DRAFT

Climate Regions for Mechanistic - Empirical Pavement Design in California and Expected Effects on Performance

Report Prepared for

CALIFORNIA DEPARTMENT OF TRANSPORTATION

By

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June 2000

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EXECUTIVE SUMMARY

The two primary factors that cause distresses in pavement are traffic and the environment. The environmental factors affecting pavements are temperatures and water. Differences in air temperature and rainfall can have a profound impact upon pavement distress mechanisms and pavement performance in different climate regions. California has at least seven unique climatic regions; most other states have at most two or three.

The effects of traffic have been studied extensively. The effects of the environment and the interactions between traffic and environment are not as well understood for some distresses and pavement types. The effects of the environment on pavement distresses are difficult to accelerate on test sections, either on closed tests such as the AASHO Road Test, or mainline test sections, and information regarding environmental effects must therefore be obtained from a large database of long-term test sections. Some acceleration of the effects of water can be gained from controlled tests under the CAL/APT Heavy Vehicle Simulators.

Currently, Caltrans pavement design procedures do not typically account for environmental variables or for differences between climate regions largely due to the absence of a database that allows the engineer to incorporate environmental data into the process of pavement design. Therefore, the first step toward the inclusion of environmental data in pavement design is the development of a database of important pavement temperature and rainfall variables. An initial database has been developed as part of the Caltrans Accelerated Pavement Testing Project (CAL/APT) and is presented in this report. Data are presented for critical temperature and rainfall variables for different climate regions in California, with analysis relating the climate differences between the regions to specific pavement distresses.

The development of an environmental database and understanding of the impact on pavement design is required for development of a comprehensive mechanistic-empirical pavement design procedure for the California Department of Transportation.

Climate regions for California were identified based on rainfall and air temperature data. The Integrated Climate Model (ICM) software was used with data obtained from the National Climate Data Center (NCDC). Seven climate regions were selected, and six representative cities with complete weather data were used to calculate average hourly pavement temperatures and rainfall (two adjacent regions are represented by one of the cities).

The effects of pavement temperatures and rainfall on distress mechanisms for rigid, flexible and composite (concrete pavements overlaid with asphalt concrete) were identified, and compared for each of the regions. Recommendations are made for incorporation of environmental factors in materials and pavement design where they have a large impact. For flexible pavements these are asphalt concrete mix design for rutting, asphalt binder selection for rutting and thermal cracking, thickness design for fatigue cracking and subgrade rutting, and drainage requirements and the need for drainage features. A simplified map for selection of PG binder grades is included, and it is recommended that Caltrans implement portions of the PG specification.

For rigid pavements, environmental factors are critical for concrete mix design for shrinkage and strength, cement selection for shrinkage, strength and coefficient of thermal expansion, maximum slab lengths for cracking caused by thermal stresses, slab thickness for fatigue, base type selection for mitigation of erosion, and drainage requirements and the need for drainage features. It is recommended that environmental factors be included in both cement selection, concrete mix design, and concrete pavement design.

Environmental factors are critical for the performance of composite pavements for the following distresses: asphalt concrete mix design for rutting and reflection cracking, asphalt binder selection for rutting, reflection cracking and thermal cracking, and overlay thickness design for reflection cracking.

INTRODUCTION

Environmental data is required for development of a comprehensive mechanistic-empirical pavement design procedure for the California Department of Transportation. Differences in air temperature and rainfall can have a profound impact upon pavement distress mechanisms and pavement performance in different climate regions. California has at least seven unique climatic regions; most other states have at most two or three.

Currently, Caltrans pavement design procedures do not typically account for these climatic differences, largely due to the absence of a database that allows the engineer to incorporate environmental data into the process of pavement design. Therefore, the first step toward the inclusion of environmental data in pavement design is the development of a database of important pavement temperature and rainfall variables. An initial database has been developed as part of the Caltrans Accelerated Pavement Testing Project (CAL/APT). This report presents data and analysis for critical temperature and rainfall variables for different climate regions in California.

OVERVIEW

Chapter 2 contains an outline of the methodology of this study. The methodology includes a characterization of the climates studied, a brief introduction to the software used to estimate pavement temperatures, and an outline of assumptions. Chapter 3 presents analysis of the pavement temperature and thermal gradient data. The analysis is organized according to pavement type and distress type. Chapter 4 presents an overview of the rainfall data. Chapter 5 presents the conclusions drawn from the data analysis and recommendations for inclusion of the results in current Caltrans operations and in the mechanistic-empirical design procedure being developed for Caltrans by the University of California Berkeley Contract Team.

1.0 METHODOLOGY AND CLIMATE REGION DEFINITION

1.1 Weather Data

The weather data used in this research was extracted from EarthInfo NCDC Summary of the Day CD ROMS (*1*). The extraction included 30 years (1961-90) of hourly records for the following parameters: temperature, percent sunshine, rainfall, and wind speed. This data was extracted for six locations that represent climatically unique regions in California. They include Arcata (CA), Reno (NV), Sacramento (CA), San Francisco (CA), Daggett (CA), and Los Angeles (CA).

In order to prepare this data for input, 30 years of data were averaged to develop the profile of a typical year for each region. The daily maximum and minimum air temperatures were determined within the 30-year averaged year. Additionally, from the hourly records, the average daily percent sunshine, the average daily wind speed and the total daily rainfall were calculated. These values were used as inputs to the Integrated Climatic Model (ICM) (*2*). The weather stations used to represent each climate region were selected based on availability of full sets of the input data required by the ICM.

Table 1 Locations representing each climate region

Representative Location	Climate Region	Latitude
Arcata, California	North Coast	40.98
Reno, Nevada	Mountain, High Desert	39.50
Sacramento, California	Central Valley	38.52
San Francisco, California	Bay Area	37.62
Daggett, California	Desert	34.87
Los Angeles, California	South Coast	33.93

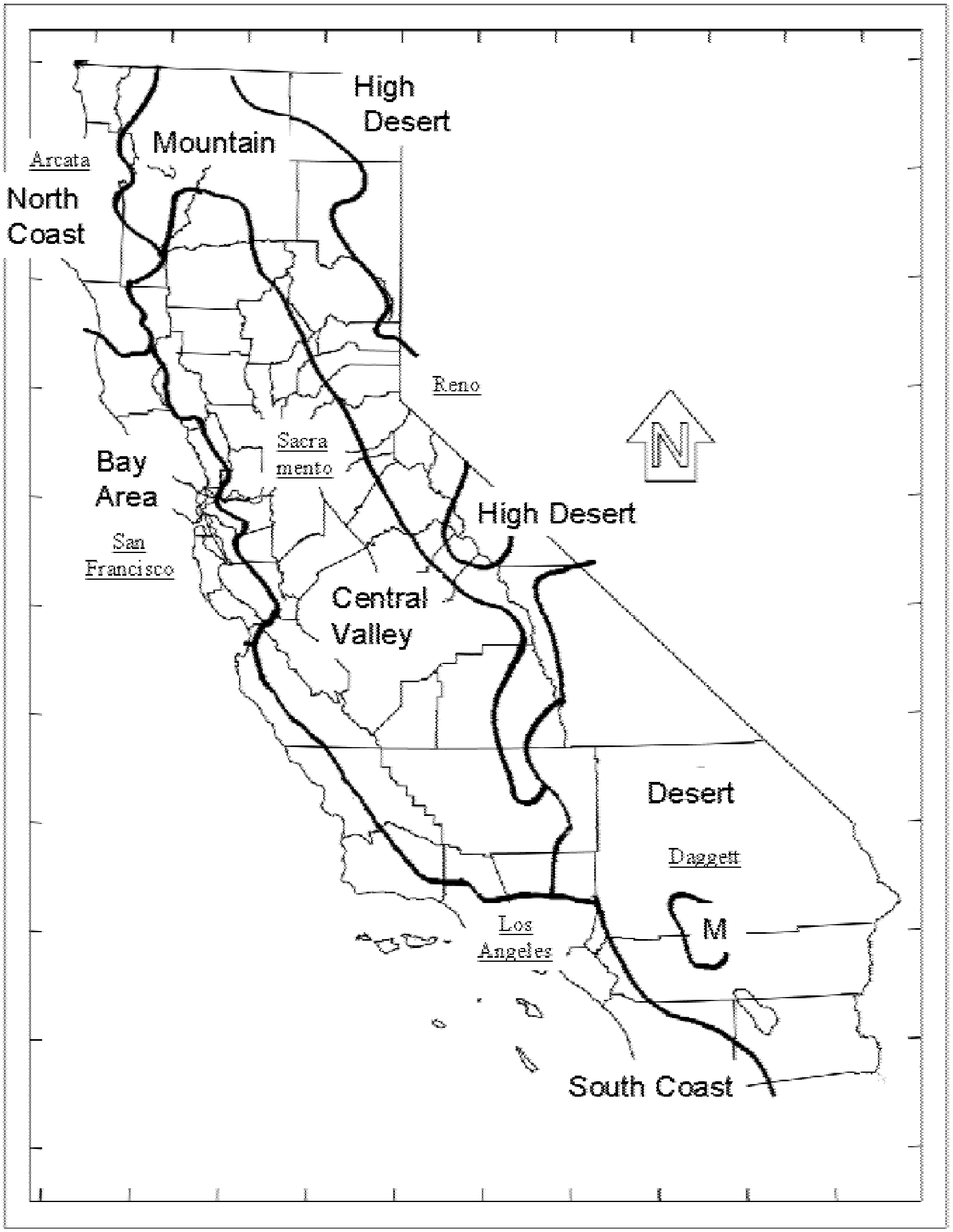


Figure 1. **Map of climate regions and representative cites.**

1.2 Definition of Climate Region Boundaries

Boundaries for the climate regions were developed based on evaluation of rainfall maps and several important air temperature parameters. Air temperatures were used instead of pavement temperatures to establish climate region boundaries because calculation of pavement temperatures requires data for daily percent sunshine and wind speed in addition to daily air temperatures and rainfall. Data for all the variables required to calculate pavement temperatures were only available for a few weather stations.

Maps of critical temperatures and rainfall were overlaid. Boundaries for pavement design climate regions were selected from analysis of the combination of the important isometric boundaries for rainfall and air temperature. Each region also had to have a representative weather station with a complete data set to permit calculation of pavement temperatures.

Data were obtained for California from the National Oceanic and Atmospheric Administration (*3*). Average annual rainfall is plotted in Figure 2. The temperature parameters mapped were:

- Average maximum temperature for the six summer months, April through October (Figure 3);
- Average minimum temperature for the six summer months, April through October (Figure 4);
- Average maximum temperature for the six winter months, November through March (Figure 5);
- Average minimum temperature for the six winter months, November through March (Figure 6);
- Extreme maximum temperature ever recorded (Figure 7).

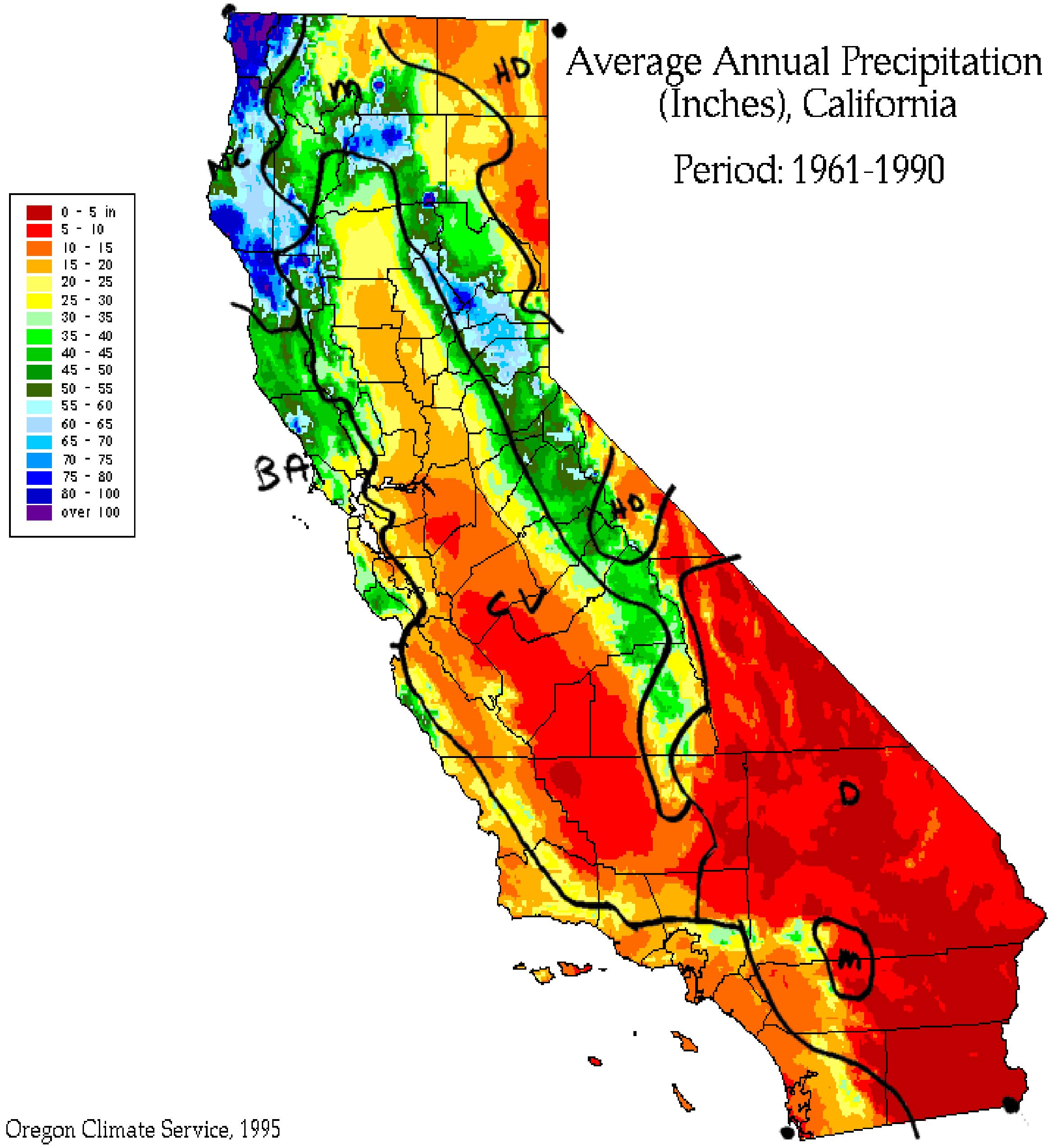


Figure 2. **Average annual rainfall in California (data from Reference 3).**

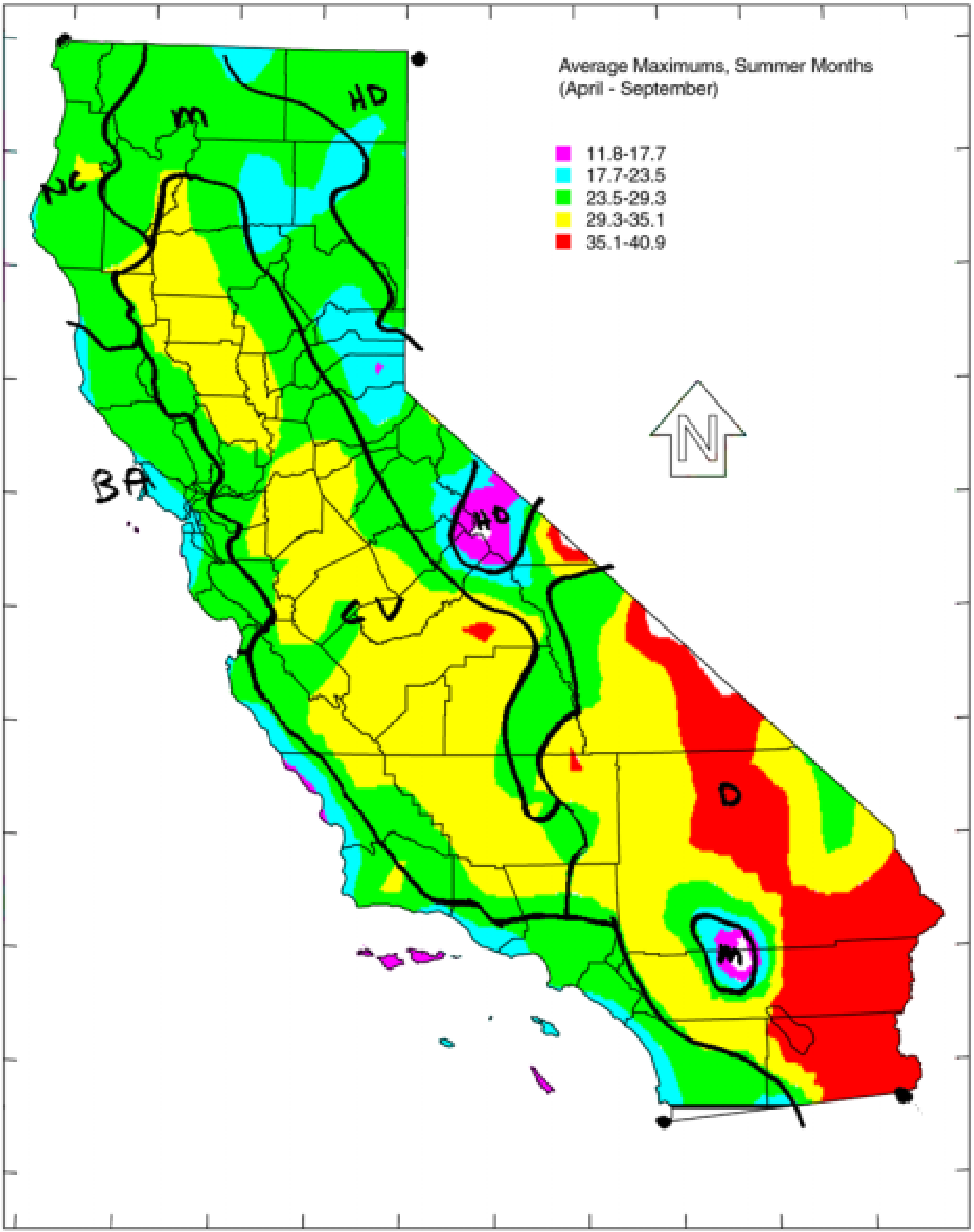


Figure 3. **Average maximum temperature for the six summer months, April through October (data from Reference 3).**

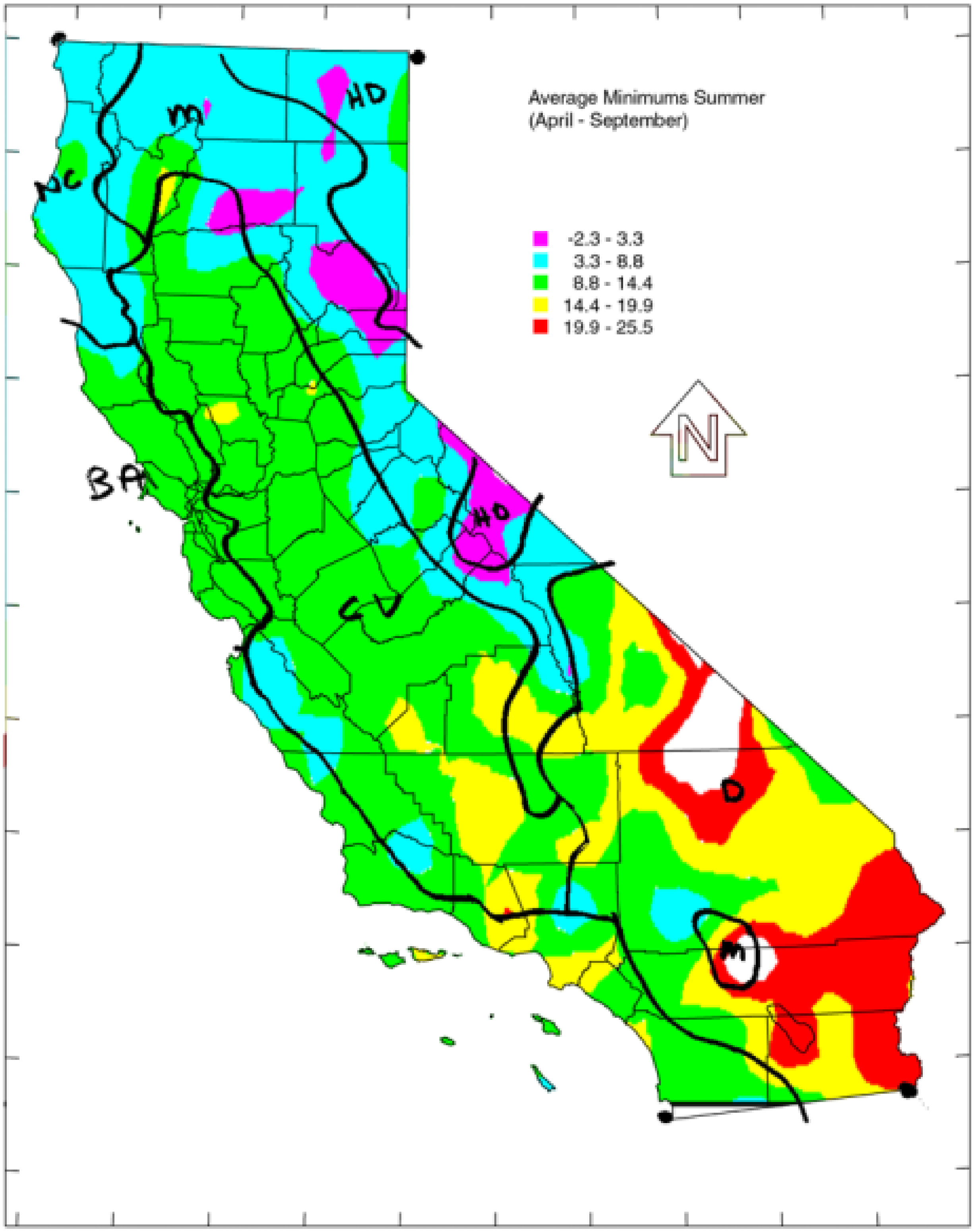


Figure 4. **Average minimum temperature for the six summer months, April through October (Figure C) (data from Reference 3)**

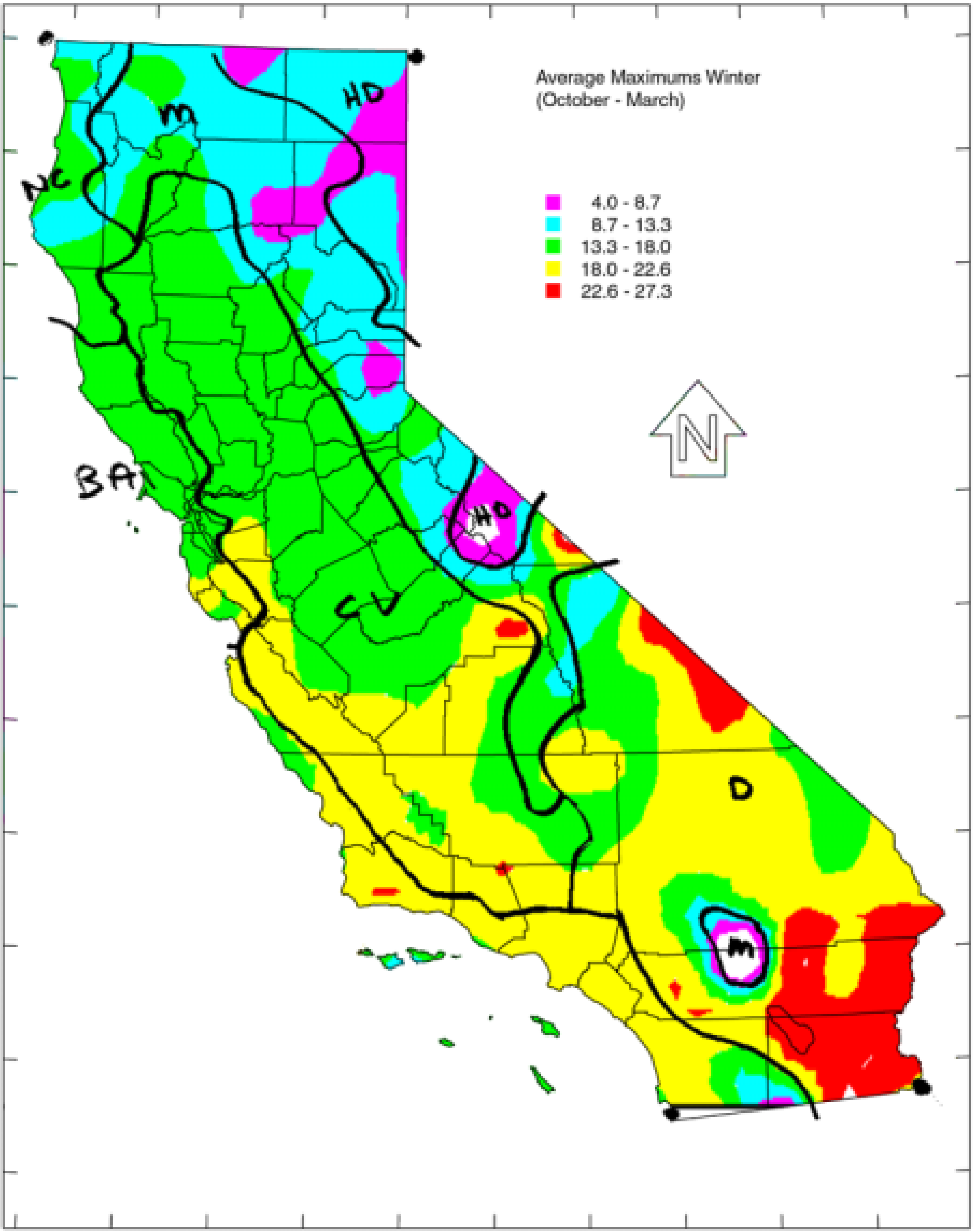


Figure 5. **Average maximum temperature for the six winter months, November through March (data from Reference 3)**

