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# Treatment Performance Capacity – A Tool to Predict the Effectiveness of Maintenance Strategies

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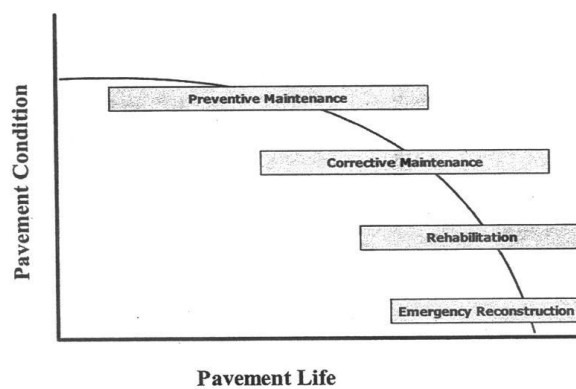
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ABSTRACT. The California Department of Transportation (Caltrans) employs a variety of pavement preservation treatments to maintain and preserve their network of paved highways. In this work a model was developed to relate asphalt treatment life in terms of Treatment Performance Capacity (TPC), pavement condition, traffic level and location temperatures for all asphalt based treatments. This model is able to provide estimates of the performance of 23 treatments, in three climatic zones, three pavement conditions levels and three traffic magnitudes. Using the TPC values for each treatment and the price of each treatment, the cost effectiveness for all treatments was developed. The results indicate that there are huge differences in values between treatments currently used in California and that there appears to exist a great opportunity for Caltrans to optimize (i.e. minimize) its annual budget by applying only treatments with highest cost-effectiveness at the correct time.

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## 1. Introduction

The California Department of Transportation (Caltrans) employs a variety of pavement preservation (preventive maintenance or corrective maintenance) treatments to maintain and preserve their network of paved highways as shown in Figure 1 (Caltrans, 2003). The primary purpose of the proactive pavement preservation program is to delay the need for costly pavement rehabilitation or reconstruction.



**Figure 1.** *Pavement Condition vs. Life and Type of Work Required*

The purpose of this paper is to estimate, in a rational manner, the pavement treatment life. In addition, this approach can help establish the cost effectiveness of pavement preservation treatments and information on treatment lives.

This paper is based on the reports produced by Sousa and Way (Sousa, 2007) and Sousa (Sousa, 2009) and it was based on subjective data developed by the California Pavement Preservation Task Group (PPTG) and data and numerous studies conducted in Arizona (Kaloush, 2002), (Way, 1976), (Way, 1979), (Way, 1980), and (Zborowski and Kaloush, 2006).

Table 1 shows the treatments that were considered for this study. All the treatments involve the use of asphalt based materials and may be applied very thin like a fog or rejuvenating seal or as thick as a one inch HMA surfacing.

Furthermore, new tables representing the expected life of treatments in each of the major climate zones in California are included in this report. It was recognized that heavy traffic affects treatment lives more than light traffic. The proposed tables reflect the traffic index (TI) as used by Caltrans but they can be easily converted to

the standard AASHTO 18-kip equivalent single axle loads (ESAL's) by the Equation 1 (AASHTO, 1993).

