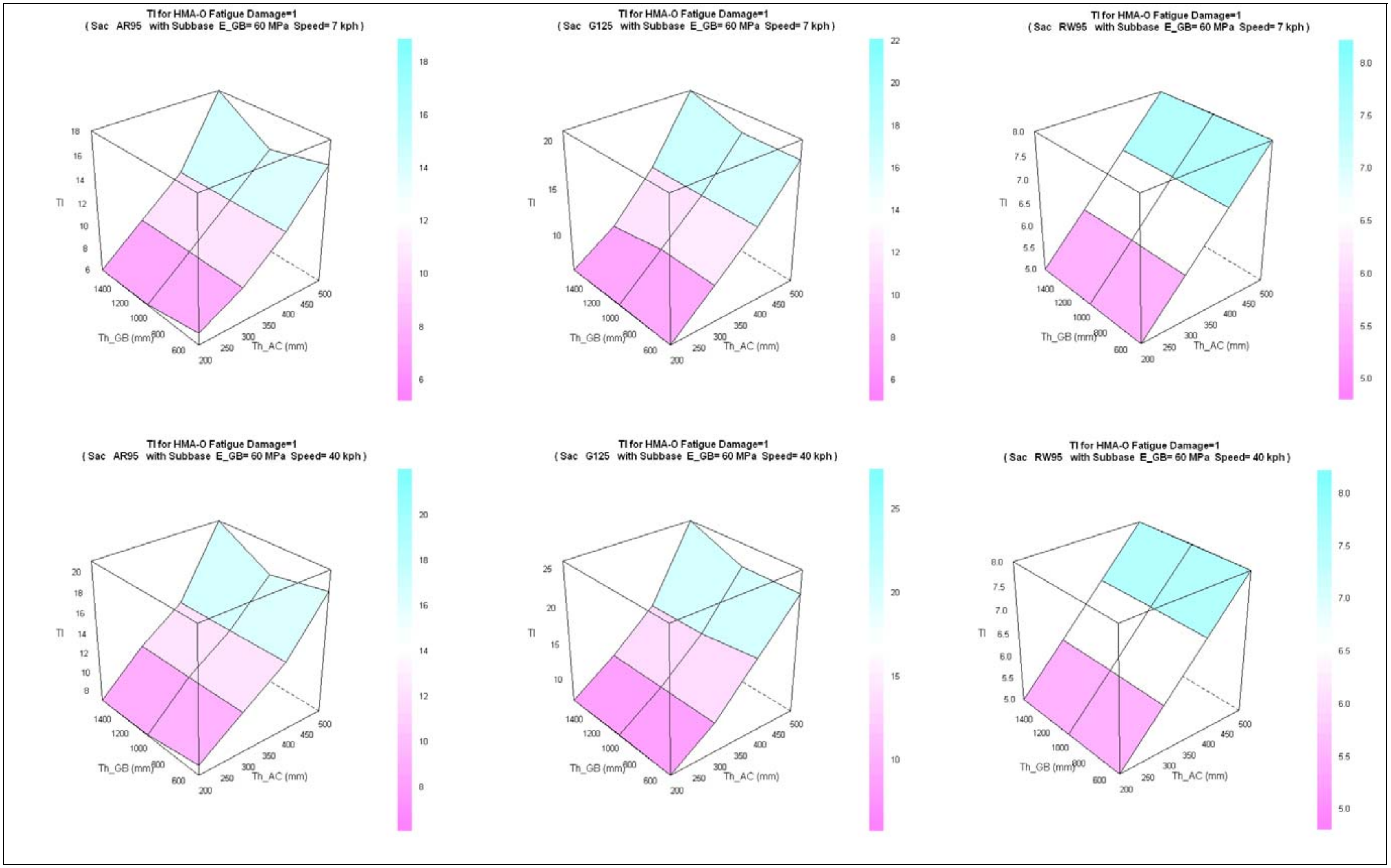

Figure 4.10: Example fatigue design life for HMA-O in Sacramento County #2.
(AR95, G125, RW95 HMA mixes, with PCC-O subbase, speeds of 7 km/h and 40 km/h)

Chapter 5. Summary and Future Work

This technical memorandum summarizes the computer modeling of the expected pavement performance of fully permeable pavements using laboratory test results described in an earlier report, and development of pavement designs for critical distresses. Full-factorial experimental designs were followed, taking pavement type, material type, pavement geometry (thicknesses, and slab dimensions for concrete pavement only), climate, truck axle type, traffic load, and traffic speed (HMA only) into consideration. This resulted in almost 20,000 analysis cases using layer elastic theory for HMA and finite element analysis for concrete.

The results indicate that sufficient structural strength can be obtained with appropriate and reasonable pavement designs for fully permeable concrete and hot mix asphalt pavements. A methodology for selecting an appropriate pavement design considering both structural and hydraulic performance for a given set of circumstances, as well as elementary cost estimates will be discussed in the final report. A final set of proposed pavement designs, draft materials specifications and recommendations for which designs should be included in a full-scale validation experiment using accelerated pavement testing and field sections will be included in the final report. Although functional performance in terms of permeability was considered in the designs, functional performance in terms of raveling and clogging can only be quantified in full-scale experiments. Recommendations for these will also be provided in the final report.

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