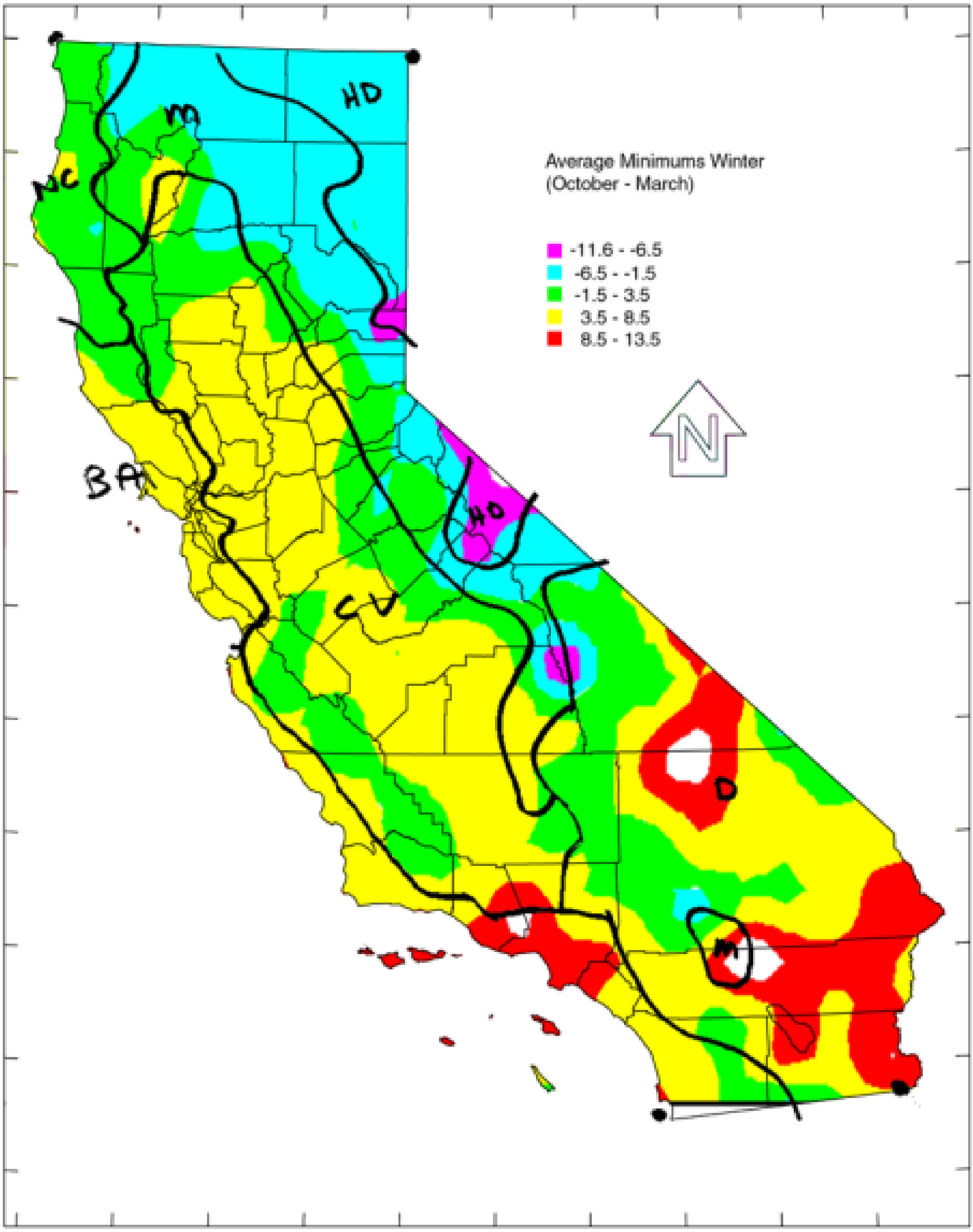


Figure 6. **Average minimum temperature for the six winter months, November through March (data from Reference 3)**

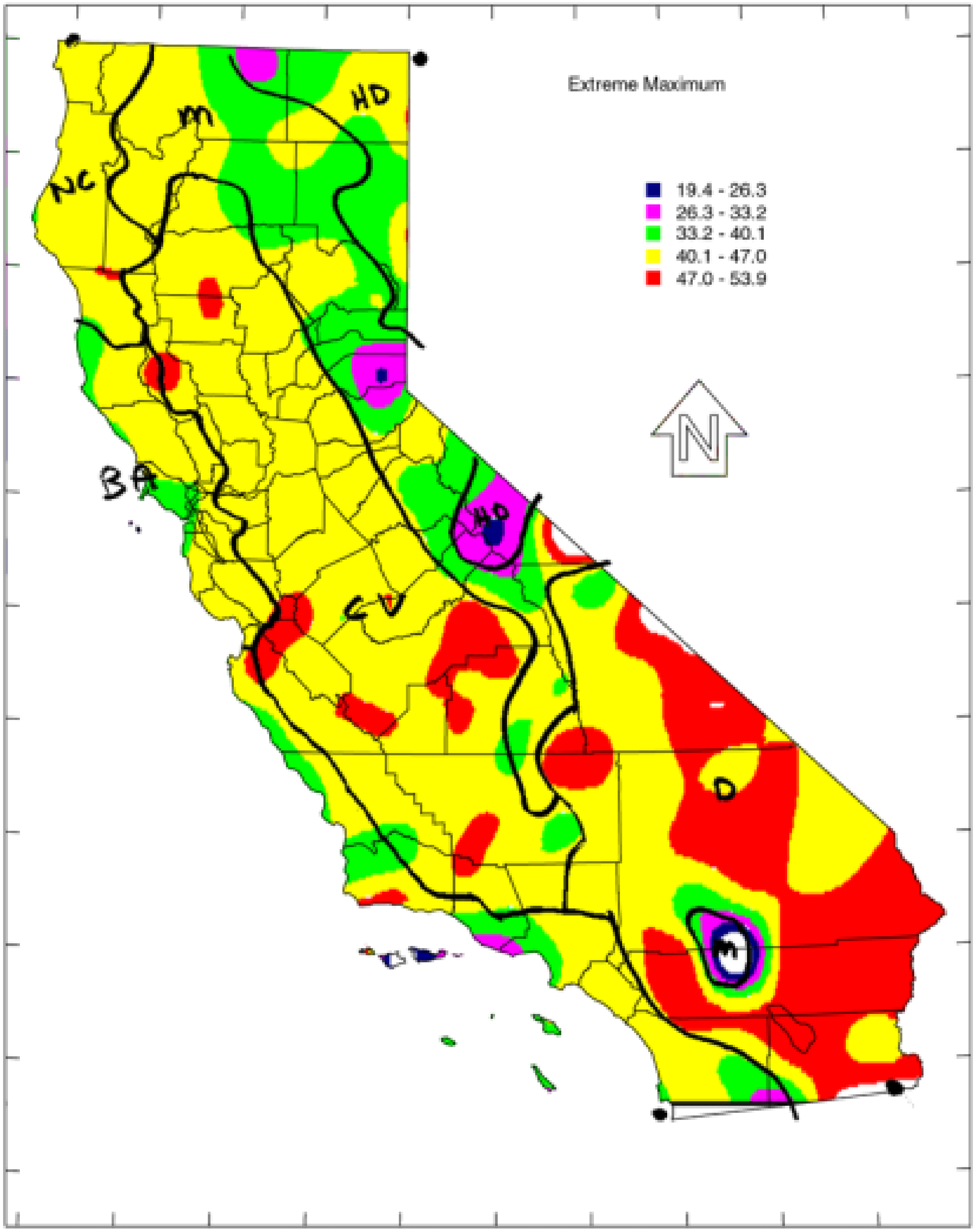


Figure 7. Extreme maximum temperature ever recorded (data from Reference 3)

A detailed description of the boundaries of the climate regions in terms of highway numbers and kilometer-posts will not be possible until a GIS map of the highway system is obtained.

1.3 Climate Characterization

In general, Daggett (Desert) and Arcata (North Coast) are the extreme regions within the climates studied. Daggett experiences the highest day and nighttime temperatures over the course of an average year (Figures 8 and 9). Conversely, Arcata's highest temperature is generally lower than all the other climates, making it the overall coolest climate in this study. Reno experiences the coldest minimum temperatures during the winter months (Figure 8).

Arcata, receives approximately 97.2 cm (38.3") of rainfall each year making it the region with the greatest amount of rainfall (Figure 10). Daggett, in the Desert region, typically has an insignificant annual rainfall. The rainfall for Reno is typical of locations on the leeward (eastern) side of mountain ranges in the mountain region; this phenomenon is often referred to as the "rain shadow." Rainfall is more abundant on the windward (western) sides. However, no complete data climate sets were available for mountain locations on the windward site of the Sierra Nevada. Blue Canyon, in the Sierra Nevada mountains had the most complete set, which consisted of only four complete years of data.

Additionally, Daggett is exposed to the greatest percentage of daily sunshine among the seven climates being evaluated (Figure 11). On average, Daggett experiences a sky that is 72.8 percent sunshine, while Arcata experiences a sky that is only 34.1 percent sunshine. Daggett has the highest daily average wind speed, experiencing an average wind speed of 17.9 km/hr (11.1 mph) (Figure 12). Arcata experiences the calmest daily average wind speed, 10.2 km/hr (6.4 mph). Throughout this report, comparison will be made of Arcata and Daggett, representing the North Coast and Desert environments, to demonstrate the effects of different climates on pavement temperature and thermal gradient which have large impacts on pavement distress mechanisms.

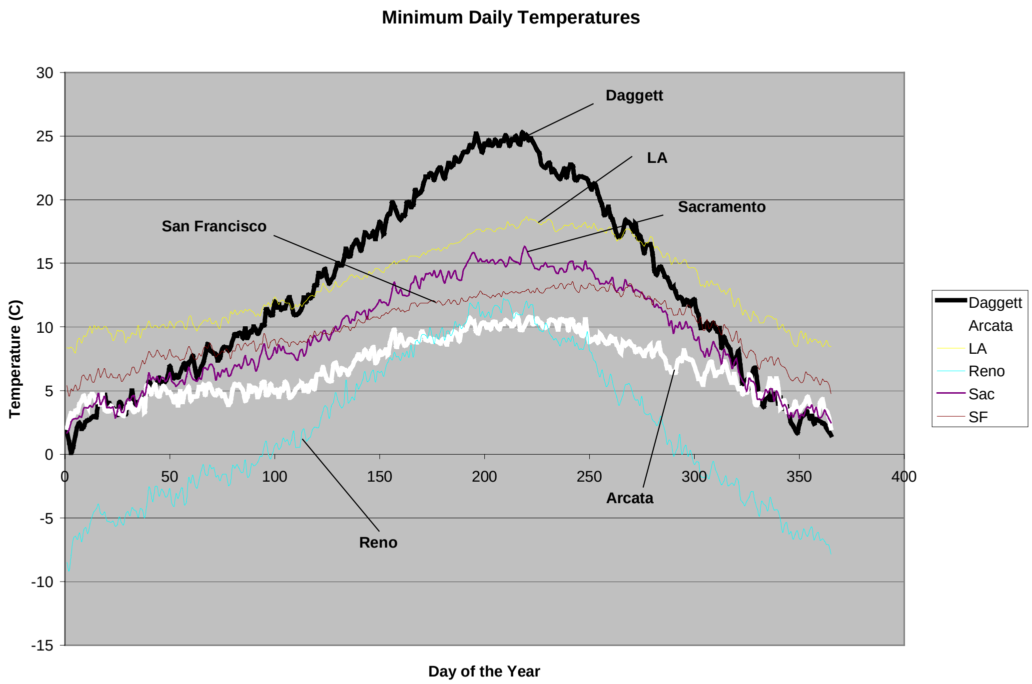


Figure 2. Daily Minimum Air Temperatures (°C) for 6 Different Climates

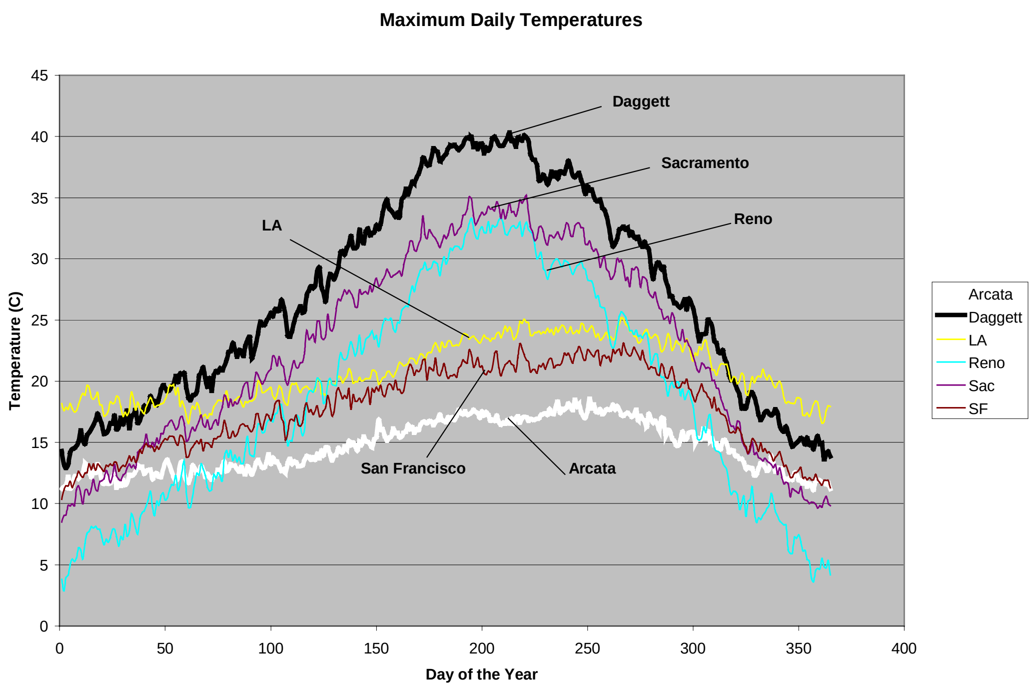


Figure 9. Daily Maximum Air Temperatures (°C) for 6 Different Climates

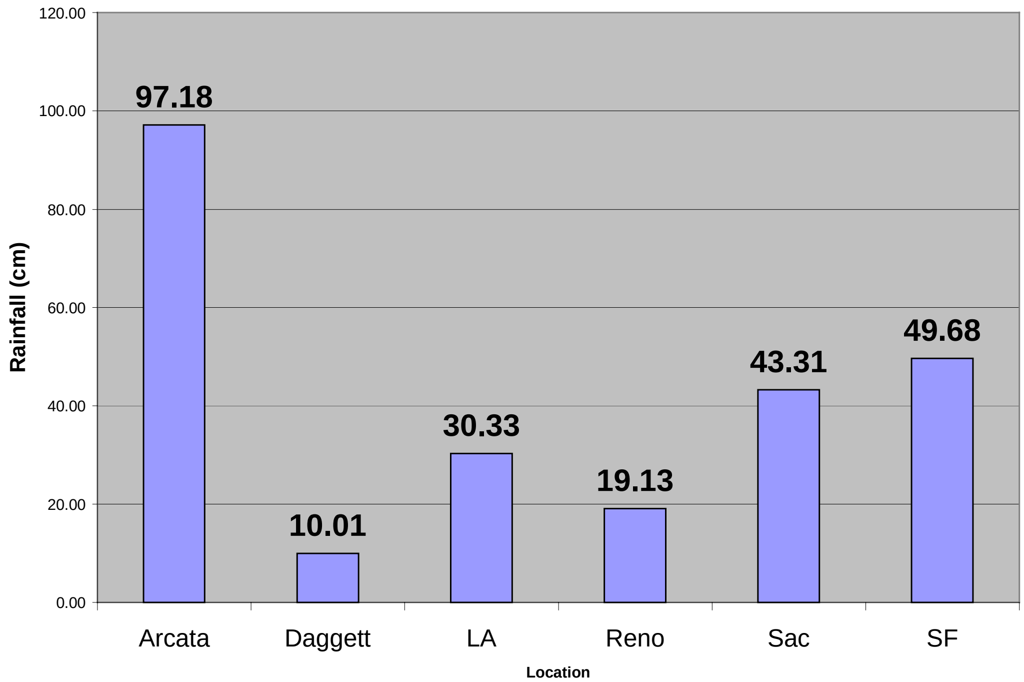


Figure 10. 30 Year Average of Total Annual Rainfall (cm) in 6 Different Climates

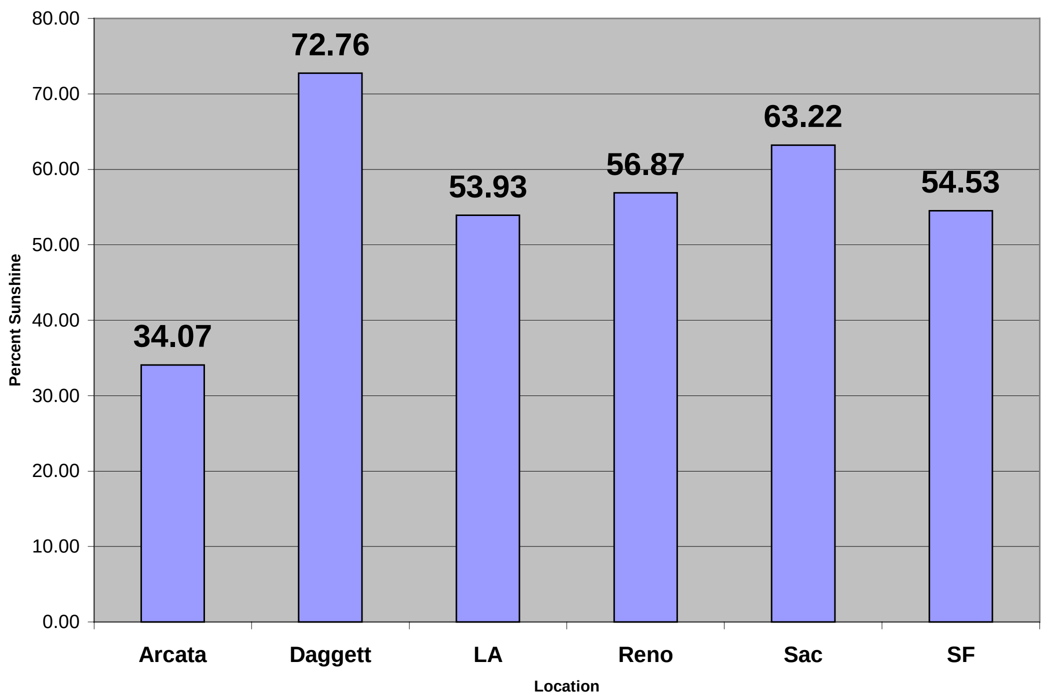


Figure 11. 30 Year Daily Average Percent of Sunshine in 6 Different Climates

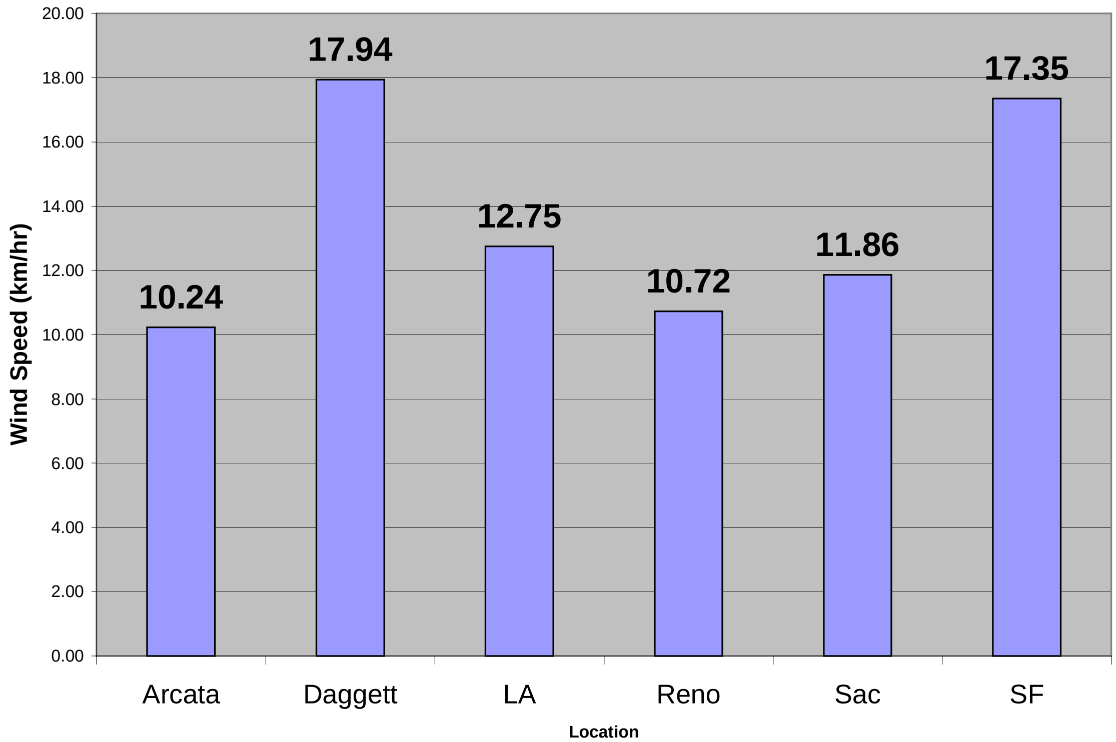


Figure 12. 30-Year Daily Average Wind Speed (km/hr) in 6 Different Climates

1.4 Integrated Climatic Model

ICM version 2.0 was utilized for the purposes of simulating pavement temperatures and thermal gradients. ICM, developed by B. J. Dempsey of the University of Illinois, is "a one-dimemsional coupled heat and moisture flow program that is intended for use in analyzing pavement-soil systems"(*2*). ICM takes into account the structure of the pavement and a given location's climatic data for up to 365 consecutive days.

The database of pavement temperatures simulated using ICM includes 15 different flexible pavements, 6 different rigid structures, and 8 different composite (asphalt concrete over portland cement concrete) structures for each of the representative locations. This report, however, will place emphasis on only a select group of these structures to demonstrate the broader implications of climate on pavement distress mechanisms and key insights to designing pavements in different climates in California. Tables 2-4 describe the structures analyzed in this report.

Table 2 Flexible Pavement Thickness Profile, cm (inches)

	Asphalt Concrete	Aggregate Base	Aggregate Subbase	Subgrade	Designation
AC Structure 1	10 (4 in.)	15 (6 in.)	15 (6 in.)	325 (128 in.)	AC 0-4-6-6
AC Structure 2	20 (8 in.)	30 (12 in.)	30 (12 in.)	284 (112 in.)	AC 0-8-12-12
AC Structure 3	41 (16 in.)	15 (6 in.)	15 (6 in.)	295 (116 in.)	AC 0-16-6-6

Table 3 Rigid Pavement Thickness Profile, cm (inches)

	PCC	Base	Aggregate Subbase	Subgrade	Designation
PCC Structure 1	30 (12 in.)	15 (6 in.")	15 (6 in.)	305 (120 in.)	PCC 0-12-6-6
PCC Structure 2	20 (8 in.)	15 (6 in.)	15 (6 in.)	315 (124 in.)	PCC 0-8-6-6

Table 4 Composite Portland Cement Concrete Structure Thickness Profile, cm (inches)

	Asphalt Concrete	PCC	Base	Subbase	Subgrade	Designation
Composite Structure 1	20 (8 in.)	20 (8 in.)	15 (6 in.)	15 (6 in.)	295 (116 in.)	COMP 0-8-8-6-6
Composite Structure 2	10 (4 in.)	20 (8 in.)	15 (6 in.)	15 (6 in.)	305 (120 in.)	COMP 0-4-8-6-6

1.4.1 ICM Inputs

ICM operates in a user-friendly environment that permits the user to manually input values through a series of dialog boxes. Importing properly formatted files can also efficiently load climate data. Four different types of data files for each location were prepared to describe the climate for a given region: 1) average daily maximum and daily minimum air temperatures, 2) daily average percentage of sunshine, 3) daily total rainfall and 4) daily average wind speed. Beyond pavement structure and climatic inputs, ICM requests additional information regarding thermal properties, infiltration/drainage considerations, material properties, and the initial pavement-soil temperature and pore pressure profile conditions.