**Table 1.** *Maintenance Pavement Treatments Used by Caltrans (Flexible Pavements)*

|    | Maintenance Treatment<br>Hot Mix Asphalt (HMA)  |    | Maintenance Treatment<br>Asphalt Concrete (AC) |
|----|-------------------------------------------------|----|------------------------------------------------|
| 1  | HMA Crack Sealing                               | 14 | Conventional HMA, 1 inch                       |
| 2  | HMA Crack Filling                               | 15 | Open Graded OGAC, 1 inch                       |
| 3  | Fog Seals                                       | 16 | PBA HMA, 1 inch                                |
| 4  | Rejuvenator Seals                               |    |                                                |
| 5  | Scrub Seals                                     |    | Rubberized AC (RAC)                            |
| 6  | Slurry Seals                                    | 17 | RAC-G Gap Graded, 1 inch                       |
| 7  | REAS Slurry Seal                                | 18 | RAC-O Open Graded, 1 inch                      |
| 8  | Micro-Surfacing                                 | 19 | RAC-O(HB) High Binder, 1 inch                  |
| 9  | Polymer Modified Emulsion (PME)<br>Chip Seal    |    |                                                |
| 10 | Polymer Modified Asphalt (PMA)<br>Chip Seal     |    | Bonded Wearing Course (BWC)                    |
| 11 | Asphalt Rubber (AR) Chips Seal                  | 20 | BWC- Open, ¾ inch                              |
| 12 | Asphalt Rubber Cape Seals AR<br>(slurry) ½ inch | 21 | BWC- Gap, ¾ inch                               |
| 13 | Asphalt Rubber Cape Seals AR<br>(micro) ¾ inch  | 22 | BWC- RAC- ¾ inch                               |
|    |                                                 | 23 | BWC- RAC-O, ¾ inch                             |

$$TI = 9.0 \times \left( \frac{ESALs}{10^6} \right)^{0.119} \quad [1]$$

The estimated life information compiled in this document is based on the collective experience of the California Pavement Preservation Task Group (PPTG) to which the experience and best engineering judgment of a few experts in the industry were added. The extensive empirical tables prepared by the PPTG relating treatment duration to TI, percent cracking and location are presented in reports by Sousa and Way (Sousa, 2007) and Sousa (Sousa, 2009).

The data used in this study still needs to be verified in California using actual performance data from the existing Caltrans performance data bases or pavement management systems. Of course, the life of the treatment is highly dependent on the timing of the treatment, the traffic it experiences, and the climate it is placed in and these factors are addressed in the models as well as possible given the limited data and information.

The time of placement of the treatments can influence the performance of the treatment. In other words, treatments placed on good pavements will last longer than treatments placed on bad pavements. Many times, a treatment is scheduled to be placed on a good pavement, but by the time it is actually placed, the condition of the

pavement has deteriorated and this will affect the expected life of the treatment. The models developed in this study are limited by this observation of actual practice.

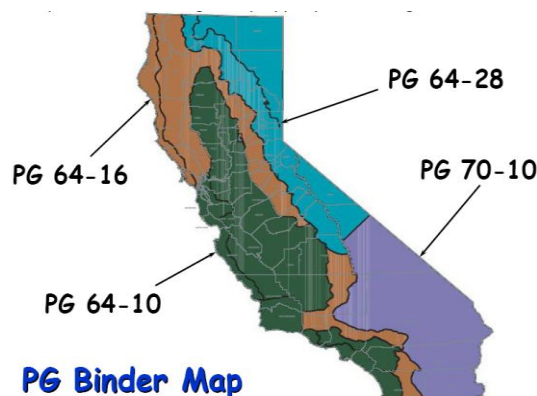
To the degree practical, the models in this report address the lives of the treatment as a function of the level of traffic and climate (coastal, valley, mountains, and desert) in which the treatment is placed.

## 2. Study approach-estimating treatment lives

### 2. 1. *Estimate of treatment lives*

The initial tables were first developed by the PPTG strategy selection committee, although the original tables provided ranges of average life. As part of this study, the PPTG original tables were converted into the average and standard deviation of life for each treatment. Some corrections were also made so that the treatment lives were adjusted for different climatic regions. The asphalt PG grading regions shown in Figure 2 were used to identify treatment lives by climatic regions. It was decided that the treatment lives developed by the PPTG most appropriately fit into the Coastal and Valley areas (PG 64-10 and PG 64-16). Following this approach, tables were developed for the Mountainous (PG 64-28) and the Desert regions (PG 70-10). The Mountainous and Desert values represent the estimates of the treatment lives based on the experience of the authors, and like the Coastal and Valley regions represent a surrogate group of values based on engineering experience and judgment. This was done in lieu of real California performance data. In the future, it is hoped that the Caltrans pavement management system will provide more definitive measures of treatment life for the various climate regions.