ICM default values were used in instances where ICM parameters do not affect the estimated temperature. Default values are indicated by "(def)" in Tables 6 through 9. Literature review or standard specifications were used to provide acceptable values for pertinent parameters. Tables 5 through 9 identify parameters that were held constant throughout all the ICM runs.

Table 5 ICM Thermal Property Inputs

Input	Value
Modifier of Overburden Pressure During Thaw	0.5
Emissivity Factor	0.9
Surface short-wave absorptivity	No surface treatment: 0.9 (AC), 0.65 (PCC)
Cloud base factor	0.85
Maximum convection coefficient, J/s-m-C (BTU/hr-ft-F)	3
Coefficient of variation unsaturated permeability	1
Time of day when minimum air temperature occurs	4
Time of day when maximum air temperature occurs	15
Upper temperature limit of freezing range, C (F)	0 (32)
Lower temperature limit of freezing range, C (F)	-1 (30)

Table 6 ICM TTI Infiltration and Drainage Model Inputs

Input	Value
Linear Length Cracks/Joints One Side Pavement, m (ft)	30.5 (100) (def)
Total length surveyed for cracks and joints, m (ft)	30.5 (100) (def)
Type of fines added to the base course	Inert Filler (def)
Percentage of fines added to base course	2.5 (def)
Percentage of gravel in base course	70 (def)
Percentage of sand in base course	27.5 (def)
One side width of base, m (ft)	7.6 (25) (def)
Slope ratio/base tangent value (percent)	1.5 (def)
Internal Boundary Condition	Suction (def)
Evaluation Period (years)	10 (def)
Constant K for intensity-duration-recurrence eqn	0.3 (def)
Power of recurrence interval	0.25 (def)
Power of rainfall duration	0.75 (def)
Shape constant for rainfall intensity-period curve	1.65 (def)

Table 7 ICM Asphalt Material Property Inputs

Input	Value
Coarse aggregate content in asphalt (%)	80
Air content asphalt layer (%)	4
Gravimetric water content of asphalt layer (%)	2 (def)
Resilient Modulus: Temperature (F)/Stiffness (psi)	-10 °F/1.7e+6 (def)
Resilient Modulus: Temperature (F)/Stiffness (psi)	60 °F/43,000 (def)
Resilient Modulus: Temperature (F)/Stiffness (psi)	130 °F/1,500 (def)
Unfrozen Thermal Conductivity (BTU/hr-ft-F)	0.7
Freezing Thermal Conductivity (BTU/hr-ft-F)	0.7
Frozen Thermal Conductivity (BTU/hr-ft-F)	0.7
Unfrozen Heat Capacity (BTU/lb-F)	0.22
Freezing Heat Capacity (BTU/lb-F)	1.2
Frozen Heat Capacity (BTU/lb-F)	0.22
Unfrozen Total Unit Weight (pcf)	148
Freezing Total Unit Weight (pcf)	148
Frozen Total Unit Weight (pcf)	148

Table 8 ICM Portland Cement Concrete Material Property Inputs

Input	Value
Thermal Conductivity (BTU/hr-ft-F)	0.6
Heat Capacity (BTU/lb-F)	0.3
Total Unit Weight (pcf)	154
Resilient Modulus (psi)	3.5e+006 (def)
Poisson’s Ratio	0.2
Coefficient of Expansion (1/F)	6e-006(def)

Table 9 ICM Material Properties for Asphalt Concrete Base, A-1 soil and A-7 soil

Material Property	AC Base (Stabilized)	A-1 Soil	A-7 Soil
Porosity of layer material	0.2	0.4 (def)	0.6 (def)
Saturated permeability (ft/hr)	0.2	0.2 (def)	1e-005 (def)
Dry unit weight of layer material (pcf)	148	125 (def)	80 (def)
Dry thermal conductivity (BTU/hr-ft-F)	0.7	0.3 (def)	0.1 (def)
Dry Heat Capacity (BTU/lb-F)	0.22	0.17 (def)	0.17 (def)
Coefficient of volume compressibility	0.1	0.1 (def)	1 (def)
Gardener's unsat. Permeability function (multiplier)	0.01 (def)	0.01 (def)	0.001 (def)
Gardener's unsat. Permeability function (exponent)	2 (def)	2 (def)	2.4 (def)
Gardener's moisture content function (multiplier)	0.5 (def)	0.6 (def)	0.07 (def)
Gardener's moisture content function (exponent)	0.3 (def)	0.3 (def)	0.9 (def)
Unfrozen Resilient Modulus (psi)	200000 (def)	50000(def)	4000 (def)
Frozen Resilient Modulus (psi)	400000 (def)	100000(def)	50000 (def)
Unfrozen Poisson's Ratio	0.25 (def)	0.25 (def)	0.25 (def)
Frozen Poisson's Ratio	0.25 (def)	0.25 (def)	0.25 (def)
Length of Recovery period (days)	N/A	N/A	60 (def)

The initial temperature and pore pressure of each ICM run was set at 10°C (50°F) and 0 Pa (0 psi), respectively, throughout the entire pavement/soil profile. Daggett's daily rainfall was assumed to be zero for all Daggett ICM runs.

2.0 ANALYSIS OF ICM ESTIMATED PAVEMENT TEMPERATURES AND RAINFALL AND EFFECTS ON PAVEMENT PERFORMANCE

As previously mentioned, the locations representing the climatically extreme North Coast and Desert regions, Arcata and Daggett respectively, are emphasized in the following analyses for summary illustrative purposes. Los Angeles is also used to demonstrate climatic effects on rigid and composite pavement structures because the South Coast region is facing a large reconstruction and rehabilitation program. Sacramento is used to demonstrate the climatic effects on flexible pavements for the Central Valley. When data represents typical summer or winter trends, the data utilized is in reference to the following dates: July 23 - 29 and February 1-7 for summer and winter, respectively.

2.1 Climate Effects on Flexible Pavement

2.1.1 Mix Rutting

It has been found from the WesTrack study, Heavy Vehicle Simulator testing, and mechanistic pavement analysis that the critical location for mix rutting in a flexible pavement structure is within the top 100 mm (approximately 4 in.) of the asphalt layer (*4*,*5*,*6*). As shown in Figure 13, pavement temperatures drop dramatically below the asphalt concrete surface, making the upper 100 mm more susceptible to rutting. The higher the temperatures are in the upper region of the asphalt layer, the more prone the pavement is to experiencing mix rutting.

An example of the effect on rutting performance of a 10ºC difference in temperature in the asphalt concrete from Heavy Vehicle Simulator tests is shown in Figure 14 (*4*).

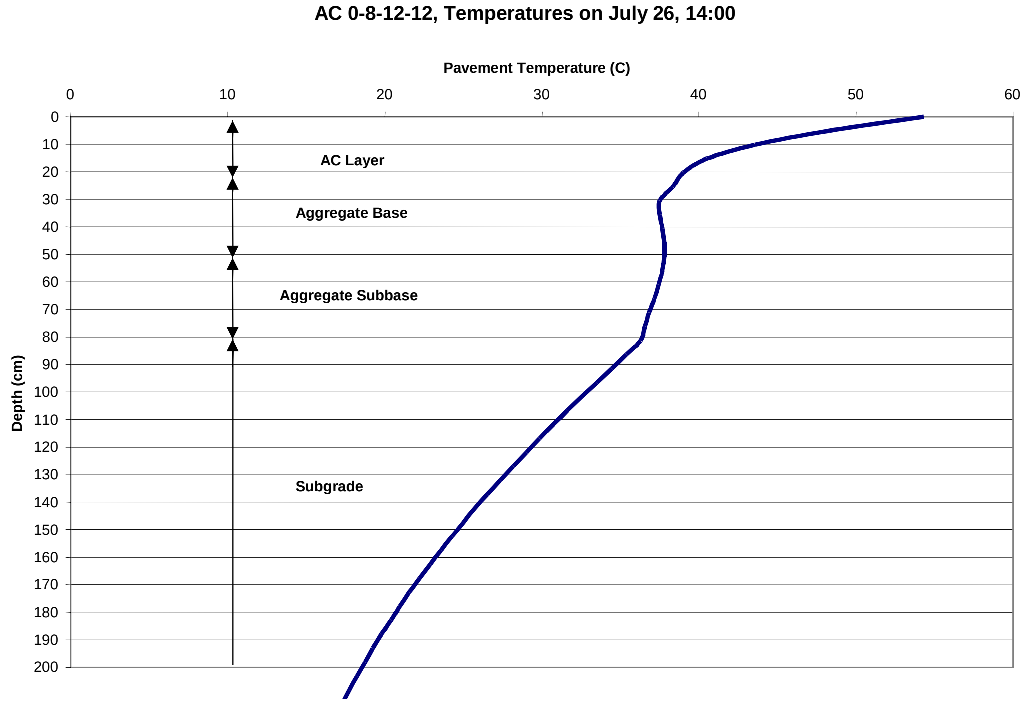


Figure 13. Illustration of Flexible Pavement Temperatures with Respect to Depth

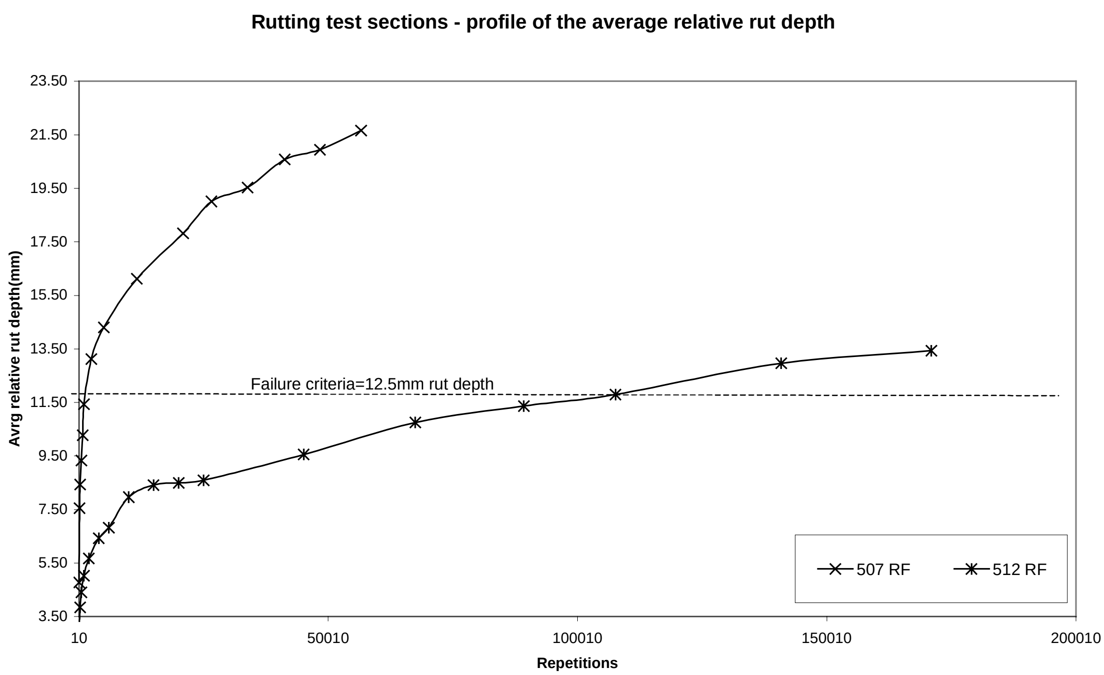


Figure 14. Effect of 10°C difference in temperature at 50 mm depth on asphalt concrete rutting under channelized Heavy Vehicle Simulator loading (507 average

temperatures = 54°C at surface, 49°C at 50 mm depth; 512 average temperatures=42°C at surface, 41°C at 50 mm depth)(*4*)

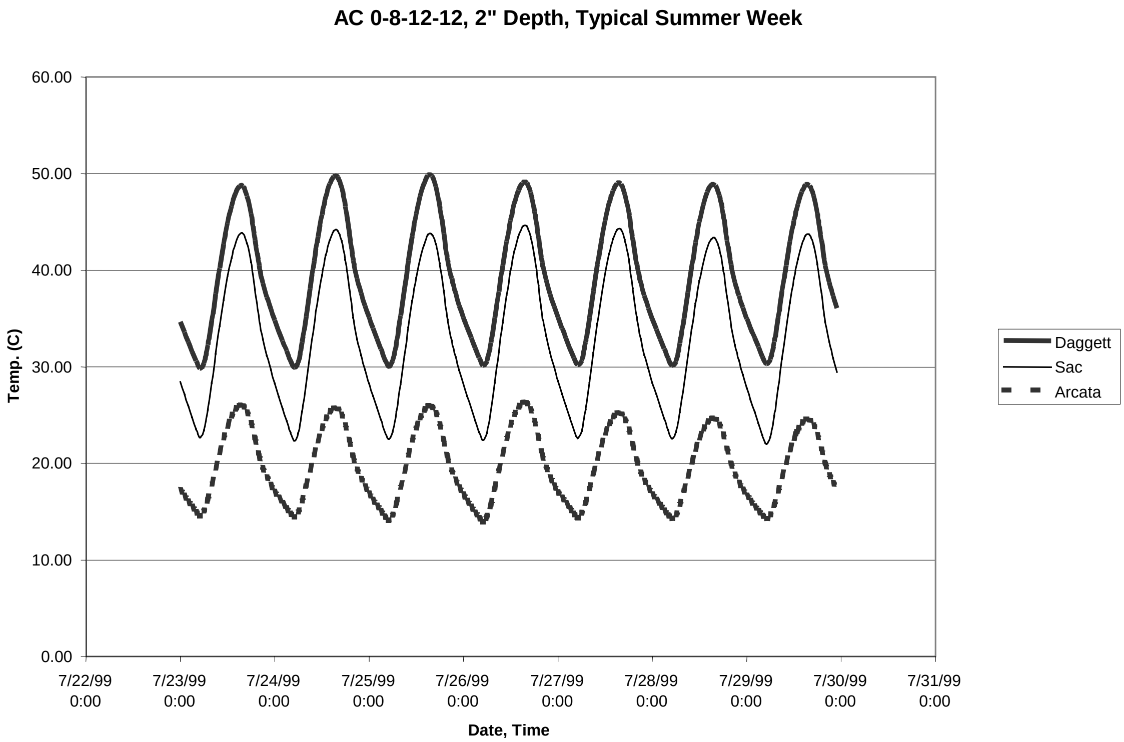
It should be noted that limited validation data from the WesTrack project analyzed by the University of California Berkeley Pavement Research Center indicated that the original software core of ICM (Climate-Materials-Structure model [*7*]) may calculate slightly cooler temperatures than the actual temperatures measured at the surface. In the WesTrack validation, wind speed and pavement sunshine, input data for ICM were taken from Reno, Nevada and air temperatures were measured at the WesTrack site, located in Carson City, Nevada. Below the surface, ICM results typically matched measured temperatures.

Table 10 lists the expected maximum pavement temperatures at shallow depths 0, 5, and 10 cm (0, 2, and 4 in.) for the flexible pavements evaluated for all six climates. Table 10 indicates that there is generally a difference of over 22°C (40°F) at each depth for each structure between Daggett and Arcata. Figure 15, which depicts pavement temperatures at a depth of 5 cm (2 in.) in a typical flexible structure in Daggett, Aracta, and Sacramento illustrates this same observation. Such differences indicate that mix rutting is a much greater threat in Daggett than in Arcata. Note that the Sacramento temperatures are not much cooler than those in Daggett.

Table 10 Average Yearly Maximum Temperatures °C (°F) at 0-, 5-, and 10 cm Depths in Flexible Pavements

Structure (Depth)	Daggett	Los Angeles	Sacramento	San Francisco	Reno	Arcata
10 cm (4 in.)						
thick AC (0 cm)	57 (134)	42 (107)	52 (126)	41 (105)	50 (120)	32 (89)
(5 cm)	52 (126)	38 (101)	48 (118)	37 (99)	44 (112)	29 (84)
(10 cm)	51 (123)	37 (98)	46 (114)	36 (96)	42 (108)	28 (82)
20 cm (8 in.)						
thick AC (0 cm)	56 (133)	41 (106)	52 (125)	41 (105)	48 (119)	31 (88)
(5 cm)	51 (123)	37 (98)	46 (114)	36 (96)	42 (108)	27 (81)
(10 cm)	47 (116)	34 (93)	42 (107)	30 (90)	38 (101)	25 (77)
41 cm (16 in.)	56 (133)	41 (106)	52 (125)	41 (105)	50 (120)	31 (88)
thick AC (0 cm)	51 (123)	37 (99)	46 (114)	36 (96)	43 (109)	28 (82)

(5 cm) (10 cm)	47 (116)	34 (93)	42 (107)	30 (90)	38 (101)	25 (77)



(Note: AC 0-8-12-12 indicates a flexible pavement with no open graded friction course, 8 inches of asphalt concrete, 12 inches of asphalt sub-base).

Figure 15. 30-year average high temperatures near the surface of the flexible pavement fluctuate in varying climates over the course of a summer week

Figure 16 illustrates the cumulative distribution of each location's average maximum daily surface temperature for a typical flexible pavement from April through September. Again, one can observe that Arcata and Daggett are at opposite extremes. It can be further noted that Arcata's maximum temperatures are distributed over a narrow range of temperatures (approximately 20C-30°C [70-85°F]), while Daggett's maximum temperatures occur over a much broader range (approximately 30-50°C [90-130°F]).

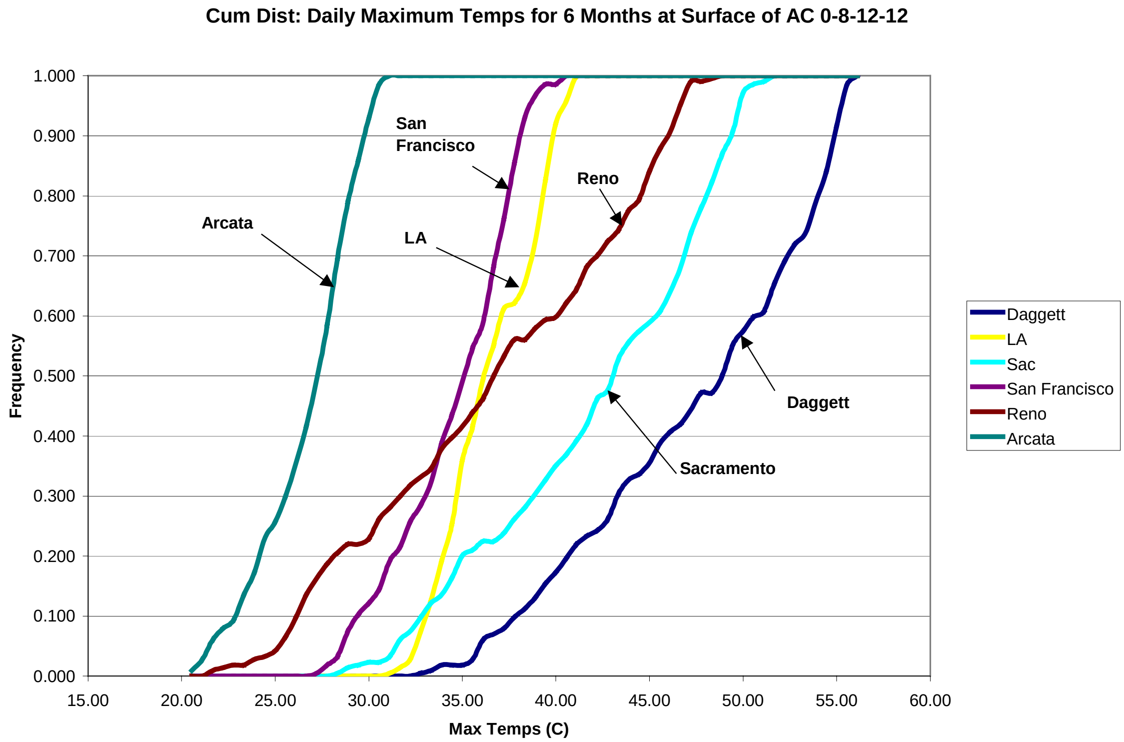


Figure 16. Cumulative distribution of 30-year average daily maximum temperatures at the surface of an AC 0-8-12-12 for six months (April-September)

Rutting of the asphalt concrete in flexible pavements is primarily controlled through good mix design. Factors influencing the resistance of asphalt concrete mixes to rutting are (in approximate typical order of importance): asphalt content, aggregate properties (surface texture, gradation and shape), and asphalt binder stiffness at the maximum temperatures expected near the surface of the asphalt concrete.

Caltrans currently uses what are essentially the same mix design criteria for the entire state. The current Caltrans mix design procedure (California Test Methods [CTM] 304, 305, 307, 308, 366, and 367) is based on work performed by Francis Hveem and his associates in the 1940s, 1950s, and 1960s. The original Hveem criteria included in the California Test Methods are minimum Hveem stabilometer values at 60°C of 37 for Type A mixes and 35 for Type B mixes and a minimum air-void content under standard laboratory compaction of 4 percent.

The only exceptions to the Hveem criteria are some increases in the minimum allowable air-void content under standard laboratory compaction for the Desert and Central Valley. In other words, less asphalt cement is allowed in the Desert for the same mix design. These differences are primarily applied for asphalt-rubber hot mix gap-graded (ARHM-GG). Nevertheless, the Hveem stabilometer requirements and stabilometer test temperature are the same for all climate regions. The criterion for minimum air-void content under laboratory compaction is the same across the state except for ARHM-GG used in the Desert and Central Valley.

Caltrans also currently typically specifies asphalt binders using the AR system. The AR system is based on aged residue binder stiffness at 60°C (140ºF), regardless of temperatures expected in the pavement. The AR system does not account for differences in binder stiffness at maximum temperatures expected in locations along the California coast (North Coast, Bay Area and South Coast). The high temperature specification in the SHRP PG binder specification system requires that binders meet a stiffness requirement for high temperatures *expected in the pavement at each project location.*

At the time that the Hveem criteria were developed, climate data of the type used in this study was not readily available. The large differences in pavement temperatures near the surface of the asphalt concrete layer between climate regions in California presented in this report indicate that greater consideration should now be made of pavement temperatures in mix design for two reasons.

First, the potential for rutting at the time that the current Hveem criteria were developed was less than it is today because:

- tire inflation pressures were much lower (about 520 kPa (75 psi) versus about 700 kPa (102 psi) today),
- most tires were bias-ply which resulted in greater lateral wander than radial tires do today, and
- there were fewer heavy trucks using the state highways than there are today.

These changes have increased the probability of rutting in the critical high temperature climate regions: the High Desert/Mountain, the Desert and the Central Valley. Increase of the minimum Hveem stabilometer requirements, in addition to the current changes in minimum air-void content under laboratory compaction are likely warranted for these regions.

However, it will be difficult to change the Hveem criteria because they are empirical and can only be adjusted through trial and error in mainline pavements or Heavy Vehicle Simulator testing. Caltrans cannot sustain many rutting failures because of the high cost of fixing them. Alternatively, Caltrans can move towards implementation of a mechanistic-empirical mix design method that includes laboratory testing at temperatures selected for the project site, and incorporates estimation of the probabilities of high temperatures occurring at the site (as in Figure 16).

Secondly, the Hveem criteria were developed to prevent rutting in the critical Desert and Central Valley areas, which they essentially did for many decades. The Hveem criteria were therefore very conservative at the time for those regions with low temperature near the surface of the asphalt concrete, such as the North Coast region, and possibly the Bay Area, South Coast and High Desert/Mountain regions. The result is that asphalt contents are probably lower than they need to be for the North Coast, which results in reduced fatigue cracking resistance and greater susceptibility to water damage (stripping), ravelling, and aging. The net effect of the changes in traffic (inflation pressures, tire type and number of heavy trucks) and overestimation of the rutting potential of mixes at lower temperatures is unknown for the Bay Area, South Coast and High Desert/Mountain regions.

Implementation of a mechanistic-empirical mix design method that includes site-specific pavement temperature information would help with rutting.

2.1.2 Fatigue

Flexible pavement fatigue that begins at the bottom of the asphalt concrete involves two mechanisms that are highly dependent on pavement temperatures. The first mechanism is crack initiation, which occurs at the bottom of the AC layer and is the result of damage throughout the asphalt concrete from repeated loads. For pavements with four inches or more of asphalt concrete, fatigue damage occurs more frequently when the bottom of the AC layer is experiencing moderate to high temperatures (15°C [59°F] and greater). For pavements with less than three to four inches of asphalt concrete, fatigue damage occurs at colder temperatures. Given that Caltrans has very few pavements with less than three inches of asphalt concrete, the discussion in this report will not focus on pavements with thin AC layers.