The tables previously developed (Sousa and Way, 2007) take into consideration that the maintenance treatments are strongly affected by climate, traffic and pavement condition. It was considered important to try to evaluate treatment lives as a direct function of the treatment itself and these key factors.



**Figure 2.** *Climate Regions Proposed For California- Coastal, Valley, Mountain and Desert*

## **2.2. Effect of climate in life of treatments**

As previously stated the first step was to identify significant climatic zones that affect the performance of the maintenance treatments. It was considered that the expected life of a treatment and life extension is influenced by the weather and to facilitate integration with other areas, it was decided to develop four tables of expected performance; one for each PG region in California as shown in Figure 2.

## **2.3. Effect of traffic in life of treatments**

It was recognized that traffic is also a key aspect that affects the life of maintenance strategies. However, the number of cars is not a key factor. The recognized factor that affects any treatment is indeed the effect of heavy traffic which is defined by the American Association of State Highway and Transportation Officials (AASHTO) as 18-kip equivalent single axle loads (ESAL's). Caltrans uses the Traffic Index which can be easily converted into ESAL's. Also, most structural analysis and reflective modeling programs require some input to calculate stress caused by actual loads derived from ESAL's.

Likewise, the traffic volume and truck volume is incorporated to the degree it can be identified in three major traffic categories. Namely, Interstate which generally has a high truck percentage, non interstate divided routes ( includes sections with four or more lanes that might not be divided) which has a lower percentage of trucks and non-interstate, non divided routes (essentially two lane highways) that have a lower traffic volume and lower truck percentage level of traffic. The traffic loading per year was divided into three categories as follows:

- Low       $TI < 6$     [Less than 33,000 ESAL's]
- Intermediate       $6 < TI < 12$       [Between 33,000 and 1.1 million ESAL's]
- Heavy       $TI > 12$     [Greater than 1.1 million ESAL's]

## **2.4. Effect of existing pavement condition**

It was recognized that for treatment life and life extension to be meaningful, one must know the actual pavement condition at the time of the application of the treatment. Currently there is no easy way to derive information on treatment performance from the existing PMS data in California. Also, Pavement Condition Index (PCI) similar to the ASTM D6433 standard (ASTM, 2007) used by many cities and counties in California by itself may not be descriptive enough to be of significant help in this area.

Since pavement preservation is a non-structural treatment, this means these treatments should only be used on pavements with low deflection values and low levels of distress. If high deflections (beyond a certain limit) are present, rehabilitation of the pavement will be needed. There is also a maximum cracking threshold before a certain treatment is applied. For pavement preservation, it is suggested that a maximum value of 5% cracking and a minimum PCI of 70 be used as the limits for applying pavement preservation treatments.

If the pavement is in poor condition, it can have structural problems. Therefore, pavement preservation should not be used as an option in these situations. In the tables, "poor condition" is identified along with the associated maintenance treatment option. This is done in order to develop treatment lives that will demonstrate that preventive maintenance treatments are not cost effective in the late cycle of pavement life. When determining extended life benefits, it may be found that placing some pavement preservation treatments on pavements in poor condition is not cost effective.

In summary, the primary concern for preservation treatments is surface cracking or raveling when the pavement is in good to medium condition and structural cracking when the pavement is in poor condition. It could be either reflective or structural cracking in the medium condition. It should be noted that this study focuses mainly on maintenance treatments to seal out moisture from cracks and as such raveling or bleeding are not directly addressed in this approach.

Pavement preservation should preserve the structural integrity of the pavement so that it can perform for a longer time where structural integrity implies load carrying capacity of the pavement. For example, crack sealing may provide the benefits of minimizing water intrusion into the base and subgrade and prevent fines from accumulating in the crack.

However, when taking a more in depth look at what affects a treatment life, it was considered that cracking extent by itself may be the most significant aspect. The percent of cracking is an indication of the capacity of the existing pavement to be relatively impervious to water and the affect moisture has on the underlying layers. Also, the extent of cracking is an indication of the possible relative movement between the tips of the crack that have a strong effect on the life of the treatment. Although the treatments considered in this report are not considered to add structural capacity to the pavement, they may to some degree reduce the amount of water that penetrates into the pavement, which can contribute to extending the pavement life.

Treatment life is defined as the number of years a given treatment will serve its function (before another treatment is required). Treatment life is a function of the existing pavement condition and other factors such as traffic, climate, quality of materials and construction. Following are tentative definitions for the various categories of pavement condition.

- Good – Minor distress (< 5 % cracking). Expected life of 8-10 years or more;
- Fair – minor to moderate distress (5-20% cracking). Expected life of 4-6 years;
- Poor condition (>20 % cracking). Moderate to severe distress and with structural problems. Expected life of 1-3 years.

### **2.5. *Intrinsic maintenance material properties***

Clearly if a good Pavement Management System (PMS) were available, it would be populated with adequate data so that the intrinsic properties of each treatment would not be needed because a rigorous multiple variable regression over all the data would give directly the life of each treatment. However, these data do not exist yet for most treatments and therefore it is necessary to use a mathematical modelling approach to bridge this gap. As such, the need to use some “models” in some cases to model or at least to relate and compare estimated lives from similar treatments arises.

It was felt that there was a need to present in a simple format a summary of the data of the key aspects that contribute to what is intrinsically valuable in a treatment. Generically, it can be considered that many aspects will or may contribute to the quality and durability of a flexible pavement treatment such as the following;

- Quantity of binder,
- Aging characteristics of the binder used in treatments
- Elastic characteristics of binder,
- Strain energy at break of the binder,
- Types of additives (none, polymer, rubber, others),
- Mix stiffness (if applicable)

### **2.6. *Effect of amount of binder on treatment life***

A preliminary summary research allowed the determination of the effective binder content available for each of the treatment as presented in Table 2. Some of the numbers were obtained from the MTAG reports while others were based on the authors’ experience and submitted for review to the Pavement Preservation Task Group (PPTG). In this table, the average values of the amounts of binder were used in the treatments; while for emulsions the residual binder content was used. It was also considered the use of tack coats add to the binder content available to each treatment. Clearly one important aspect is also thickness of the treatment as it provides some indication of the degree of protection the treatment provides to the underlying layer and to itself.

**Table 2.** *Maintenance Treatment Thickness and Asphalt Content (Gallons per Square Yard) or Percent Asphalt in the Mix*