The second mechanism affecting flexible pavement fatigue is crack propagation. At cold temperatures, the asphalt becomes stiffer and more brittle (fractures under smaller tensile strains), while at the same time the asphalt concrete mix contracts causing increased tensile strains. Propagation of the initial crack up through the asphalt concrete may be accelerated under these conditions.

Considering both of these mechanisms, it can be stated that moderate to hot conditions are likely to be most conducive to crack initiation while cold conditions are conducive to crack propagation.

Table 11 indicates that all climates are in danger of experiencing temperatures at which fatigue damage occurs and could result in crack initiation. Specifically, the table indicates that all flexible pavements at all locations will experience temperatures well above 15°C (59°F) at the bottom of the asphalt concrete layer in a typical year. Temperatures typically remain above 15°C (59°F) for the entire duration of the day during the summer.

Figure 17 demonstrates how the temperatures fluctuate over the course of a summer week for three flexible pavements in Daggett and in Sacramento. Notice that temperatures for all six scenarios fluctuate well above 15°C (59°F). This implies that the damage rate per traffic pass may be in the critical range for fatigue damage for long periods of time.

Table 11 Six month (Apr-Sept) averaged daily maximum temperatures °C (°F) at the bottom of the AC layer in flexible pavements.

Structure	Daggett	Los Angeles	Sacramento	San Francisco	Reno	Arcata
10 cm (4 in.) thick AC	43 (110)	33 (91)	38 (101)	31 (88)	33 (91)	24 (75)
20 cm (8 in.) thick AC	38 (100)	29 (84)	32 (90)	26 (79)	27 (81)	21 (69)
41 cm (16 in.) thick AC	34 (93)	26 (79)	29 (84)	23 (74)	24 (75)	18 (65)

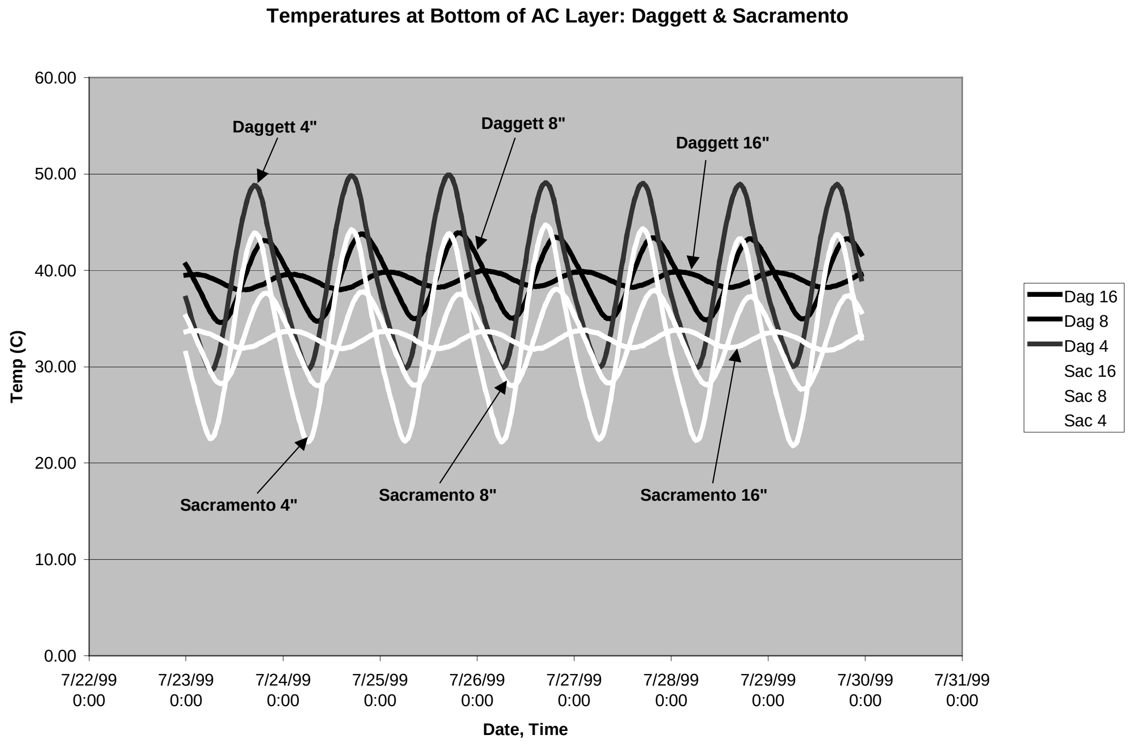


Figure 17. Summer temperatures at the bottom of the AC layer in 3 flexible structures in Daggett and Sacramento.

To explore crack propagation, low temperatures at the center of the asphalt concrete layer are considered. Table 12 indicates that temperatures in the cooler months can be low in all six climates.

It can also be seen that thinner pavements experience colder temperatures than thicker pavements. The minimum temperature difference increases by up to 6°C (10°F) when the asphalt concrete layer thickness increases from 10 cm (4 in.) thick to a 41 cm (16 in.) thick. This suggests that crack propagation may be slower in thicker pavement due to greater temperatures, in addition to the other benefits of thicker pavements: reduced damage per truck pass, lower strains under load, and the greater thickness through which the crack must propagate.

Table 12 Six Month (Oct-Mar) Averaged Daily Minimum Temperatures °C (°F) at the Center of the AC Layer in Flexible Pavements

Structure	Daggett	Los Angeles	Sacramento	San Francisco	Reno	Arcata
10 cm (4 in.) thick AC	9 (49)	12 (54)	8 (46)	9 (48)	1 (33)	7 (44)
20 cm (8 in.) thick AC	12 (54)	14 (58)	11 (51)	11 (52)	3 (38)	8 (47)
41 cm (16 in.) thick AC	14 (58)	17 (62)	12 (54)	14 (57)	6 (42)	10 (50)

Flexible pavement fatigue cracking is controlled through the interaction of the mix design and the pavement thickness design. This contrasts with rutting of the asphalt concrete and thermal cracking, which are controlled by the mix design alone.

2.1.3 Surface Aging

Surface aging is related to conditions at the surface of the asphalt concrete in a flexible structure. High temperatures and prolonged exposure to solar radiation accelerate aging. Figure 11 indicates that the Daggett region (73 percent sunshine) and Sacramento region (63 percent sunshine) are likely candidates for this type of distress. These two regions also experience high temperatures.

Table 13 lists six-month averaged maximum daily temperatures typically found at the surface of a flexible pavement for each climate region. The thickness of the asphalt concrete does not significantly affect these temperatures. Because Arcata experiences an average of only 34 percent sunshine and the lowest maximum temperatures within this study, it is likely that flexible pavement structures in the North Coast region are not as susceptible to surface aging as those in the other regions.

Table13 Six-month (April-September) averaged daily maximum temperatures °C (°F) at surface of the asphalt concrete layer in flexible pavements.

Climate Region	Temperature °C (°F)
Daggett	48 (118)
Los Angeles	37 (98)
Sacramento	43 (109)
San Francisco	35 (95)
Reno	37 (99)
Arcata	27 (81)

2.1.4 Water Damage (Stripping)

The presence of water in the asphalt concrete can lead to damage of the bond between the asphalt and aggregate. This damage reduces the stiffness and strength of the mix, and can lead to disintegration, which is sometimes referred to as stripping. High temperatures occurring when water is present tend to accelerate the process of stripping. Poor compaction that permits water to enter the asphalt concrete is a typical contributor to stripping. Chemical incompatibility between the asphalt and aggregate also contribute to stripping. In particular, aggregates from silicaceous sources often do not have strong chemical bonding with asphalt. Freezing temperatures when water is present can accelerate the damaging effects of water in the mix, although few climates in California experience significant freezing.

Figures 11 and 12 illustrate the relationship between daily rainfall and daily maximum air temperatures over the course of a year in Arcata and Sacramento, respectively. Arcata experiences large amounts of rainfall, while its temperatures remain very moderate throughout the year (Figure 11). Sacramento, on the other hand, has very high temperatures during the summer when there is very little rainfall (Figure 12).

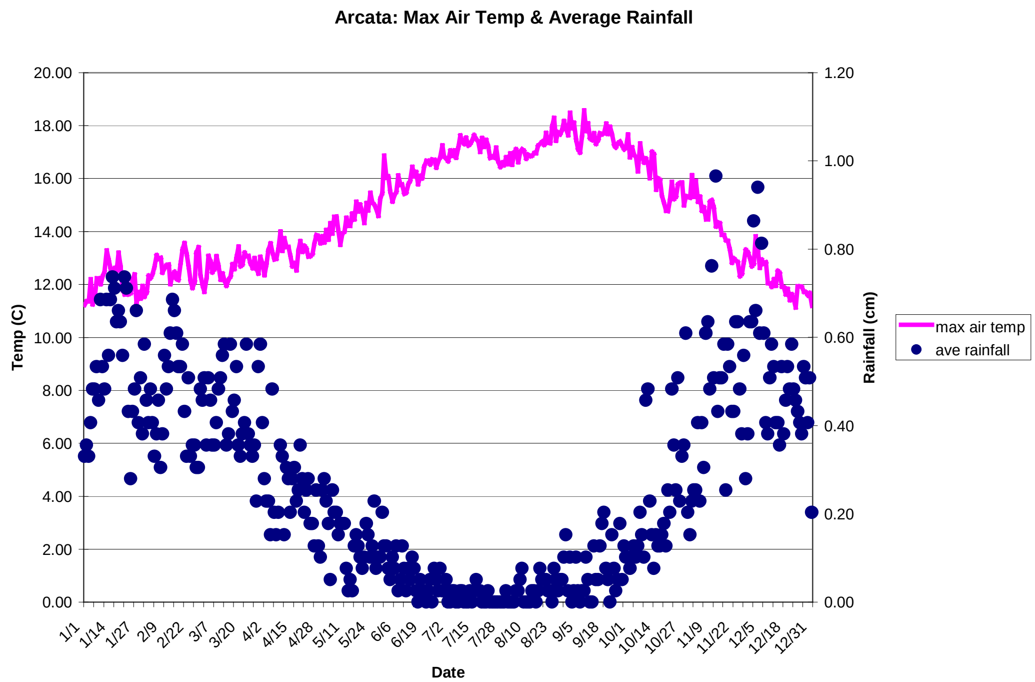
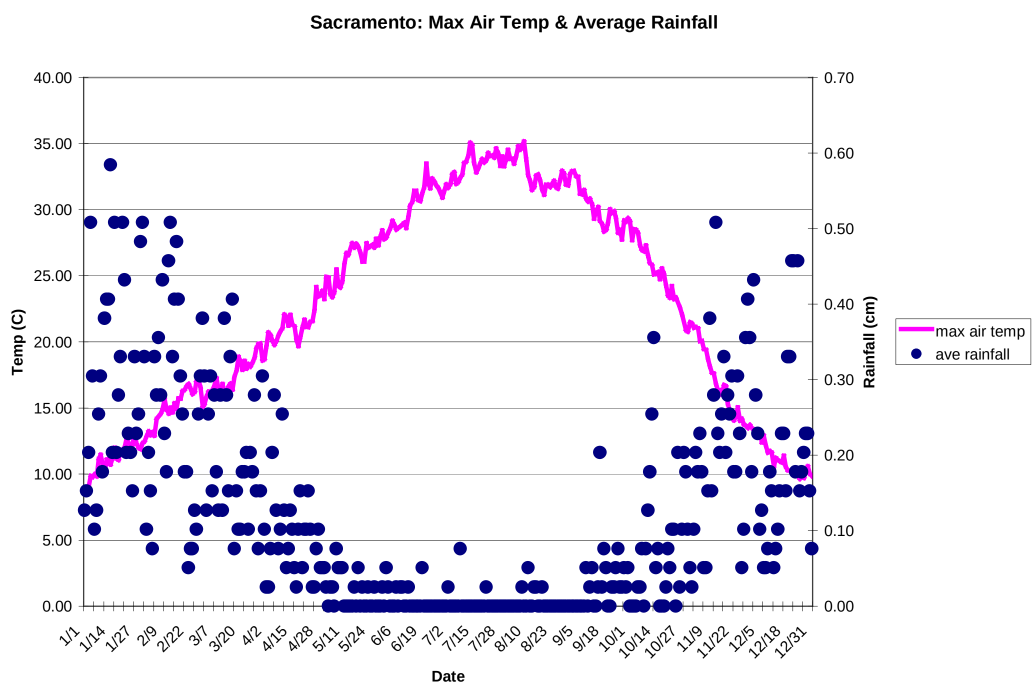


Figure 18. **Relationship between Arcata's Daily Maximum Air Temperature & Rainfall**



over the Course of a Typical Year

Figure 19. **Relationship between Sacramento's Daily Maximum Air Temperatures and Rainfall over the Course of a Typical Year**

The combination of high temperatures and appreciable rainfall is highly conducive to stripping. To better summarize the combined effect of rainfall and high air temperatures on stripping in flexible pavements in the various climates, a simple measure called the Rain-Air Temperature Index was developed for this study. The Rain-Air Temperature Index value is defined as:

$$\mathit{Daily\ Rainfall\ (cm)} \times \mathit{Daily\ Air\ Temperature\ (°C)}$$

The daily maximum temperature was used to compute this index. Figure 20 details the maximum and average daily indices for each climate region, normalized against Arcata, which has the greatest values. Daggett and Reno, on the other hand, have low indices, suggesting that the contribution of the environment to water stripping is less likely in the Desert and High Desert/Mountain regions. <u>This observation assumes that asphalt concrete compaction and asphalt-aggregate compatibility are the same in all regions</u>.

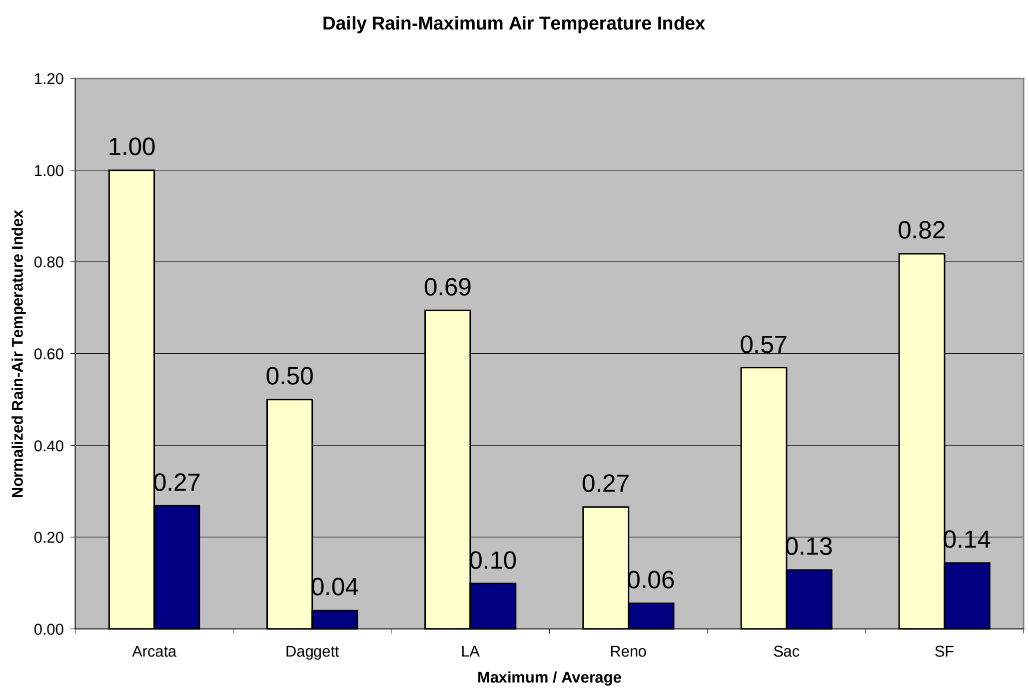


Figure 20. Maximum daily and average daily Rain-Maximum Air Temperature Index normalized over all representative locations.

Reno is the only climate region in this study that should typically encounter water damage due to freezing water in the asphalt concrete layer. Figure 21 illustrates the relationship between Reno's daily minimum temperatures and daily rainfall. Note that much of the Reno climate region's rainfall occurs at the same time as freezing air temperatures.

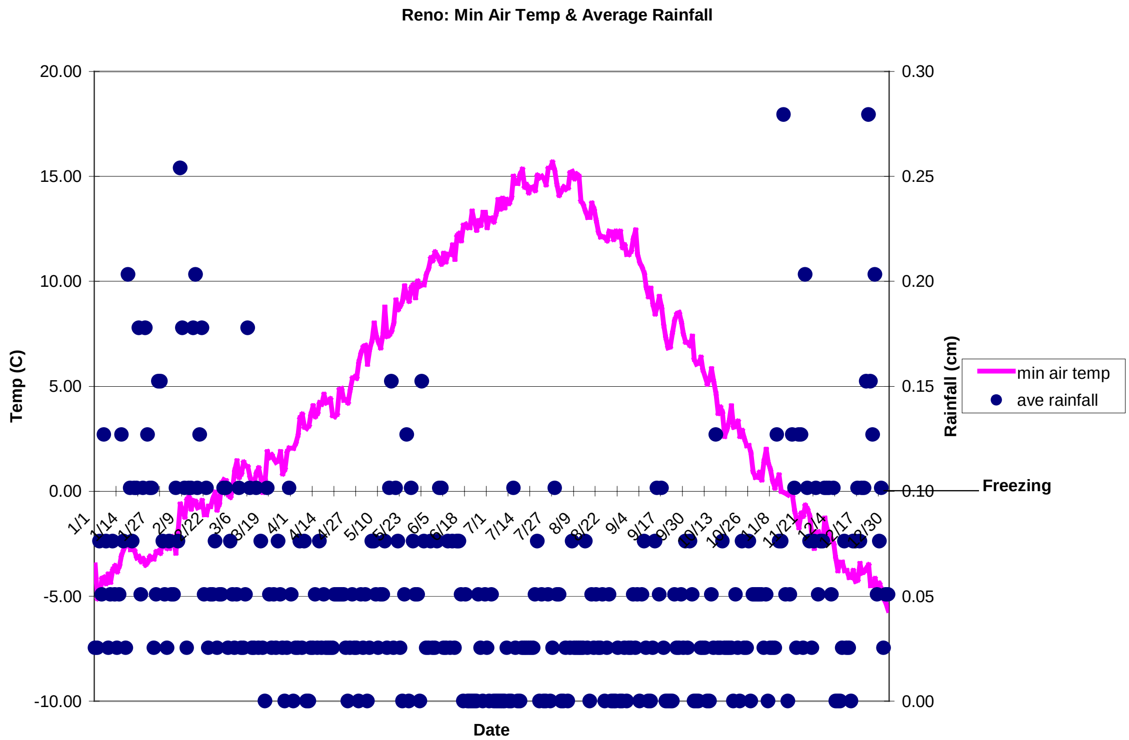


Figure 21. Relationship between Reno Daily Minimum Air Temperature & Rainfall over the Course of a Typical Year

The Rain-Temperature Index is very simplistic, and is intended only to permit a first level examination of the potential for stripping due to climate. In particular, the Index does not account for water that may enter the bottom of the asphalt concrete layer through condensation. This source of water would be particularly prevalent in hot regions in the summer, such as the Central Valley and Desert regions.

2.1.5 Thermal Cracking

Thermal cracking is related to cold temperatures near the surface of the asphalt concrete. Thermal cracking is typical of flexible pavements in climates that have prolonged periods of freezing temperatures.

Of the climates studied, the Reno climate region is the only location that endures prolonged intervals of freezing temperatures, as shown in Figure 8. On average, the Reno climate region has approximately 110 days between November and April in which its flexible pavements experience temperatures that approach or drop below freezing Figure 22. The other regions in California rarely or never experience freezing pavement temperatures. Figure 23 illustrates the cumulative distribution of average minimum daily pavement temperatures at the surface in one year for all six climate regions. Note that the Mountain (Reno) climate region trend line indicates a 50 percent frequency of daily minimum temperatures slightly lower than 4°C (40°F). None of the other locations typically experience temperatures below freezing [0°C (32 °F)].

Thermal cracking is primarily controlled through selection of appropriate asphalt binders for the minimum pavement temperatures expected. The AR binder specification system typically used by Caltrans at the time of this study does not provide much control over the thermal cracking characteristics of the binders. In contrast, the SHRP PG system includes a specification limit on the stiffness of the binder at the minimum expected pavement temperatures to control thermal cracking.

The map of PG binder grades recommended for California by the University of California, Berkeley (UCB) is shown in Figure 24. The specification includes two parts: a minimum stiffness at the highest temperatures expected in the pavement to control rutting and a maximum stiffness at the lowest temperatures expected in the pavement to control thermal cracking. These specifications have been thoroughly researched and are supported by a large body of laboratory and field data.

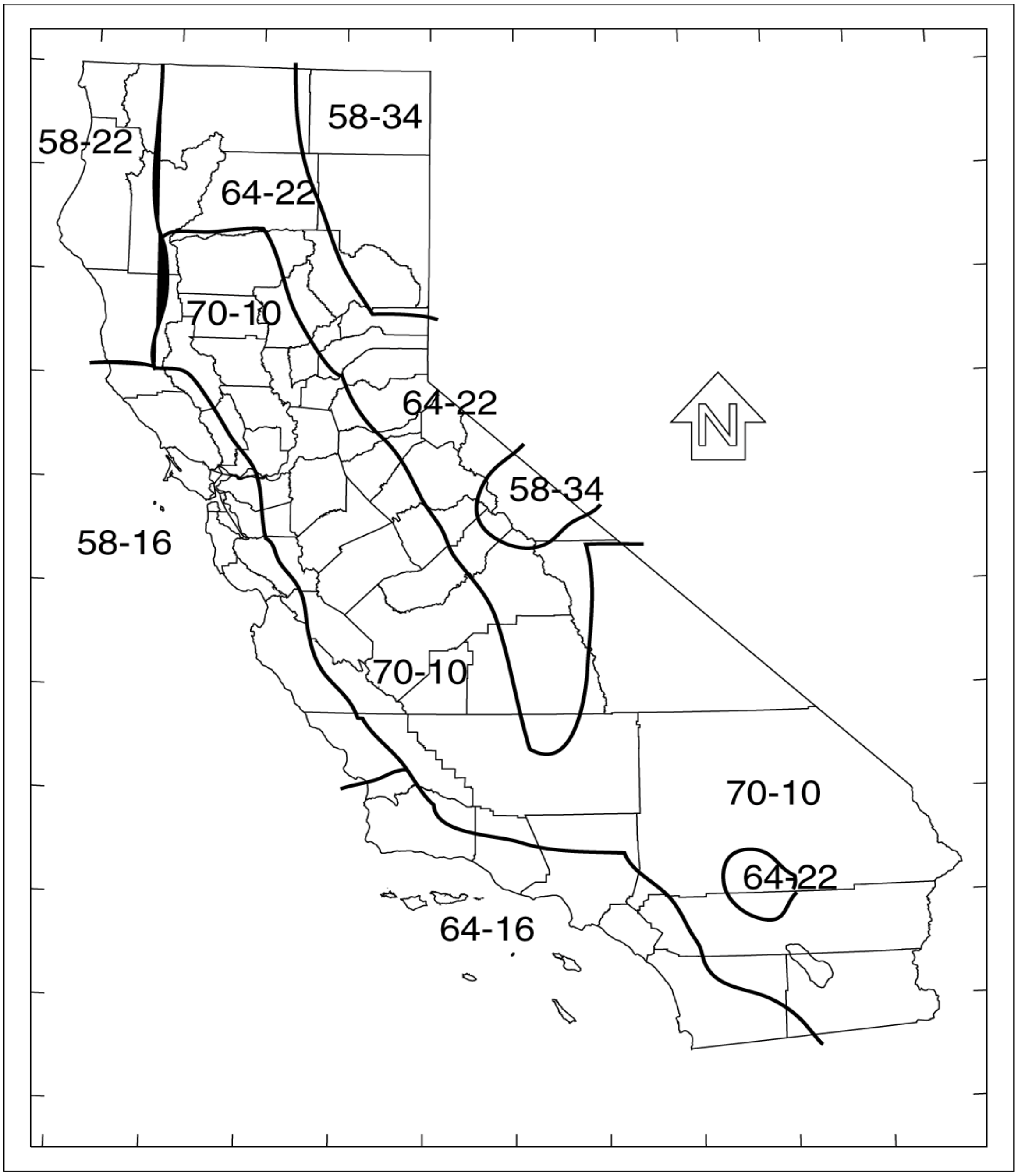


Figure 24. Recommended simplification of PG binder regions for California (simplified from Reference 8)

The requirements of the LTPPBind software (*8*) for implementation of the PG binder system indicated that 10 different PG binders are recommended for California. This number of recommended binders reflects the large number of climate regions in the state. The recommended PG binders include: PG 70-22, PG 70-16, PG 70-10, PG 64-22, PG 64-16, PG 64-10, PG 58-10, PG 58-16, PG 58-28, and PG 52-10. The state with the next nearest number of required grades is Arizona, with five different grades. The number of PG grades recommended by UCB (Figure 24) has been reduced to six to simplify binder specification in California.