| Maintenance Treatment         | Thickness of Seal Layer, inch | Overall thickness including chips and mix, inch | Asphalt/Oil Gal./sq. yd. On surface | Overall Asphalt/Oil Gal./sq. yd. On surface including tack | Mix Percent Asphalt by weight of aggregate |
|-------------------------------|-------------------------------|-------------------------------------------------|-------------------------------------|------------------------------------------------------------|--------------------------------------------|
| HMA Crack sealing             | 0.10                          | 0.10                                            | 0.59                                | 0.59                                                       |                                            |
| HMA Crack filling             | 0.03                          | 0.03                                            | 0.27                                | 0.27                                                       |                                            |
| Fog seals                     | 0.01                          | 0.01                                            | 0.07                                | 0.07                                                       |                                            |
| Rejuvenator seals             | 0.01                          | 0.01                                            | 0.07                                | 0.07                                                       |                                            |
| Scrub seals                   | 0.19                          | 0.19                                            | 0.30                                | 0.30                                                       |                                            |
| Slurry seals                  | 0.19                          | 0.19                                            | 0.30                                | 0.30                                                       |                                            |
| REAS slurry seal              | 0.19                          | 0.19                                            | 0.30                                | 0.30                                                       |                                            |
| Micro-Surfacing               | 0.01                          | 0.19                                            | 0.30                                | 0.37                                                       |                                            |
| PME chip seals                | 0.03                          | 0.37                                            | 0.27                                | 0.27                                                       |                                            |
| PMA chip seals                | 0.03                          | 0.37                                            | 0.27                                | 0.27                                                       |                                            |
| AR chip seals                 | 0.10                          | 0.37                                            | 0.59                                | 0.59                                                       |                                            |
| Cape seals AR (slurry) ½ inch | 0.10                          | 0.56                                            | 0.55                                | 0.85                                                       |                                            |
| Cape seals AR (micro) ¾ inch  | 0.10                          | 0.85                                            | 0.55                                | 0.97                                                       |                                            |
| Conventional HMA, 1 inch      | 0.01                          | 1.18                                            | 0.05                                | 0.78                                                       | 5.00                                       |
| OGAC, 1 inch                  | 0.01                          | 1.18                                            | 0.05                                | 0.81                                                       | 6.00                                       |
| PBA HMA, 1 inch               | 0.01                          | 1.18                                            | 0.05                                | 0.78                                                       | 5.00                                       |
| RAC-G, 1 inch                 | 0.01                          | 1.18                                            | 0.05                                | 0.86                                                       | 5.50                                       |
| RAC-O, 1 inch                 | 0.01                          | 1.18                                            | 0.05                                | 0.84                                                       | 6.20                                       |
| RAC-O (HB), 1 inch            | 0.01                          | 1.18                                            | 0.05                                | 1.12                                                       | 8.50                                       |
| BWC-Open, ¾ inch              | 0.02                          | 0.75                                            | 0.11                                | 0.60                                                       | 6.20                                       |
| BWC-Gap, ¾ inch               | 0.02                          | 0.75                                            | 0.11                                | 0.62                                                       | 5.50                                       |
| BWC-RAC-G, ¾ inch             | 0.02                          | 0.75                                            | 0.11                                | 0.62                                                       | 5.50                                       |
| BWC-RAC-O, ¾ inch             | 0.02                          | 0.75                                            | 0.11                                | 0.60                                                       | 6.20                                       |

## 2.7. Type of binder

Several types of binder are available for use in the various treatments. The quality of binder has been defined many different ways, such as resistance to aging, elastic recovery, stiffness and other. Clearly aging resistance is an important aspect, but specifications today are such that all binders show similar values by aging in the Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV). One key aspect contributing to the longevity of a surface treatment, beyond binder quantity, is its capability to withstand strain and not to break. Limited data are available for many binders regarding the strain energy at the break point and as such the conclusions and numbers included in this section should be revised as more data are collected. However, Kaloush et al (2002), Kaloush et al (2003) and Zborowski and Kaloush (2006) have reported data comparing the strain energy at the breaking point for

asphalt rubber (AR) binder and conventional binders. Also, relating this information to the fact that AR is known to withstand 5 times the strain (Green, 1977) before breaking, and the results of four point flexural fatigue tests where usually the ratio between fatigue life at the same strain level is 1 to 10 between conventional and AR binder mixes and 1 to 3 for polymer modified mixes in this study (Sousa et al, 2000; Sousa et al, 2003 and Sousa et al, 2006), the following ratios were adopted as shown in Table 3 (again subject to further analysis).

**Table 3. Ratios of Strain Energy at Break**

| Binder type                   | Ratio of strain energy at break of mixes (or binder) |
|-------------------------------|------------------------------------------------------|
| Conventional                  | 1                                                    |
| Polymer/Other Modified Binder | 1.5                                                  |
| Asphalt Rubber                | 5                                                    |

## 2.8. Treatment performance capacity

To bring into a single parameter several of the key aspects related to the performance of a treatment in a previous report (Sousa and Way, 2007), the authors developed a conceptual measure of treatment effectiveness called the Treatment Performance Capacity (TPC) and it is defined as follows:

$$TPC = BC \times SE \times T \quad [2]$$

where: TPC = Treatment Performance Capacity;  
 BC = Binder Content per unit area (L/m<sup>2</sup>);  
 SE = Strain Energy at failure ratio;  
 T = Thickness of treatment (mm).