The first number in the specification is the estimated high pavement temperature in degrees Celsius, and the second number is the estimated low pavement temperature. For example, PG 70-22, required for the Desert region, meets the required minimum stiffness at 70ºC (158ºF), and the required maximum stiffness at -22ºC (-8ºF).

The current AASHTO specification for PG graded (*9*) also includes a specification at moderate temperatures, which is intended to control fatigue cracking in thin asphalt concrete pavements (less than 100 mm of asphalt concrete). University of California Berkeley and FHWA researchers have produced research data that indicate that the fatigue portion of the AASHTO PG specification is counterproductive for most thicker asphalt concrete pavements. These thicker asphalt concrete pavement make up most of the Caltrans network (*10*, *11*).

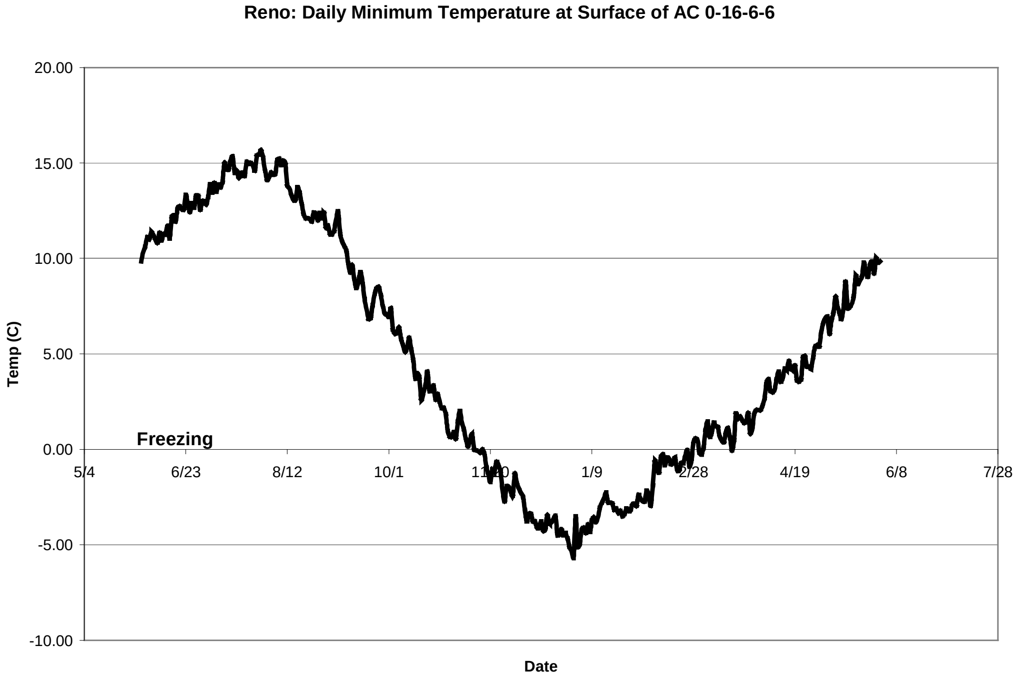


Figure 22. Reno Daily Minimum Temperatures at the Surface of an AC 0-16-6-6

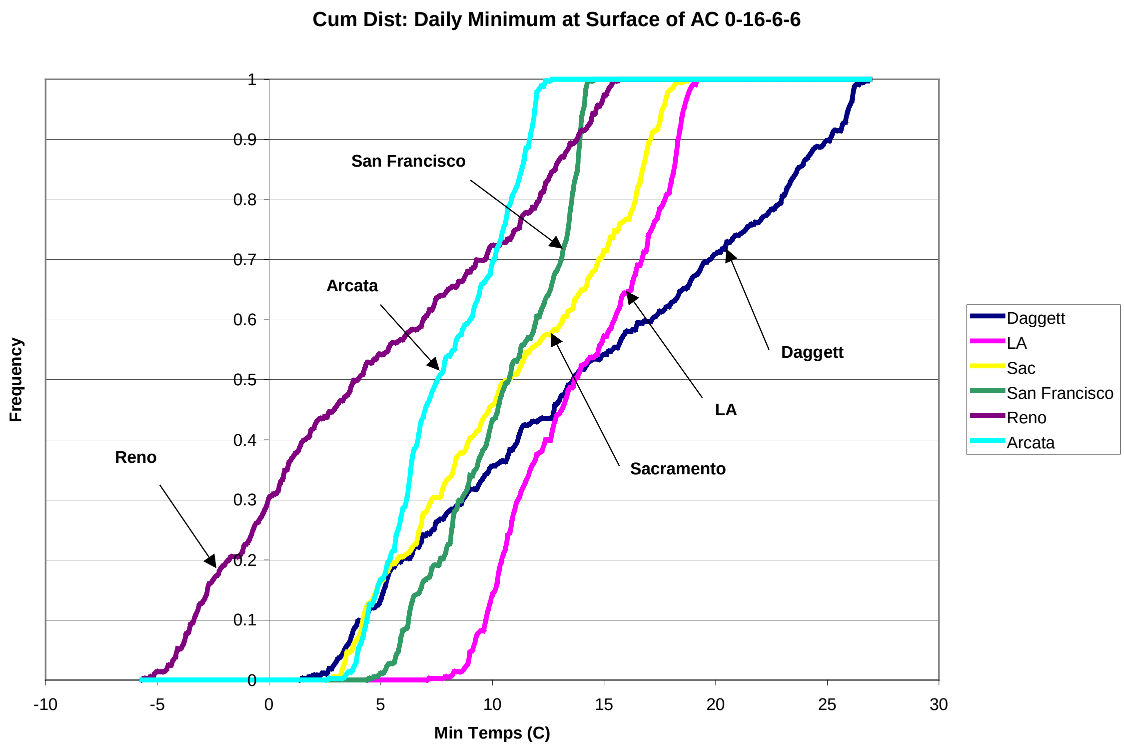


Figure 23. Cumulative Distribution of the Daily Minimum Temperatures at the Surface of an AC 0-16-6-6

2.2 Climate Effects On Rigid Pavement

2.2.1 Fatigue

Fatigue in rigid pavement structures is caused by trafficking and temperature phenomena and the interaction of stresses from both. On a daily basis, the concrete slab is subjected to tensile stresses at the bottom (daytime) and top (nighttime) caused by the daily fluctuation of temperatures and the resulting slab curl. Slab curling is a function of both the thermal gradient in the slab and the moisture gradient in the slab.

2.2.1.1 Causes of slab curling: Thermal gradient and moisture gradient

The thermal gradient is the difference in temperature between the top and bottom of the slab divided by the thickness. The greater the magnitude of the thermal gradient, the higher the bending stresses in the concrete slab. The temperature profile in the slab is usually assumed to be linear with depth for simplicity. However, the temperature profiles in concrete slabs are nonlinear with depth, which typically magnifies the nighttime curling stresses.

Moisture gradients are caused by differential moisture contents in the concrete slab at different depths. Moisture profiles are also believed to be nonlinear with depth and may not extend beyond the mid-depth of the slab (*12*).

Curling stresses are also influenced by:

- The type of base and subgrade under the slab, which influences whether the curled slab lifts off of the base. The tensile stresses that occur when the slab lifts off the base are much larger than those that occur when the slab is uniformly supported by the base. Bases with lower stiffness will result in less lift off when the slab changes shape due to curling since they deform to the shape of the curled concrete slab more easily.

- The dimensions (thickness and length) of the slab, which influences the self-weight and thereby the stresses under curling.
- The coefficient of thermal expansion of the concrete and the concrete elastic modulus.

Only thermal gradients are addressed in this study.

2.2.1.2 Thermal gradient

The magnitude of thermal gradients varies immensely across the six climates studied in California. Figure 25 illustrates that in a given rigid pavement, thermal gradient magnitudes in Daggett can be nearly double those experienced in Arcata. Tables 14a and 14b contain summary thermal gradient magnitudes in each climate region for different rigid structures. Also included in the tables are the time of year and time of day at which these extreme gradients typically occur. Note that the difference between a 20 cm (8 in.) thick and a 30 cm (12 in.) thick PCC structure results in nearly a 0.22ºC/cm (1°F/in.) gradient difference in all scenarios.

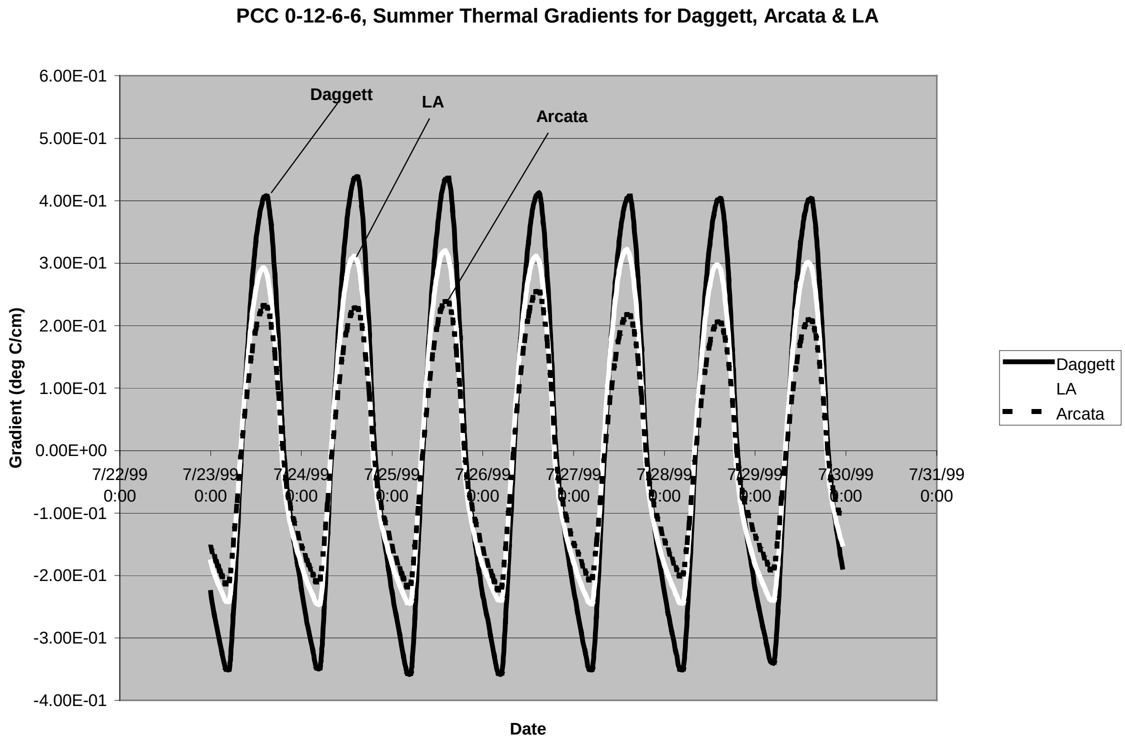


Figure 25. **Illustration of the Difference in Gradients in Daggett, Los Angeles, and Arcata climate regions over the course of a typical summer week in a rigid pavement.**

Table 14a **Average yearly maximum thermal gradient [(temperature at slab top - temperature at slab bottom)/slab thickness] and date and time of occurrence in rigid pavements.**

Climate Region	Structure	Date(s) of Occurrence	Time(s) of Occurrence	Maximum Thermal Gradient °C/cm (°F/in.)
Daggett	20 cm (8 in.) PCC	June 26	2:00 p.m.	0.72 (3.3)
	30 cm (12 in.) PCC	June 21	3:00 p.m.	0.48 (2.21)
Los Angeles	20 cm (8 in.) PCC	April 4 April 21	1:00 p.m. 1:00 p.m.	0.53 (2.43)
	30 cm (12 in.) PCC	April 4 April 21	2:00 p.m. 2:00 p.m.	0.35 (1.62)
Sacramento	20 cm (8 in.) PCC	July 13	2:00 p.m.	0.76 (3.47)
	30 cm (12 in.) PCC	July 13	3:00 p.m.	0.52 (2.36)

San Francisco	20 cm (8 in.) PCC	July 13	2:00 p.m.	0.59 (2.70)
	30 cm (12 in.) PCC	July 10 July 13	2:00 p.m. 2:00 p.m.	0.39 (1.80)
Reno	20 cm (8 in.) PCC	July 14	2:00 p.m.	0.75 (3.42)
	30 cm (12 in.) PCC	July 13 July 14	3:00 p.m. 3:00 p.m.	0.51 (2.34)
Arcata	20 cm (8 in.) PCC	May 31 September 8	2:00 p.m. 2:00 p.m.	0.46 (2.12)
	30 cm (12 in.) PCC	May 31	3:00 p.m.	0.31 (1.44)

Table 14b Average Yearly minimum thermal gradient [(temperature at slab top-temperature at slab bottom)/slab thickness] and date and time of occurrence in rigid pavements.

Climate Region	Structure	Date(s) of Occurrence	Time(s) of Occurrence	Maximum Thermal Gradient °C/cm (°F/in.)
Daggett	20 cm (8 in.) PCC	June 25	4:00 a.m.	-0.57 (-2.62)
	30 cm (12 in.) PCC	June 25 June 30	4:00 a.m. 4:00 a.m.	-0.39 (-1.80)
Los Angeles	20 cm (8 in.) PCC	July 1	4:00 a.m.	-0.38 (-1.72)
	30 cm (12 in.) PCC	June 30 July 1	4:00 a.m. 4:00 a.m.	-0.26 (-1.19)
Sacramento	20 cm (8 in.) PCC	July 6 July 15	4:00 a.m. 4:00 a.m.	-0.62 (-2.82)
	30 cm (12 in.) PCC	July 16	4:00 a.m.	-0.43 (-1.95)
San Francisco	20 cm (8 in.) PCC	July 14 July 15	4:00 a.m. 4:00 a.m.	-0.45 (-2.05)
	30 cm (12 in.) PCC	July 15	4:00 a.m.	-0.31 (-1.42)
Reno	20 cm (8 in.) PCC	July 14 July 19	4:00 a.m. 4:00 a.m.	-0.63 (-2.88)
	30 cm (12 in.) PCC	July 17 July 19 August 2 August 12	4:00 a.m. 4:00 a.m. 4:00 a.m. 5:00 a.m.	-0.43 (-1.98)
Arcata	20 cm (8 in.) PCC	June 28	4:00 a.m.	-0.35 (-1.60)
	30 cm (12 in.) PCC	June 28 July 1	4:00 a.m. 4:00 a.m.	-0.24 (-1.11)

The interaction of tensile stresses from curling and traffic depends upon the shape of the curled slab and the location of the traffic load. The curled shape of the slab depends on whether the thermal gradient is positive or negative. The traffic load can occur at the corner of the slab, edge of the slab, or at the transverse joint in the wheel path. Curling and traffic load stresses are not always additive because temperature and load stresses can be both compressive or tensile depending on wheel location and time of day.

Curling and traffic stresses are typically additive under daytime thermal gradients (positive gradient) with edge loading (Figure 26). For the daytime/edge loading case the maximum tensile stresses occur at the bottom of the slab. Curling and traffic stresses are also typically additive under nighttime thermal gradients (negative gradient) with corner and transverse joint loading (Figure 27). For the nighttime/corner loading case the maximum tensile stresses occur at the top of the slab.

For the opposite conditions, nighttime curl and edge load, and daytime and corner load, the combined tensile stress will typically be less than that caused by the traffic load or curling alone. A few high combined tensile stress repetitions may crack the slab if the maximum or minimum temperature gradient is superposed with a wheel load at the critical location.

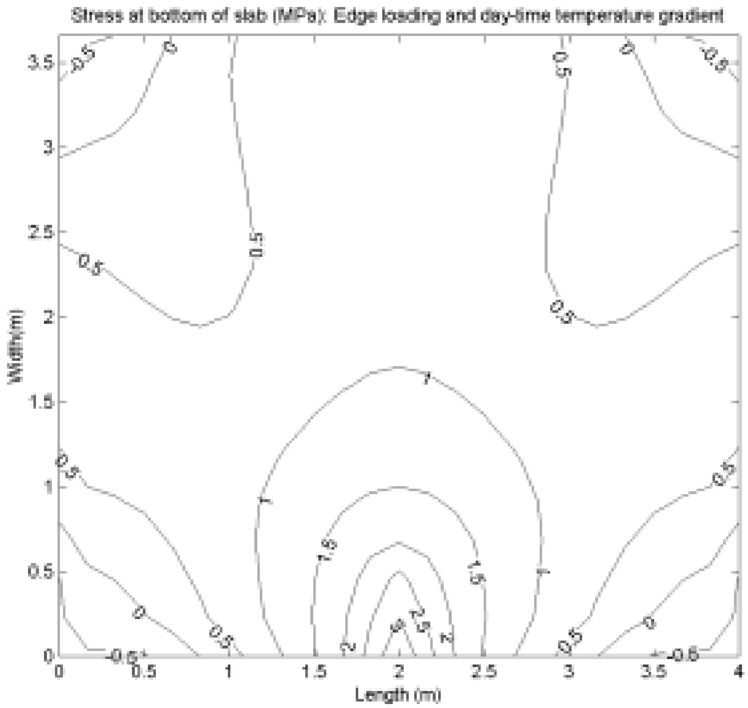


Figure 26. Combined daytime curling stress and edge load stress (*13*).

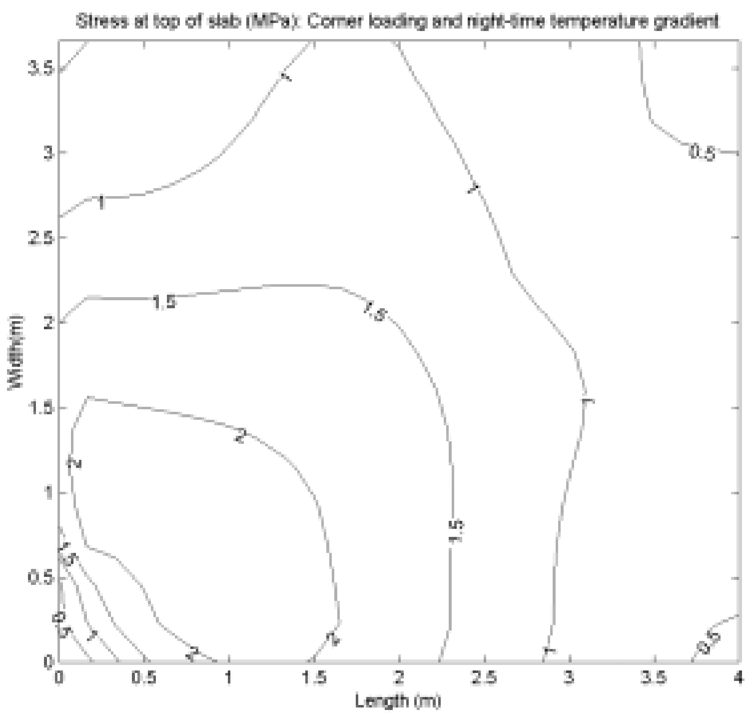


Figure 27. Combined nighttime curling stress and corner load stress or transverse joint loading (*13*)

Tensile stresses in the slab caused by temperature gradients and loads are both larger for longer slab lengths. For example, the tensile stresses caused by the maximum daytime curling for a 200-mm thick slab on a typical CTB in Sacramento and Arcata are much lower for 366 cm (12-ft.) and 457 cm (15-ft.) slab lengths than for 579 cm (19-ft.) slab lengths (Table 15).

The stress analysis results shown in Table 15 were performed using IlliSlab (*14*), assuming a 40 kN (9,000 lb) dual wheel load, no shrinkage, linear temperature gradients, a subgrade modulus of reaction (k-value) of 50 MPA/m (184 pci), and typical values for concrete stiffness and coefficient of thermal expansion (35 Gpa and 0.000008 mm/mm/°C, respectively). The use of 25 mm diameter dowels at 0.3 m spacings was also assumed.

Table 15. Effect of slab length on tensile stresses caused by maximum daytime thermal gradients and edge loads and maximum nighttime thermal gradients and corner loads (Tables 14a and 14b) for Sacramento, Los Angeles, and Arcata.

Location	Slab Temperature Gradient (°C/cm)	Maximum Stresses, MPa (psi)		
		3.65-m (12-ft.) Slab Length	4.6-m (15-ft.) Slab Length	5.8-m (19-ft.) Slab Length
Sacramento daytime	0.76	3.79 (550)	4.39 (637)	4.94 (716)
Sacramento nighttime	-0.62	1.66 (241)	1.98 (287)	2.3 (334)
Arcata daytime	0.46	3.3 (479)	3.68 (534)	4.22 (612)
Arcata nighttime	-0.35	1.3 (189)	1.45 (210)	1.62 (235)
Los Angeles daytime	0.53	3.42 (496)	3.86 (560)	3.99 (579)
Los Angeles nighttime	-0.38	1.33 (193)	1.5 (218)	1.53 (222)

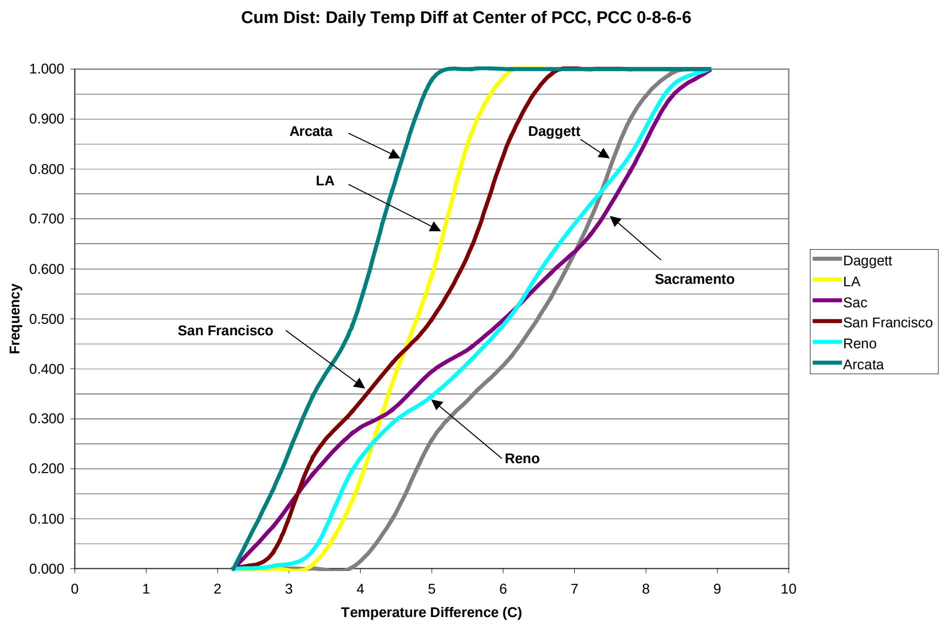
The results in Table 15 show that the combinations of tensile stresses from the maximum thermal gradient and critical wheel loads are very large, particularly for the daytime. Concrete flexural strength is typically on the order of 3.5 to 6.0 MPa after 28 days. Stresses that exceed the flexural strength can crack the slab with one application. Stresses that are near the flexural strength will result in fatigue cracks after a limited number of repetitions of the stress. For large thermal gradients, as in Sacramento, the increase in the slab length considerably increases the stresses. For smaller thermal gradients, such as in the Arcata (North Coast) and Los Angeles (South Coast), the effects of slab length are not as significant. The maximum thermal gradients in Daggett (Desert) are similar to those of Sacramento (Central Valley).

The thermal gradients calculated using ICM for the different climate regions indicate that substantially different curling stresses can be expected in different regions. This indicates that curling should be considered in rigid pavement design in California, and that different designs may be warranted in different climate regions. The large curling stresses calculated for Reno, Sacramento and Daggett (representing the High Desert/Mountain, Central Valley, and Desert regions) indicate that slab lengths must be limited in those regions to obtain reasonable fatigue cracking performance compared to the North Coast, South Coast and Bay Area regions.

In addition, the climate conditions that are responsible for large thermal gradients in the Central Valley and Desert regions can be expected to also contribute to greater differential shrinkage stresses between the top and bottom of the slab, and greater warping stresses due to moisture differences during the dry months. The warping stresses are typically additive with nighttime curling stresses.

Daily temperature changes at the center of the slab provide an indication of tensile friction stresses that can develop at mid-slab, which can contribute to cracking. Figure 28 shows the cumulative distribution of daily temperature differences at the center of a 20 cm (8 in.) PCC layer in all six locations. Note that the range of fluctuation is approximately 2-9°C (4-16ºF). The Sacramento climate region's daily fluctuations span this entire range with a value of nearly 6ºC (11ºF) in fluctuation at the 50th percentile.

Figure 29 shows the cumulative distribution of daily temperature differences at the center of 20 cm (8 in.) and 30 cm (12 in.) PCC pavements, both in Daggett. The magnitude of the daily



temperature fluctuations is greater at the center of a 20 cm (8 in.) thick PCC layer than at the center of a 30 cm (12 in.) thick PCC layer.

Figure 28. Cumulative Distribution of Daily Temperature Differences at the Center of the PCC layer in a PCC 0-8-6-6

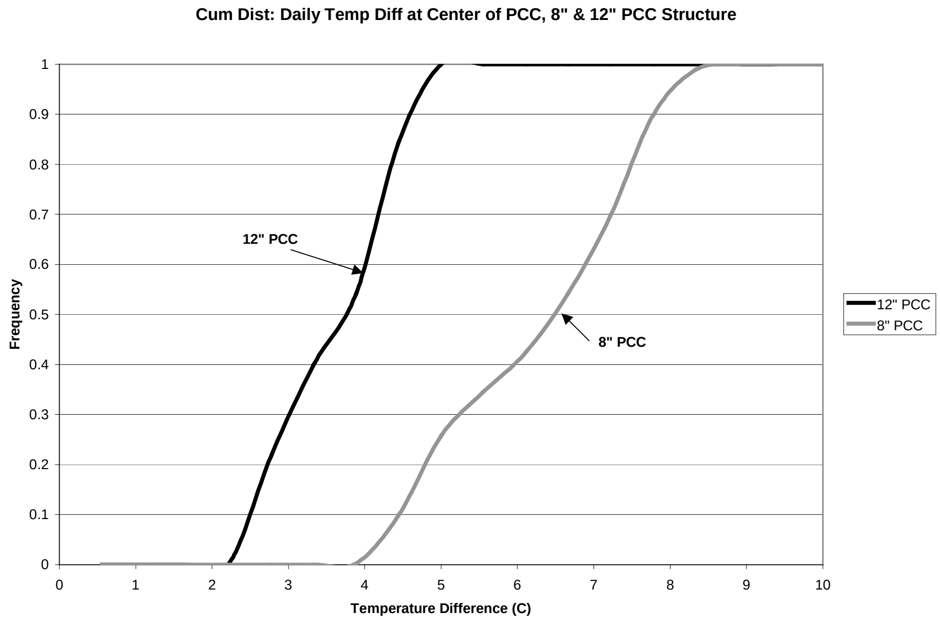


Figure 29. Cumulative Distribution for Daily Temperature Differences at the Center of the PCC layer in a PCC 0-8-6-6 & a PCC 0-12-6-6 Both in Daggett

2.2.2 Erosion (Corner Cracking, Faulting, Pumping)

Corner cracking, faulting and pumping are the results of high stresses and deformations at the joints in the concrete. These stresses and deformations are related to a number of factors.

Poor load transfer at the transverse joints caused by lack of dowels or loss of aggregate interlock and an erodible base results in faulting. This erosion of the base can cause the slab to lose support and eventually crack. Tensile stresses caused by large thermal gradients at night are additive with traffic loads at the slab corners, which contributes to corner cracking. These stresses are larger when there is poor support for the slab from the base.

Figure 30 illustrates the relationship between daily rainfall and the daily maximum thermal gradients in Los Angeles through both a 20 cm (8 in.) and a 30 cm (12 in.) thick PCC structure. While the seasonal fluctuations of the daily minimum gradients are relatively moderate, Los Angeles has a distinct rainy season. Daily minimum thermal gradients would result in slab liftoff at the corners, and therefore larger vertical deformations. Combined with rain, large corner deformations increase faulting. While rigid pavements in the Arcata and San Francisco climate regions do not experience large thermal gradients relative to the other studied climates (Tables 14a and 14b), they do have large annual rainfalls, which contributes to erosion of base support (Figure 10).

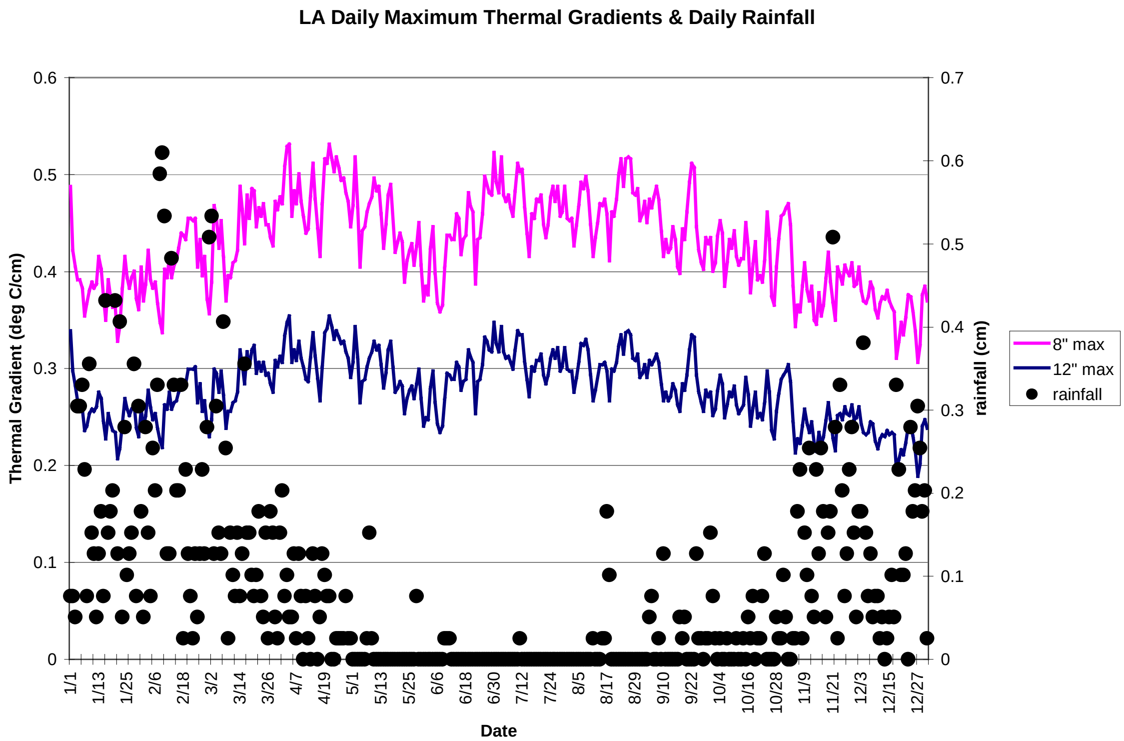


Figure 30. **Relationship between Los Angeles's Daily Maximum Thermal Gradients through 20 cm (8 in.) & 30 cm (12 in.) thick PCC Pavement Structures and Daily Rainfall**

Sacramento receives higher rainfall, approximately 43 cm (17.1 in.) of rain each year, and large thermal gradients (Tables 14a and 14b). This combination is likely to lead to problems with erosion of base at the transverse joints and corners, and therefore corner cracking and faulting.

Temperature changes also cause expansion and contraction of concrete slabs. When temperature changes cause a slab to contract, aggregate interlock can be reduced or lost at the joints, resulting in the loss of load transfer and increased deflections. The critical parameter for this mechanism is the seasonal temperature change at the center of the PCC layer. The greater the seasonal temperature change, the greater the probability of slab contractions large enough to affect load transfer. The largest contractions would occur in slabs constructed during the hottest time of the year.

Figure 31 illustrates week-long temperature trends in a given rigid structure at the center of the PCC layer for Los Angeles and Daggett during both winter and summer seasons. Notice that between summer and winter in the South Coast (Los Angeles) climate region, temperatures can be expected to differ by 10ºC (20°F) while seasonal temperature differences in the Daggett climate region can reach 25ºC (45°F).

Figure 32 shows temperatures at the middle of a 30 cm (12 in.) concrete slab over the year. It can be seen that the Daggett climate region has greater seasonal temperature fluctuations than the Arcata and Los Angeles regions. Table 16 shows the expected six-month averaged maximum temperatures during the period April to September and six-month averaged minimum temperatures during the period October to March at the center of the PCC layer for rigid structures in all six climate regions. The magnitudes of the differences between the estimated maximum and minimum temperatures provide an indication of where loss of aggregate interlock due to slab contraction would be more of a problem.

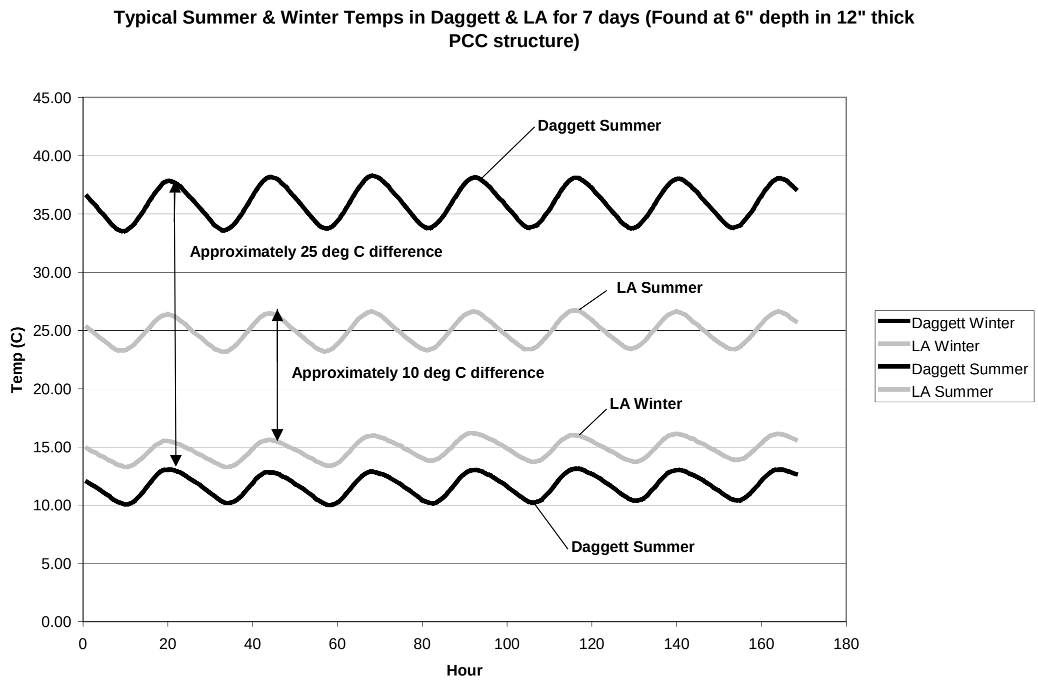


Figure 31. Illustration of seasonal temperature differences in Los Angeles and Daggett rigid pavements over the course of a typical week in the summer and winter.

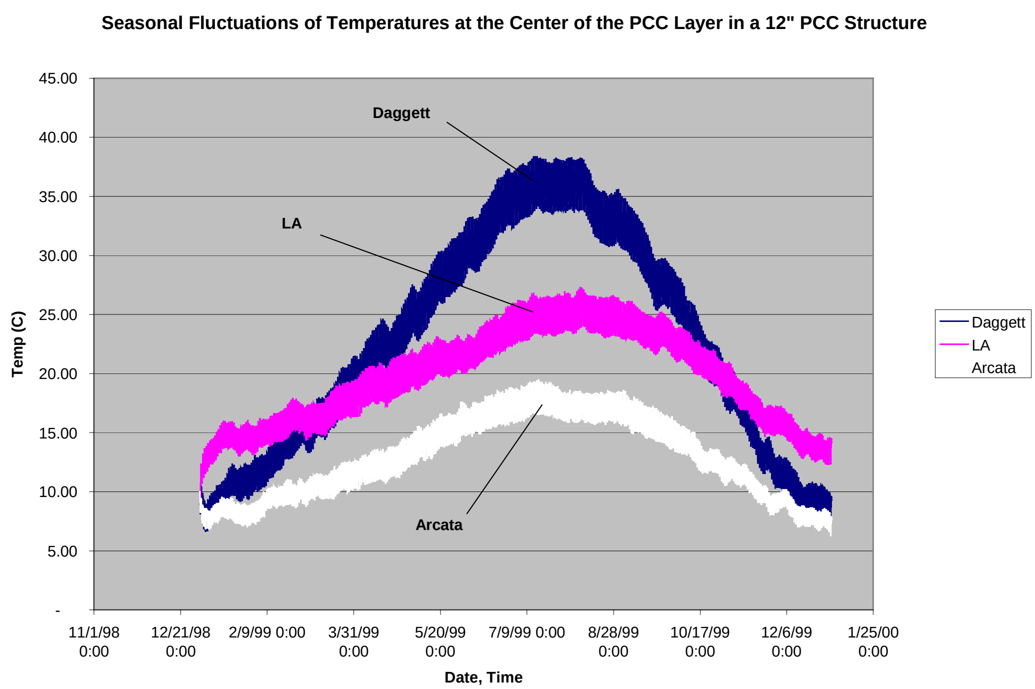


Figure 32. Illustration of seasonal fluctuations experienced in Daggett, Los Angeles, and Arcata at a 15 cm (6 in.) depth in a 30 cm (12 in.) thick PCC slab.

Table 16 **Six-month (April-Septmber) averaged daily maximum and six-month (October-March) averaged daily minimum temperatures at the bottom of the PCC layer in rigid pavements.**

Climate Region	Structure	Maximum Temperature (April-September) °C (°F)	Minimum Temperature (October-March) °C (°F)	Difference (Maximum-Minimum) °C (°F)
Daggett	20 cm (8 in.) PCC	32 (90)	13 (56)	19 (34)
	30 cm (12 in.) PCC	31 (87)	14 (58)	16 (29)
Los Angeles	20 cm (8 in.) PCC	24 (75)	16 (60)	8 (15)
	30 cm (12 in.) PCC	23 (74)	16 (61)	7 (13)
Sacramento	20 cm (8 in.) PCC	27 (80)	11 (52)	16 (28)
	30 cm (12 in.) PCC	26 (78)	12 (54)	13 (24)
San Francisco	20 cm (8 in.) PCC	22 (71)	12 (53)	10 (18)
	30 cm (12 in.) PCC	21 (69)	13 (55)	8 (14)
Reno	20 cm (8 in.) PCC	22 (72)	4 (40)	18 (32)
	30 cm (12 in.) PCC	21 (70)	6 (42)	16 (28)
Arcata	20 cm (8 in.) PCC	17 (62)	9 (49)	7 (13)
	30 cm (12 in.) PCC	16 (61)	10 (50)	6 (11)

These numbers would suggest that rigid pavements in the Daggett, Reno, and Sacramento regions would encounter larger deflections due to loss of load transfer from thermal contraction during the winter than would rigid pavements in the Los Angeles, San Francisco, and Arcata regions. The magnitude of the thermal contraction would be expected to be considerably larger for 549- or 579 cm (18- or 19-ft.) slab lengths than for 457- or 366 cm (15- or 12-ft.) slab lengths.

Analogous to the Rain-Air Temperature Index developed in this study for flexible pavements, a Rain-Temperature Differential Index was developed to evaluate the combined effects of rainfall and maximum temperature gradient in rigid pavements. The Rain-Temperature Gradient Index is defined as:

$$Daily\ Rainfall\ (cm) \times Daily\ Temperature\ Gradient\ (°C/cm)$$

The daily maximum temperature gradient was used to compute the index. Figure 33 shows the maximum daily and average daily Rain-Temperature gradient normalized over all the regions. Traffic loads at the transverse joint and slab corners would be likely to cause the greatest erosion where the Rain-Temperature gradient is highest.

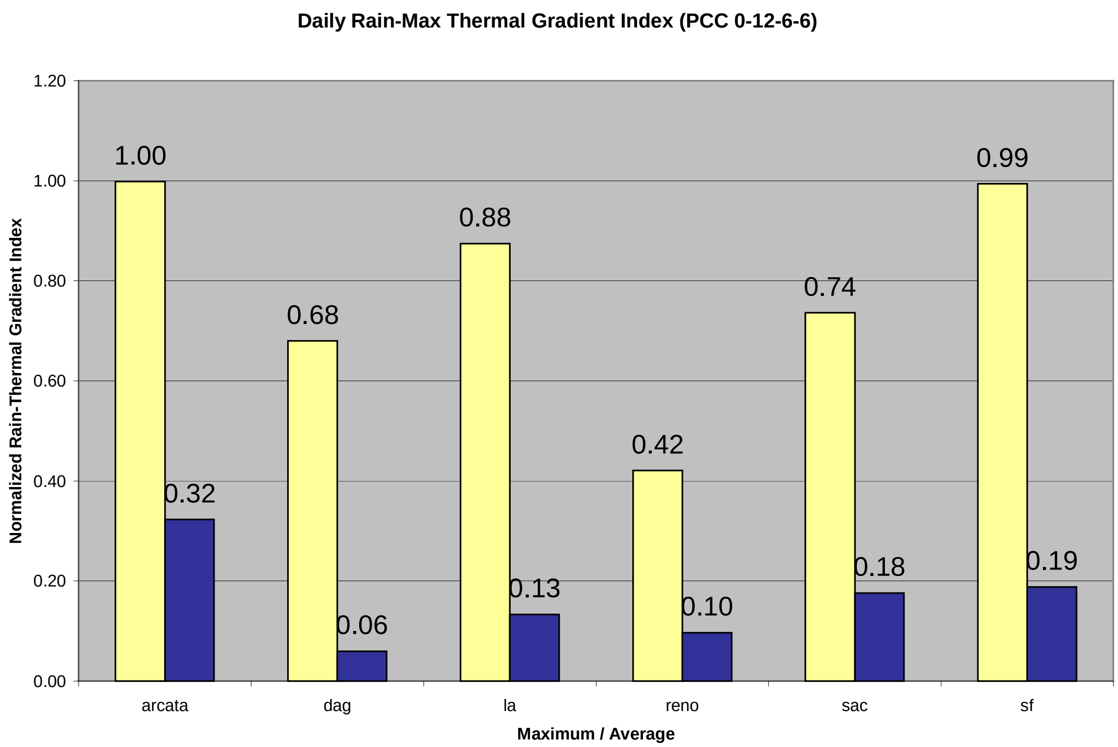


Figure 33. Maximum daily and average daily Rain-Maximum Temperature Gradient Index normalized over all representative locations for a PCC 0-12-6-6 structure.

The Arcata and San Francisco regions have the highest maximum daily indices. This means that at some point over the course of a typical year, both locations may be critical for erosion assuming all other factors are the same among the different climate regions. Arcata also has the highest average daily index, indicating that Arcata's typical daily rain and temperature conditions may make its rigid pavements more susceptible to erosion across the entire year.

2.2.3 Spalling

Spalling is the progressive disintegration of concrete at a joint or crack caused by highly localized stresses. Spalling can occur when the PCC layer experiences the partial loss of aggregate interlock at the joint or crack, and the resulting stress concentrations break off pieces of concrete. Spalling can also occur when incompressible fine material enters a joint or a crack when the slab is in a contracted state, and then the slab expands in hot weather, closing the joint and causing the incompressible material to grind the crack or joint interface. Increased slab contraction leads to a greater chance of incompressible materials entering joints or cracks, thereby leading to increased chance of spalling.

The reduction in aggregate interlock is a function of joint type and seasonal temperature fluctuations. The greater the slab contraction, the greater the loss of aggregate interlock under loading and the greater the loss in load transfer efficiency across the joint. With dowel bars, the aggregate interlock at the joint is not as critical as with plain concrete joints.

Table 17 shows the average summer and winter temperatures experienced in rigid structures at the center of the PCC layer for varying climates. The Daggett and Reno regions experience seasonal temperature differences that are almost three times the magnitude of the differences experienced in either the Arcata or Los Angeles regions. This implies that Daggett and Reno rigid pavements may have a higher probability of spalling distress than rigid pavements in the Arcata or Los Angeles regions, assuming all other factors are equal. Note that traffic plays a large role in many rigid pavement distresses, and therefore, critical climatic factors may not cause pavement distresses unless sufficient traffic is applied.

Table 17 Average summer week (June 23-29) and winter week (February 1-7) temperatures at the center of the PCC layer in rigid pavements.

Climate Region	Structure	Maximum Temperature, June 23-29 °C (°F)	Minimum Temperature, February 1-7 °C (°F)	Difference (Maximum-Minimum) °C (°F)
Daggett	20 cm (8 in.) PCC	36 (97)	12 (53)	24 (44)
	30 cm (12 in.) PCC	36 (97)	12 (53)	24 (44)
Los Angeles	20 cm (8 in.) PCC	25 (77)	15 (59)	10 (18)
	30 cm (12 in.) PCC	25 (77)	15 (59)	10 (18)
Sacramento	20 cm (8 in.) PCC	29 (85)	9 (49)	20 (36)
	30 cm (12 in.) PCC	29 (85)	9 (49)	20 (36)
San Francisco	20 cm (8 in.) PCC	22 (71)	11 (52)	11 (19)
	30 cm (12 in.) PCC	22 (71)	11 (52)	11 (19)
Reno	20 cm (8 in.) PCC	27 (80)	3 (37)	24 (43)
	30 cm (12 in.) PCC	27 (80)	3 (37)	24 (43)
Arcata	20 cm (8 in.) PCC	17 (63)	9 (48)	8 (15)
	30 cm (12 in.) PCC	18 (64)	8 (47)	9 (17)

2.3 Climate Effects on Composite Pavement

2.3.1 Mix Rutting

Composite structures experience mix rutting in the surface layer in the same manner as flexible pavements. The critical parameter for composite pavements, as with flexible pavements, is the temperatures in the top 100 mm (approximately 4 in.) of the AC layer. The extremes for hot and cool surface temperatures are encountered in the Daggett and Arcata climate regions, respectively. Temperatures in the upper 100 mm of the asphalt concrete are approximately 22ºC (40ºF) higher in Daggett than in Arcata, regardless of the thickness of AC (Table 18).

Table 18 Maximum Daily Temperatures °C (°F) at 0 cm, 5 cm & 10 cm Depths in Composite PCC Structures

Climate Region	Structure	Temperature at Depth, °C (°F)		
		0 cm (0 in.)	5 cm (2 in.)	10 cm (4 in.)
Daggett	10 cm (4 in.) thick AC Composite	56 (132)	49 (120)	44 (111)
	20 cm (8 in.) thick AC Composite	56 (133)	51 (123)	47 (116)
Los Angeles	10 cm (4 in.) thick AC Composite	41 (106)	36 (96)	32 (89)
	20 cm (8 in.) thick AC Composite	41 (106)	37 (99)	34 (93)
Sacramento	10 cm (4 in.) thick AC Composite	51 (124)	44 (111)	38 (101)
	20 cm (8 in.) thick AC Composite	52 (125)	46 (114)	42 (107)
San Francisco	10 cm (4 in.) thick AC Composite	40 (104)	11 (52)	11 (19)
	20 cm (8 in.) thick AC Composite	41 (105)	36 (96)	32 (90)
Reno	10 cm (4 in.) thick AC Composite	48 (119)	41 (106)	35 (95)
	20 cm (8 in.) thick AC Composite	49 (120)	43 (109)	38 (101)
Arcata	10 cm (4 in.) thick AC Composite	31 (88)	27 (80)	23 (74)
	20 cm (8 in.) thick AC Composite	31 (88)	28 (82)	25 (77)

For this reason, the Daggett climate region is expected to have more problems with mix rutting than the Arcata climate region. In Los Angeles, a large network of composite pavements exists, the pavement temperatures are in between the extremes of the hot Desert and Central Valley environments and the cool North Coast environment. The temperatures at each depth are nearly identical for both the structure with a 10 cm (4 in.) thick AC and that with a 20 cm (8 in.) thick AC layer. Therefore, the thickness of the AC layer has little significance when designing against mix rutting for composite structures.

2.3.2 Faulting

A composite pavement can experience faulting in the same way rigid pavements do if it is not cracked and seated. The critical parameter is the thermal gradient through the concrete slab. The thermal gradient in a composite structure is the temperature difference between the top and bottom surfaces of the PCC layer divided by the thickness of the PCC layer.

Tables 19a and 19b show the yearly maximum and minimum thermal gradients for the two composite structures studied for all six climates. Also shown are the times and dates when these gradients are expected to occur. The thermal gradients are reduced when going from a 10 cm (4 in.) inch thick AC layer to a 20 cm (8 in.) thick AC layer in all locations.

Table 19a Yearly maximum thermal gradients in composite PCC structures and time and date of occurrence.

Climate Region (city)	Structure	Date	Time	Yearly Maximum Thermal Gradient °C/cm (°F/in.)
Desert (Daggett)	10 cm (4 in.) thick AC Composite	June 10	4:00 p.m.	0.28 (1.27)
	20 cm (8 in.) thick AC Composite	June 21	7:00 p.m.	0.19 (0.89)
South Coast (Los Angeles)	10 cm (4 in.) thick AC Composite	June 30	4:00 p.m.	0.21 (0.95)
	20 cm (8 in.) thick AC Composite	June 30	7:00 p.m.	0.14 (0.66)
Central Valley (Sacramento)	10 cm (4 in.) thick AC Composite	July 13	4:00 p.m.	0.29 (1.33)
	20 cm (8 in.) thick AC Composite	July 13	7:00 p.m.	0.20 (0.92)
Bay Area (San Francisco)	10 cm (4 in.) thick AC Composite	July 10	4:00 p.m.	0.23 (1.07)
	20 cm (8 in.) thick AC Composite	July 10	7:00 p.m.	0.16 (0.73)
High Desert/Mountain (Reno)	10 cm (4 in.) thick AC Composite	July 13	4:00 p.m.	0.28 (1.30)
	20 cm (8 in.) thick AC Composite	July 13	7:00 p.m.	0.20 (0.90)
North Coast (Arcata)	10 cm (4 in.) thick AC Composite	May 31	4:00 p.m.	0.19 (0.85)
	20 cm (8 in.) thick AC Composite	May 31	7:00 p.m.	0.13 (0.61)

Table 19b Yearly minimum thermal gradients in composite PCC structures and time and date of occurrence.