Obviously a fog seal with a regular emulsion will have a much smaller number in terms of TPC than a chip seal simply because it has less binder. Also an asphalt rubber treatment will show a better capacity number (even if with the same binder content) because has a higher strain energy at failure than regular binder.

The concept that this index is trying to capture is simple: more binder is better; better binder is also better; and thicker treatment is better in all cases in generic terms. Based upon these assumptions, Table 4 was developed. Clearly having a binder that ages less is better, but this factor may be compounded or confounded (possible bleeding or flushing and low skid resistance value) with more binder which also promotes less aging.

A treatment with a high performance capacity, when placed under heavy traffic over a badly cracked pavement will have its performance capacity consumed, “drained”, faster compared to when it is placed over a low traffic non-cracked pavement. Obviously a treatment with a low performance capacity will have its

performance capacity consumed even faster under the same scenarios. The TPC is inherent to each treatment. How long it takes to “consume” that capacity depends on the cracking condition, traffic and climate where the treatment is applied.

**Table 4.** *Treatment Performance Capacity for several treatments used in California (mm l/m<sup>2</sup>)*

| Maintenance Treatment         | Treatment Performance Capacity |
|-------------------------------|--------------------------------|
| HMA Crack sealing             | 6.25                           |
| HMA Crack filling             | 0.81                           |
| Fog seals                     | 0.08                           |
| Rejuvenator seals             | 0.08                           |
| Scrub seals                   | 6.41                           |
| Slurry seals                  | 7.05                           |
| REAS slurry seal              | 12.83                          |
| Micro-Surfacing               | 8.08                           |
| PME chip seals                | 14.25                          |
| PMA chip seals                | 11.88                          |
| AR chip seals                 | 128.25                         |
| Cape seals AR (slurry) ½ inch | 274.31                         |
| Cape seals AR (micro) ¾ inch  | 473.00                         |
| Conventional HMA, 1 inch      | 107.11                         |
| OGAC, 1 inch                  | 110.54                         |
| PBA HMA, 1 inch               | 107.11                         |
| RAC-G, 1 inch                 | 585.34                         |
| RAC-O, 1 inch                 | 569.88                         |
| RAC-O (HB), 1 inch            | 767.38                         |
| BWC-Open, ¾ inch              | 62.65                          |
| BWC-Gap, ¾ inch               | 64.14                          |
| BWC-RAC-G, ¾ inch             | 267.24                         |
| BWC-RAC-O, ¾ inch             | 261.04                         |

### 3. Modeling the effect of TPC on treatment life

#### 3.1. General effect of TPC on treatment life

From the analysis of the data presented in Figures 3, 4 and 5 for Coastal and Valley, Mountain and Desert regions respectively, it can be observed that the effect of TPC appears to drive the life of a pavement preservation treatment. For a given set of conditions, treatments with higher TPC appear to outperform in general those with lower TPC.