Climate Region (city)	Structure	Date	Time	Yearly Minimum Thermal Gradient °C/cm (°F/in.)
Desert (Daggett)	10 cm (4 in.) thick AC Composite	June 30	6:00 a.m.	-0.21 (-0.97)
	20 cm (8 in.) thick AC Composite	September 20	8:00 a.m.	-0.16 (-0.71)
South Coast (Los Angeles)	10 cm (4 in.) thick AC Composite	August 23	6:00 a.m.	-0.15 (-0.69)
	20 cm (8 in.) thick AC Composite	August 23	8:00 a.m.	-0.11 (-0.49)
Central Valley (Sacramento)	10 cm (4 in.) thick AC Composite	July 29 August 12	6:00 a.m. 6:00 a.m.	-0.23 (-1.05)
	20 cm (8 in.) thick AC Composite	August 12	8:00 a.m.	-0.16 (-0.75)
Bay Area (San Francisco)	10 cm (4 in.) thick AC Composite	July 15	5:00 a.m. 6:00 a.m.	-0.18 (-0.80)
	20 cm (8 in.) thick AC Composite	July 21	8:00 a.m.	-0.12 (-0.57)
High Desert/Mountain (Reno)	10 cm (4 in.) thick AC Composite	August 14 August 15	6:00 a.m.	-0.23 (-1.06)
	20 cm (8 in.) thick AC Composite	January 1	10:00 a.m.	-0.18 (-0.81)
North Coast (Arcata)	10 cm (4 in.) thick AC Composite	July 1	5:00 a.m.	-0.14 (-0.62)
	20 cm (8 in.) thick AC Composite	September 7	8:00 a.m.	-0.10 (-0.45)

Los Angeles represents the South Coast climate region, which includes a large number of concrete pavements that either already have, or are candidates for asphalt concrete overlays. Comparing the thermal gradients for composite pavements (Tables 19a and 19b) to those of the 20 cm (8 in.) thick PCC rigid structure (Tables 14a and 14b), it can be seen that the addition of the AC overlays reduces the maximum gradient in Los Angeles by approximately 0.33ºC/cm (1.5° F/in.). Similarly, the addition of AC overlays reduces the magnitude of the minimum gradient in Los Angeles by approximately 0.22º C/cm (1.0° F/in.) (Tables 14b and 18b). The extent of this reduction in thermal gradient is consistent for all the climates studied. The thermal gradient reduction is larger for the 20 cm (8 in.) AC layer than for the 10 cm (4 in.) AC layer.

2.3.3 Reflection Cracking

Reflection cracking is the propagation of discontinuities from an underlying structure through an asphalt concrete overlay. In composite pavements, the discontinuities are typically cracks or joints in an underlying concrete layer. Reflection cracking can be caused by repeated shear stresses from trafficking, and by tensile strains caused by thermal expansion/contraction of the PCC layer that occur on a daily basis and from season to season. The likely critical parameters for expansion and contraction are the daily temperature fluctuations at the AC/PCC interface, as well as the yearly maximum and minimum temperatures found at the same location.

Table 20 shows the maximum, minimum, and average daily extreme temperature differences at the AC/PCC interface of each of the composite structures evaluated. The temperature differences in Table 20 were calculated by first finding the daily maximum and minimum temperatures for each day of the year, and then calculating the difference between extremes for each day. The values presented in Table 20 are the maximum, minimum, and average differences found over the course of the entire year.

Table 20 The maximum, minimum and average daily extreme temperature differences at the AC/PCC interface of composite structures.

Climate Region	Structure	Maximum Difference, °C (°F)	Minimum Difference, °C (°F)	Average Difference, °C (°F)
Daggett	10 cm (4 in.) thick AC Composite	9 (17)	4 (8)	7 (12)
	20 cm (8 in.) thick AC Composite	6 (11)	3 (5)	4 (8)
Los Angeles	10 cm (4 in.) thick AC Composite	7 (13)	3 (6)	6 (10)
	20 cm (8 in.) thick AC Composite	5 (9)	2 (4)	3 (6)
Sacramento	10 cm (4 in.) thick AC Composite	10 (18)	2 (4)	6 (11)
	20 cm (8 in.) thick AC Composite	7 (12)	2 (3)	4 (7)
San Francisco	10 cm (4 in.) thick AC Composite	8 (14)	3 (5)	6 (10)
	20 cm (8 in.) thick AC Composite	6 (10)	2 (3)	3 (6)
Reno	10 cm (4 in.) thick AC Composite	9 (17)	2 (4)	6 (11)
	20 cm (8 in.) thick AC Composite	6 (11)	1 (2)	4 (7)
Arcata	10 cm (4 in.) thick AC Composite	6 (11)	2 (4)	4 (8)
	20 cm (8 in.) thick AC Composite	4 (8)	2 (3)	3 (5)

The average temperature differences are similar for each climate. Increasing the AC layer from 10 cm (4 in.) thick to 20 cm (8 in.) reduces temperature differences from approximately 1.7 ºC (3°F) to 3.3ºC (6 °F)

Reflection cracking can also be a result of large seasonal temperature fluctuations. Large differences in temperature between summer and winter will increase the strain in the asphalt concrete, and probably more important, large temperature differences can cause potential loss of aggregate interlock in the winter, which will cause higher shear stresses under traffic.

Table 21 shows the yearly extreme temperatures that are experienced at the AC/PCC interface of the composite structures and the difference between these extremes. Composite structures in the Arcata, San Francisco, and Los Angeles climate regions experience the least seasonal temperature fluctuation, while the Daggett, Reno, and Sacramento climate regions all experience dramatic changes in seasonal temperatures.

Table 21 Yearly maximum and minimum temperatures at the AC/PCC interface of composite structures.

Climate Region	Structure	Maximum Temperature, °C (°F)	Minimum Temperature, °C (°F)	Difference (Maximum-Minimum), °C (°F)
Daggett	10 cm (4 in.) thick AC Composite	44 (111)	7 (45)	37 (66)
	20 cm (8 in.) thick AC Composite	42 (108)	8 (46)	34 (62)
Los Angeles	10 cm (4 in.) thick AC Composite	32 (89)	9 (49)	22 (40)
	20 cm (8 in.) thick AC Composite	31 (87)	9 (49)	21 (38)
Sacramento	10 cm (4 in.) thick AC Composite	38 (101)	6 (43)	32 (57)
	20 cm (8 in.) thick AC Composite	37 (98)	7 (44)	30 (54)
San Francisco	10 cm (4 in.) thick AC Composite	29 (85)	8 (46)	22 (39)
	20 cm (8 in.) thick AC Composite	28 (93)	8 (47)	20 (36)
Reno	10 cm (4 in.) thick AC Composite	35 (95)	-1 (30)	36 (65)
	20 cm (8 in.) thick AC Composite	33 (92)	0 (32)	33 (60)
Arcata	10 cm (4 in.) thick AC Composite	23 (74)	7 (44)	17 (30)
	20 cm (8 in.) thick AC Composite	22 (72)	7 (45)	15 (27)

Figure 34 shows different representative seasonal temperature fluctuations for composite structures within this study, with the Daggett and Arcata climate regions being the extremes and the Los Angeles climate region being a moderately fluctuating climate. Figure 35 depicts the typical summer and winter temperatures for the same composite structure in Los Angeles and in Daggett. It can be seen that while the Daggett region is expected to experience approximately a 28ºC (50°F) difference between summer and winter, the Los Angeles region is expected to experience only a 10ºC (18°F) difference. Overall, the Daggett, Reno, and Sacramento regions are expected to encounter relatively more problems with reflection cracking caused by seasonal temperature fluctuations, all other factors assumed equal.

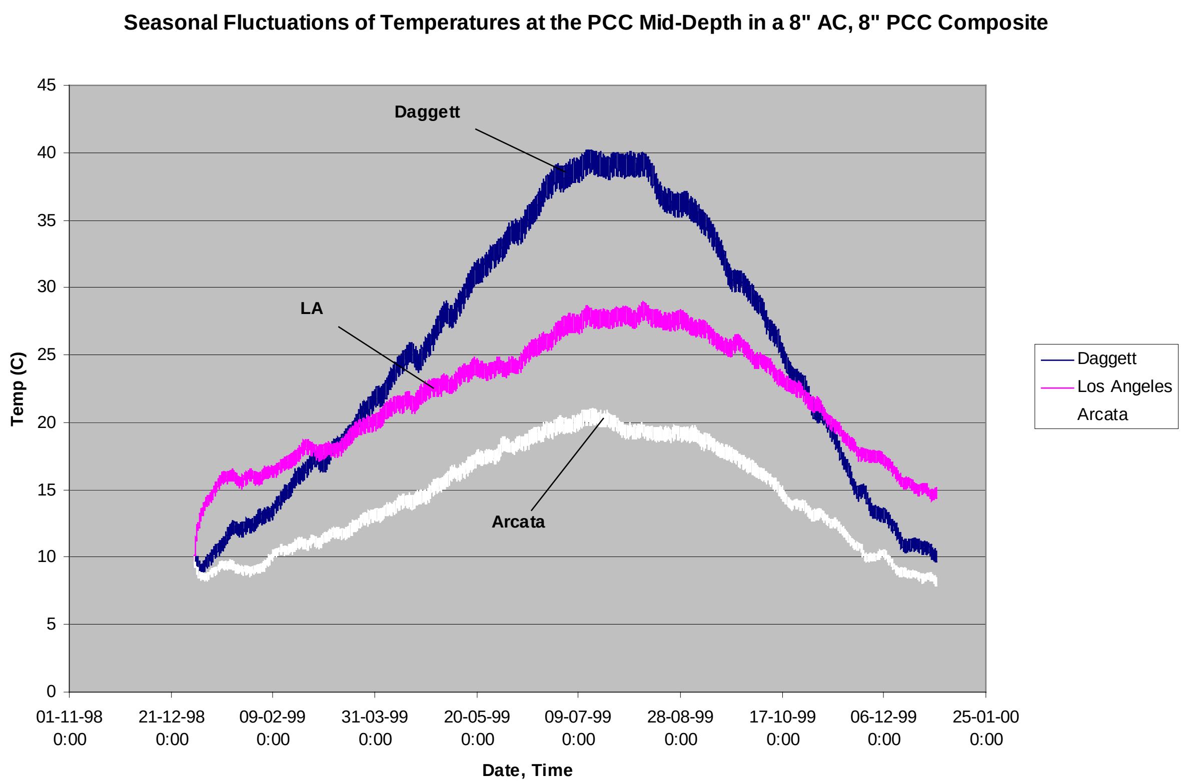


Figure 34. Illustration of seasonal fluctuations experienced in the Daggett, Los Angeles, and Arcata climate regions at the mid-depth of the PCC layer of an 20 cm AC/20 cm PCC (8 in. AC/8 in. PCC) composite structure.

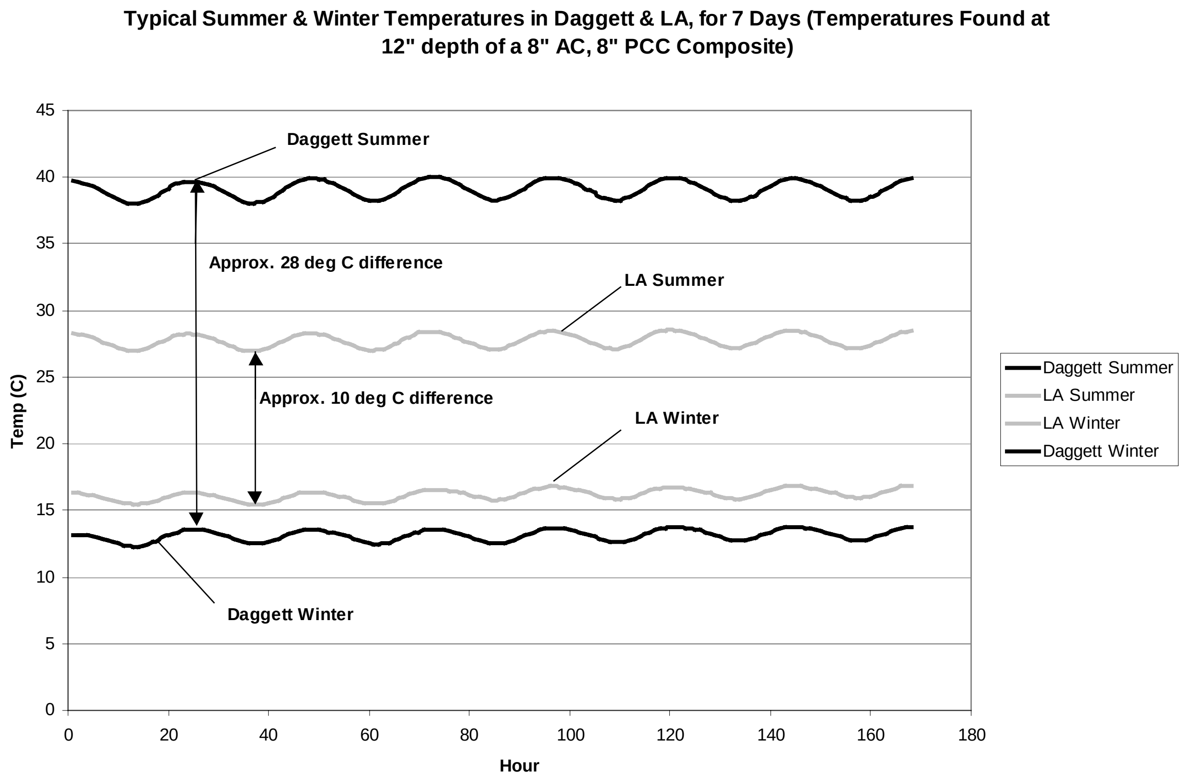


Figure 35. Illustration of seasonal temperature differences in the Daggett and Los Angeles climate regions over the course of typical weeks in summer and winter for a given composite pavement.

Cumulative distribution functions for daily temperature changes at the interface of the AC overlay and underlying PCC pavement are shown for the 10 cm (4 in.) AC and 20 cm (8 in.) AC composite structures in Figures 36 and 37, respectively.

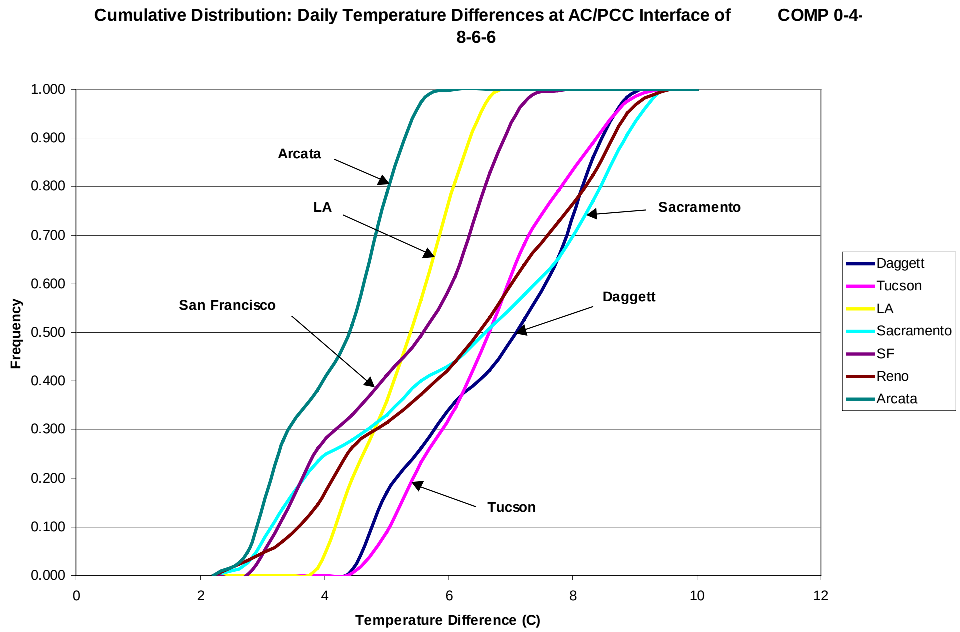


Figure 36. Cumulative distribution of daily temperature differences at the AC/PCC interface in a COMP 0-4-8-6-6 pavement.

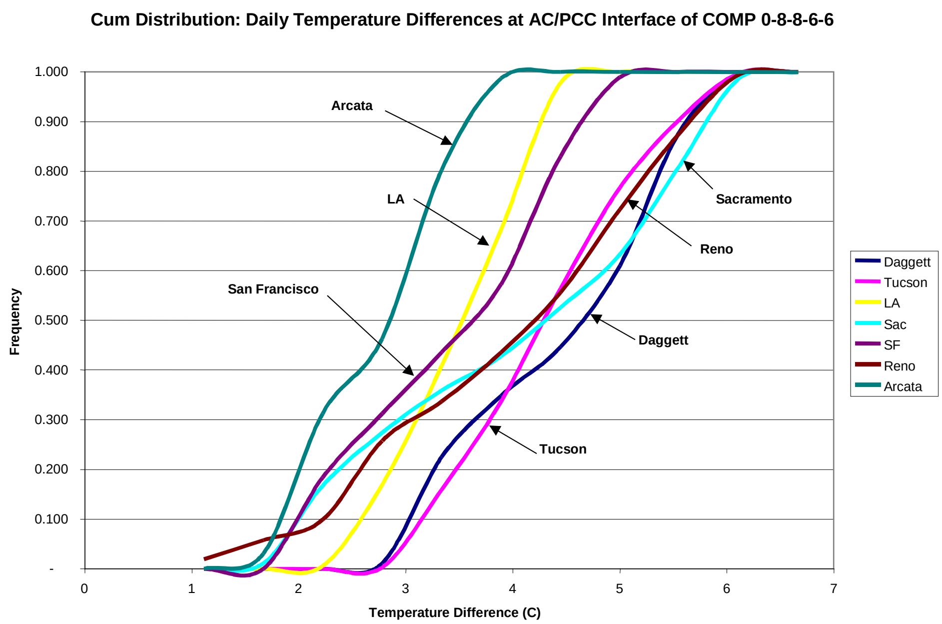


Figure 37. Cumulative distribution of daily temperature differences at the AC/PCC interface in a COMP 0-8-8-6-6 pavement.

3.0 RAINFALL DATA – DRAINAGE CONSIDERATIONS

Rainfall has a large impact on the occurrence of distress in a pavement. In flexible pavements, water primarily reduces the stiffness and strength of the unbound materials, which contributes to AC fatigue cracking and rutting of the unbound layers. In rigid pavements, the primary effect of water is erosion of the base. Erosion contributes to faulting and corner cracking.

Rainfall data for the six climate locations is summarized in this chapter to provide the engineer with additional decision-making tools when considering drainage needs for pavement design. California has a wider range of rainfall than most other states. The following section illustrates the differences in the amount of rainfall over a typical year for the regions studied. The need for drainage and drainage design depends upon expected rainfall, rainfall intensity, pavement materials, and highway geometry considerations such as cut versus fill, and transverse and longitudinal cross slope.

Figure 38 shows the 30-year average total annual rainfall experienced in the different climate regions. The Los Angeles, Sacramento, San Francisco, and Reno climate regions fall within the mid-range of annual rainfall, while the Arcata and Daggett regions are at opposite extremes.

Figure 39 shows average maximum monthly rainfall experienced in the different climate regions. In all regions, it is common for the greatest amount of rainfall to occur at the beginning of the year, usually in January. The maximum monthly rainfall constitutes approximately 10-20 percent of the annual total rainfall for each location.

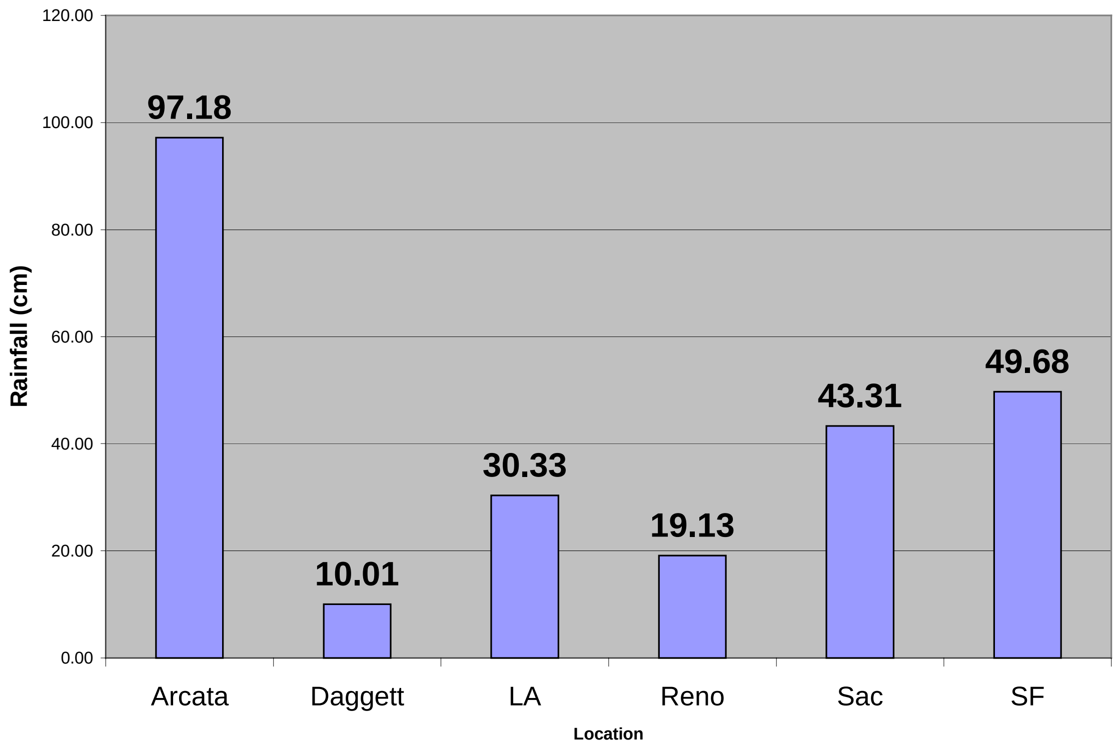


Figure 38. **Typical total annual rainfall for each studied climate.**

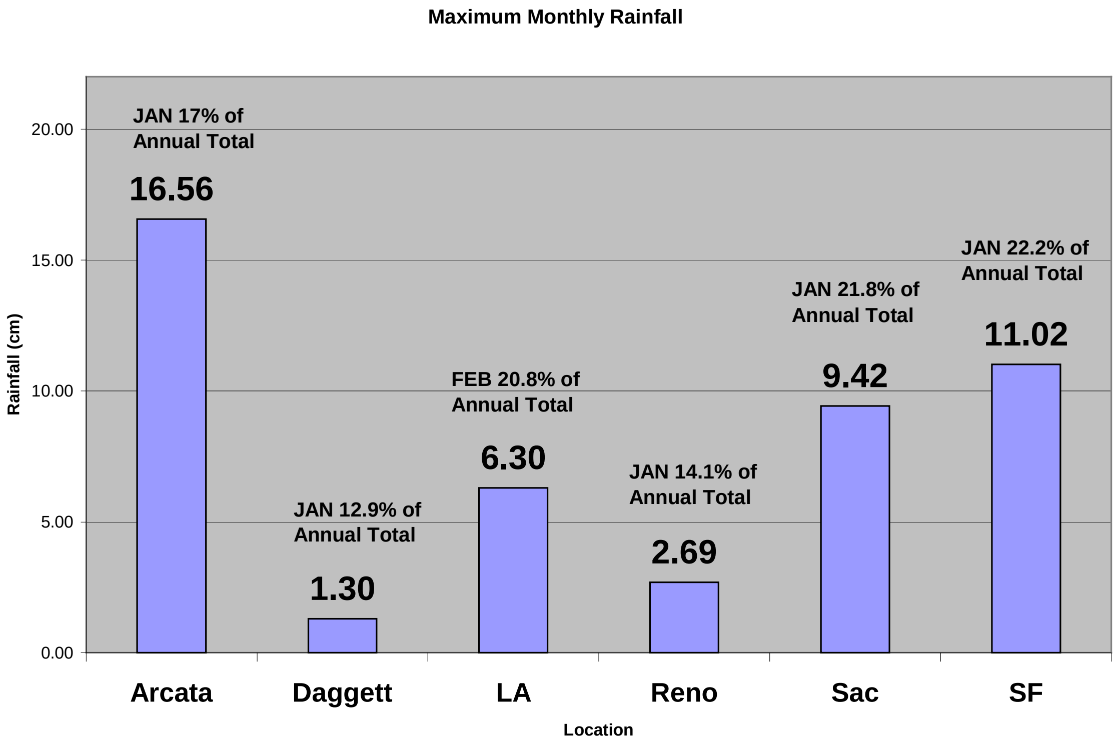


Figure 39. **Maximum monthly rainfall for each studied climate in a typical year**

Figure 40 shows the average maximum weekly rainfall for each climate region. Weeks were defined as 7-day intervals taken at the start of each month, resulting in four 7-day weeks with the addition, if necessary, of a remaining week composed of 2 to 3 days. Maximum weekly rainfalls do not always occur within the maximum rainfall month, as shown in the data for the Arcata and Reno regions. The maximum weekly rainfall typically constitutes 5 percent of the annual total rainfall. The extreme exception to this trend is Los Angeles, where approximately 9 percent of the typical year's total rainfall takes place during a week in February.