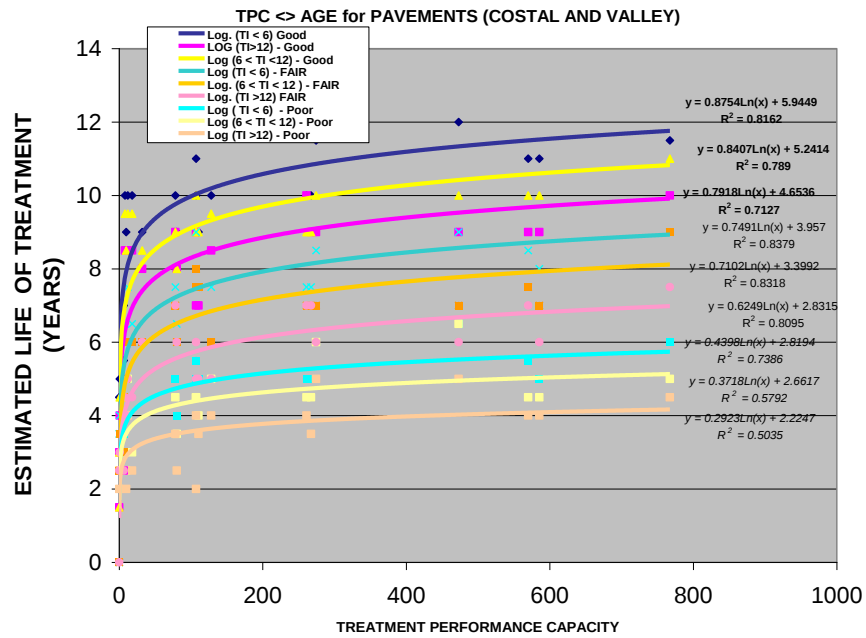
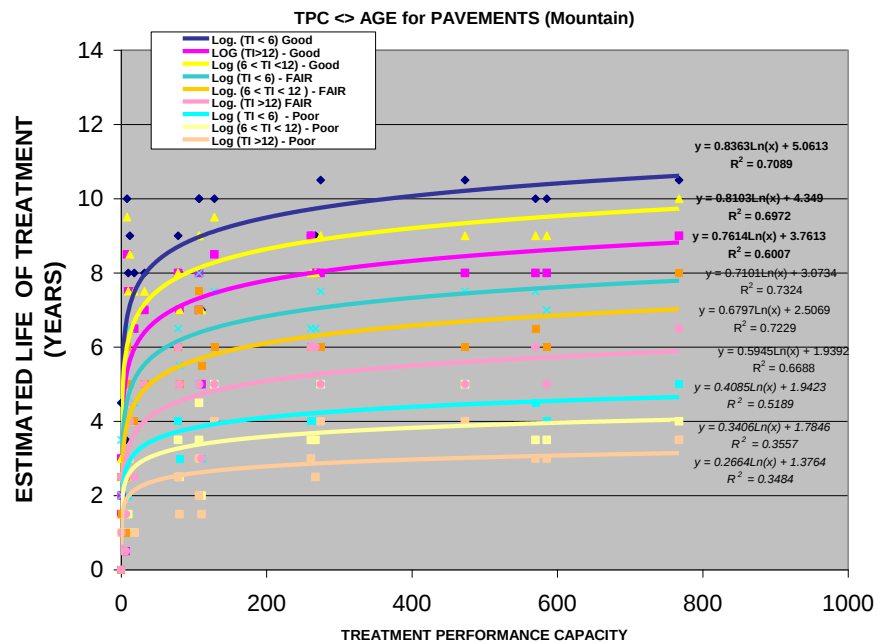
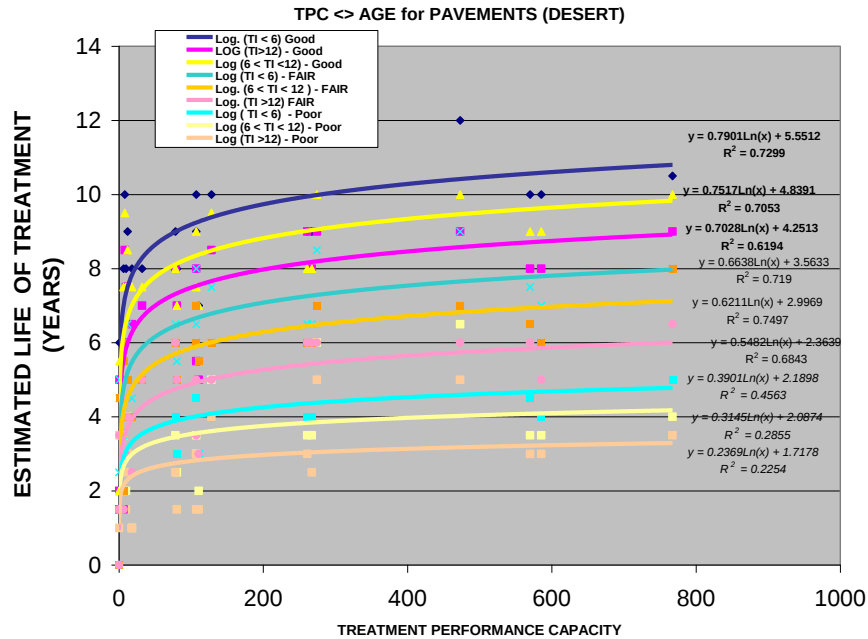