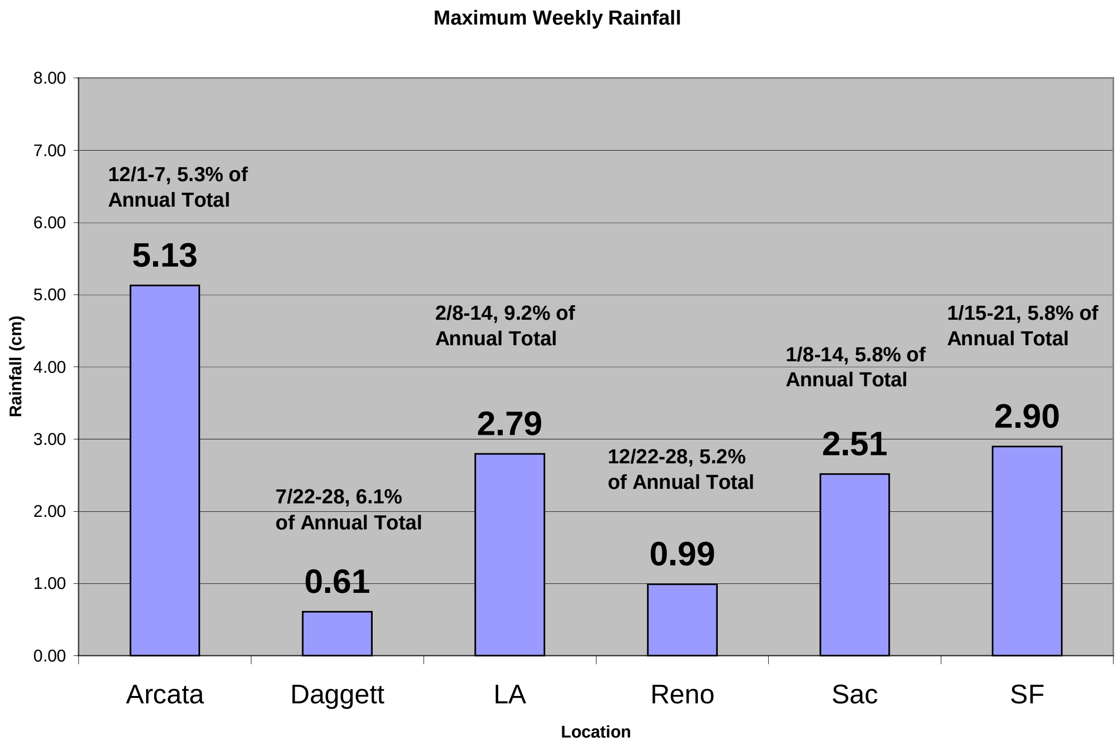


Figure 40. Maximum weekly rainfall for each studied climate in a typical year

Figure 41 shows the average maximum daily rainfall for each location. This information is critical for designing the appropriate drainage capacity for heavy downpours. On average, the maximum daily rainfall for all climates ranges between 1 and 2 percent of the annual total rainfall. More importantly, however, are the actual rainfall amounts experienced within a 24-hour period. Arcata and San Francisco experience the largest daily maximum rainfalls.

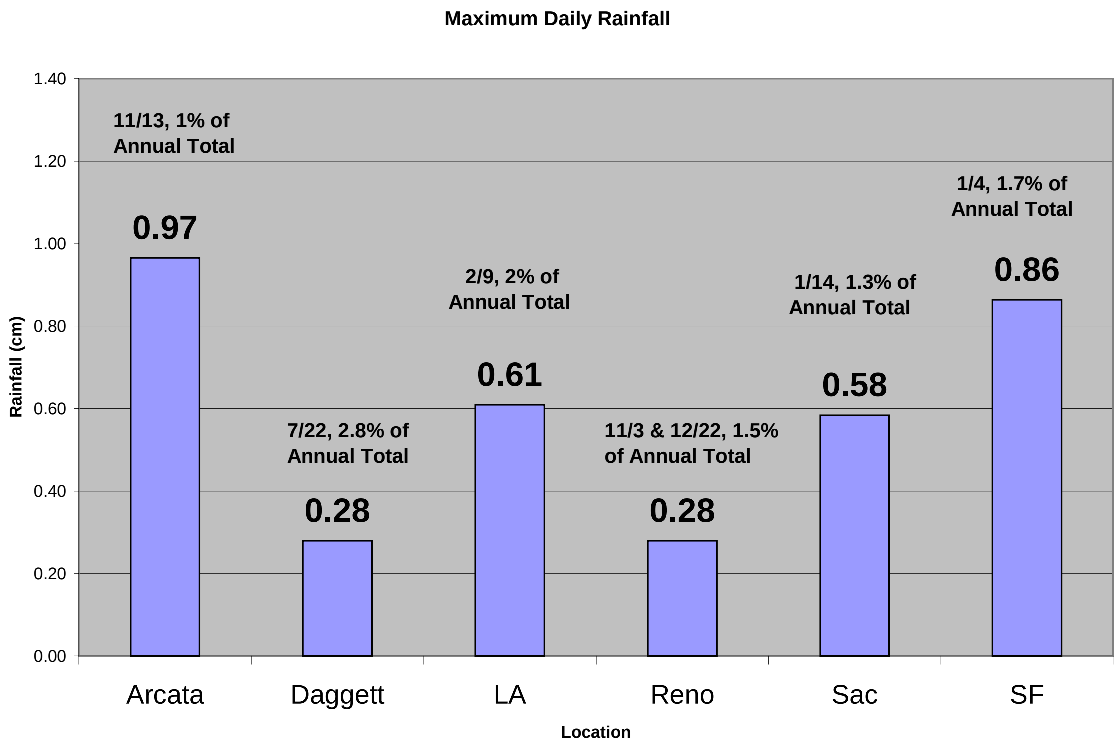


Figure 41. Maximum daily rainfall for each studied climate in a typical year

Figures 42-45 compare the rainfalls previously presented in Figures 38-41 juxtaposed with their respective 30-year 95th percentile counterparts. Larger differences between the 30-year average value and the 30-year 95th percentile value indicate the potential for rare events that are much more severe than the average events.

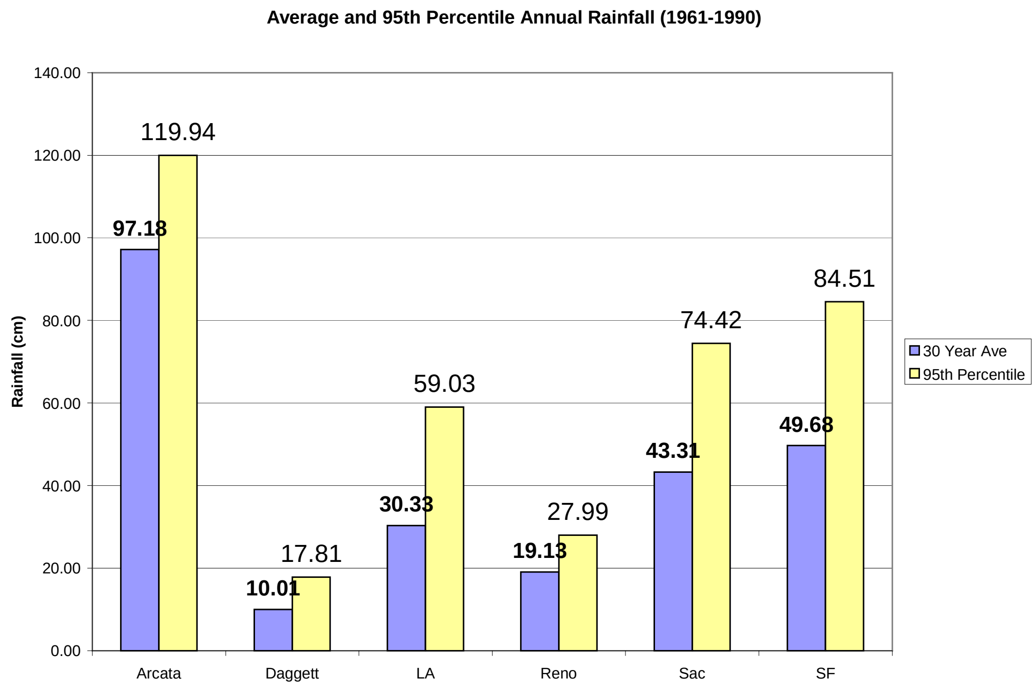


Figure 42. **Average and 95th percentile of 30-year rainfall between 1961-90**

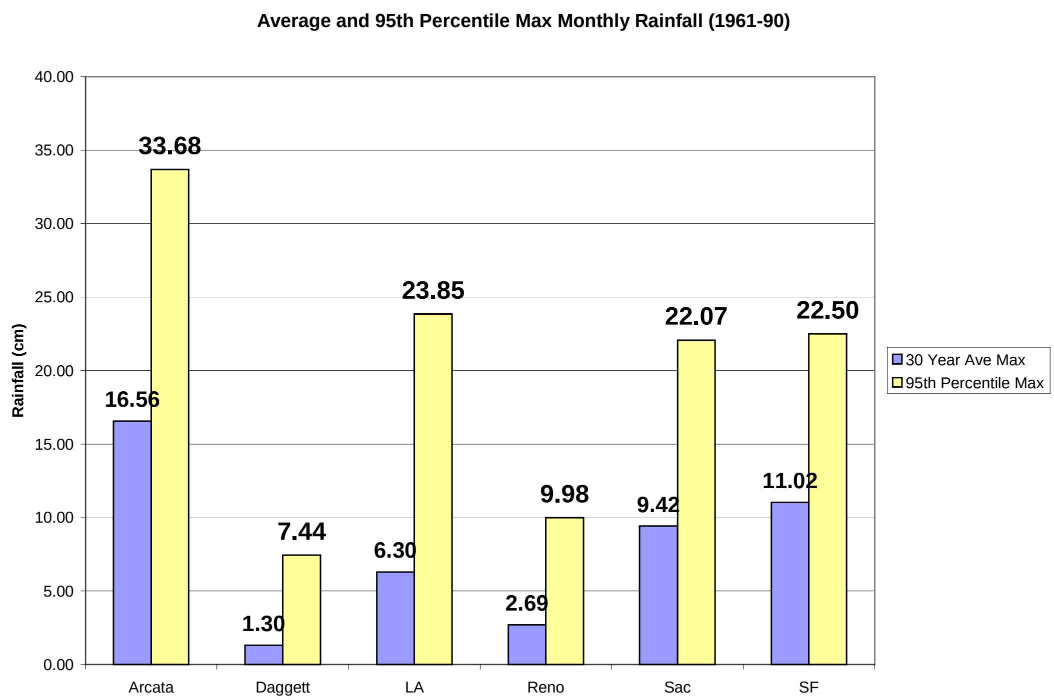


Figure 43. **Average and 95th percentile of 30-year maximum monthly rainfalls between 1961-1990**

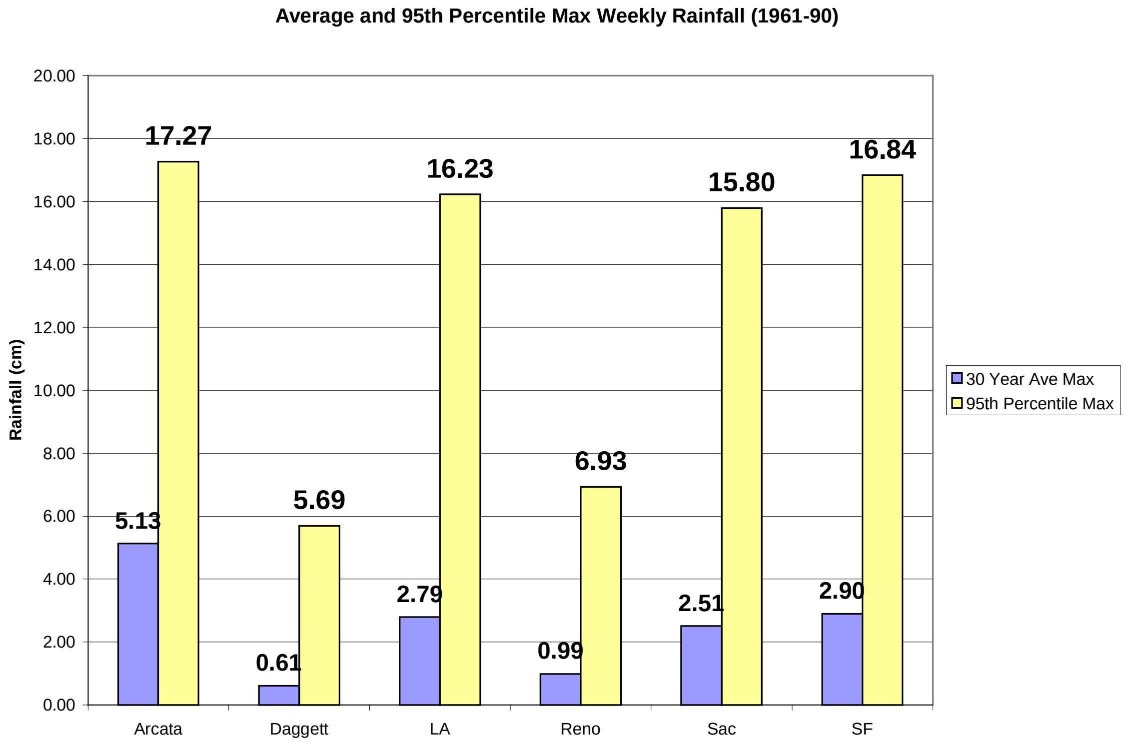


Figure 44. Average and 95th percentile of 30-year maximum weekly rainfalls between 1961-1990

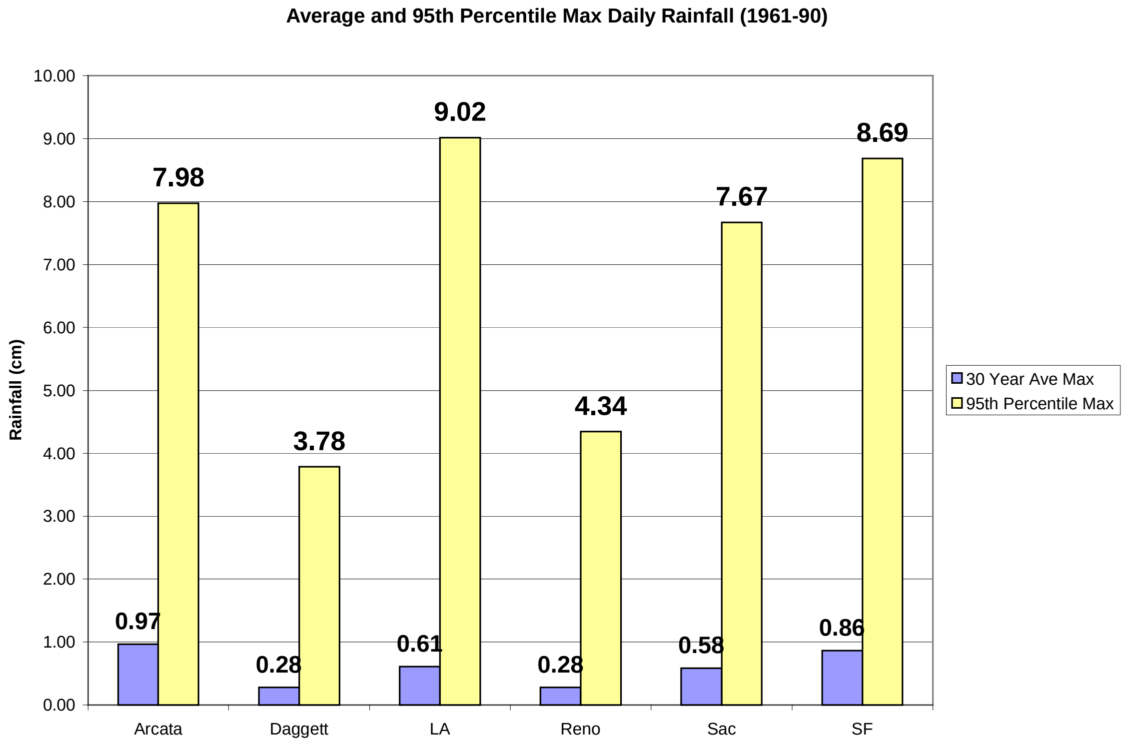


Figure 45. **Average and 95th percentile of 30-year maximum daily rainfalls between 1961-1990**

Figure 46 shows the average percent of annual rainfall occurring in each month. The Desert (Daggett) region was not included because it has an insignificant amount of rainfall. Figure 46 allows the identification of when the rainy season typically occurs at each location. The rainy season for most climates takes place in the winter between November and February.

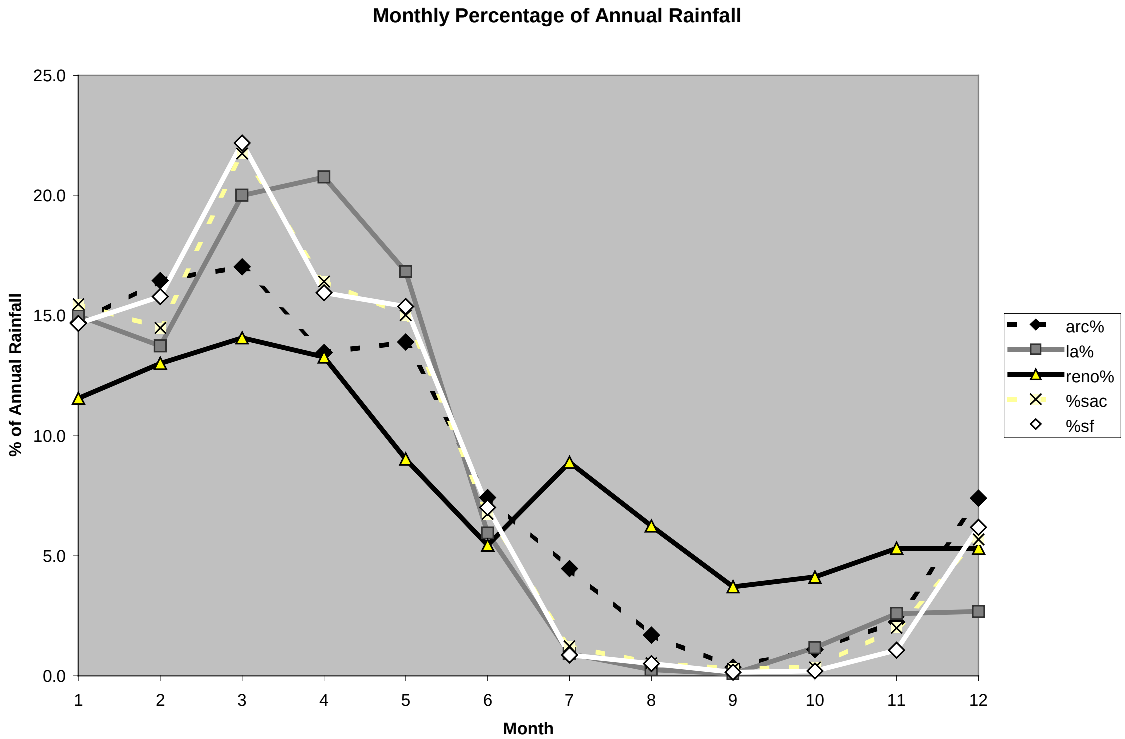


Figure 46. **Illustration of each climate's rainfall pattern through the course of a typical year.**

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

It is apparent from the data and analyses presented in this report that California has several distinct climate regions with respect to the variables that affect pavement performance: temperatures in the pavement and rainfall. The results strongly indicate that climate region should be considered in the design of flexible, rigid, and composite pavement structures. The results also strongly indicate that the historical performance of pavement structures may be significantly different in the different climate regions of the state because climate has not been considered in any past or current Caltrans pavement design procedures.

A map of climate regions and the locations of the weather stations used to evaluate the climates for each region were developed. Physical descriptions of the climate regions were also developed. These descriptions may be changed as further experience is obtained.

Consideration of climate region is likely to play an important role in determining the following design features for new pavements, rehabilitation, and reconstruction:

- Flexible pavements: asphalt concrete mix design for rutting, asphalt binder selection for rutting and thermal cracking, thickness design for fatigue cracking and subgrade rutting, and drainage requirements and the need for drainage features;
- Rigid pavements: concrete mix design for shrinkage and strength, cement selection for shrinkage, strength and coefficient of thermal expansion, maximum slab lengths for cracking caused by thermal stresses, slab thickness for fatigue, base type selection for mitigation of erosion, and drainage requirements and the need for drainage features; and

- Composite pavements: asphalt concrete mix design for rutting and reflection cracking, asphalt binder selection for rutting, reflection cracking and thermal cracking, and overlay thickness design for reflection cracking.

The expected ranking of severity of individual climate regions with respect to individual pavement distress mechanisms is summarized in Table 22.

Table 22 Summary of expected effects of climate region on specific pavement distress mechanisms.

Structure	Distress Mechanism	Expected Severity and Associated Region	Comments
Flexible Pavements	AC Rutting	Most Severe: Desert, Central Valley Moderate: Mountain/High Desert, Bay Area, South Coast Least Severe: North Coast	
	Thermal cracking	Potential problem: Mountain/High Desert Problems not likely: all others	
	Temperature effects contributing to fatigue cracking	Similar problems for crack initiation and propagation for all regions	Much more sensitive to thicknesses, compaction, and materials than climate differences
	Rainfall and high temperatures contributing to stripping potential	Most Severe: North Coast Moderate: all others Least Severe: Mountain/High Desert	Results tentative, Aggregate source plays large role
Rigid Pavements	Thermal stresses contributing to fatigue cracking	Most Severe: Desert, Central Valley, Mountain/High Desert Moderate: Bay Area, South Coast Least Severe: North Coast	Interaction of long slab lengths and temperature gradient particularly important
	Rainfall and thermal stresses contributing to faulting and corner cracking	Most Severe: see comment Moderate: see comment Least Severe: see comment	All regions susceptible without dowels
	Thermal expansion and contraction contributing to spalling	Most Severe: Desert, Central Valley, Mountain/High Desert Moderate: Least Severe: North Coast, Bay Area, South Coast	
Composite Pavements	AC Rutting	Most Severe: Desert, Central Valley, Mountain/High Desert Moderate: Bay Area, South Coast Least Severe: North Coast	
	Thermal expansion and contraction contributing to reflection cracking	Most Severe: Desert, Central Valley, Mountain/High Desert Moderate: Bay Area, South Coast Least Severe: North Coast	

4.2 Recommendations

The following recommendations are based on the conclusions of this study:

1. The pavement temperature data developed in this report should be validated and calibrated for each of the climate regions studied, near the representative locations for each climate region. This validation and calibration exercise should be performed using existing instrumented test sections, such as LTPP test locations, and where necessary, pavements should be instrumented with thermocouples and weather stations.
2. Climate regions should be considered in the mechanistic-empirical pavement design method being developed for Caltrans by the University of California Berkeley team.
3. To validate and calibrate the observations made in this report, the influence of climate region on rigid, flexible, and composite pavement performance should be statistically evaluated through the development of empirical pavement performance models. The models should include typical values for the critical parameters taken from this study, or at least include climate region as a class variable. To the extent permitted by the information in the Caltrans Pavement Management System database, models should be developed for as many of the distress mechanisms to be included in the mechanistic-empirical design method as possible.
4. Where climate parameters are critical to pavement performance, specific recommendations should be developed regarding critical pavement design elements. These elements may include materials selection and pavement features such as drainage considerations and slab length.
5. The information developed in this report should be used for mix design for asphalt concrete and hydraulic cement concrete materials.

6. Expected high temperatures within 100 mm of the surface should be considered for asphalt concrete mix design to prevent rutting. Extreme high and low temperatures should be considered in the selection of asphalt binder.
7. Expected temperature gradients should be considered with slab length for cement selection based on coefficient of thermal expansion, and for hydraulic cement concrete mix design for shrinkage and strength requirements.
8. Implementation of the high and low temperature elements of the PG asphalt binder specification will achieve the recommendation regarding consideration of climate region in the selection of asphalt binders.

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