Figure 3. Influence of TPC on Treatment Life for Coastal and Valley Regions



**Figure 4.** Influence of TPC on Treatment Life for Mountain Region**Figure 5.** Influence of TPC on Treatment Life for Desert Region

### 3.2. Effect of temperature

Treatment life is also strongly affected by environment. After several trials, it was determined that the temperature that best explained the observed effect was the difference between the weighted mean monthly air temperature (Shell, 1985) and the minimum air temperature. Table 5 shows the various average temperature statistics for the California climate zone. For model calibration, the average of the temperatures and temperature differences (RCT) of Valley and Coastal regions shown in Table 5 were grouped together as the Costal – Valley (CV) statistics since they are so similar.

It is noteworthy to mention that in a totally unrelated project the difference in temperatures was shown to have a strong influence in the reflective cracking life of overlays (Sousa et al, 2001). Thus it makes sense that as this temperature difference widens it indicates more overall tension (stress and strain) in the surface layers which leads to increase in the likelihood of reflective cracking.

**Table 5.** *Average Temperatures for the regions in California*

|               | <b>A</b>             | <b>B</b>                           | <b>C</b>                                | <b>D</b>             | <b>B-D</b>                  | <b>C-D</b>        |
|---------------|----------------------|------------------------------------|-----------------------------------------|----------------------|-----------------------------|-------------------|
| <b>Region</b> | Maximum Air Temp. °C | Maximum 7 Day Average Air Temp. °C | Mean Annual Air Temp. °C (Shell Design) | Minimum Air Temp. °C | Max. 7 Day Ave.-Min. Air °C | RCT (Mean-Min) °C |
| Valley        | 38.8                 | 35.3                               | 16.2                                    | -10.0                | 45.3                        | 26.2              |
| Coastal       | 38.1                 | 32.7                               | 17.3                                    | -5.7                 | 38.4                        | 23.0              |
| CV            | 38.5                 | 34.0                               | 16.8                                    | -7.9                 | 41.9                        | 24.6              |
| Mountain      | 36.1                 | 33.0                               | 11.2                                    | -30.7                | 63.7                        | 41.9              |
| Desert        | 46.9                 | 44.7                               | 24.8                                    | -9.1                 | 53.8                        | 33.9              |

### 3.3. Model determination and parameters

The statistical analysis used to develop the model to fit the treatment life results was performed using the nonlinear estimation option of the SPSS software. This option allows the user to define a specified regression equation which is fitted to the existing data. The use of a suitable estimation method, in the case the Levenberg-Marquardt estimation method produced a precise estimation of the model parameters. The model developed was based on the fact that the Treatment Life (LIFE) of a given pavement condition can be correlated with the TPC by a logarithmic equation:

$$LIFE = k_1 \times \log(TPC) + k_2 \quad [3]$$

where: LIFE = Treatment Life;  
 TPC = Treatment Performance Capacity;  
 $k_1$  and  $k_2$  = Coefficients.

The inclusion of the other independent variables (Reflective Cracking Temperature (RCT), Percent Cracking (PC), and TI), is applied in the  $k_1$  and  $k_2$  coefficients of the logarithmic equation.

Thus, the difficult job of this task is selection of the equations that best define the influence of Reflective Cracking Temperature (RCT), Percent Cracking, and Traffic Index in the logarithmic equation. Among the known equations, a parabolic regression seems to be best at producing a fit of the existing data, resulting in the model expressed in Equations 4 and 5,

$$k_1 = \prod_{i=1}^3 (a_{i1} + a_{i2} \times X_i + a_{i3} \times X_i^2) \quad [4]$$

$$k_2 = \prod_{i=1}^3 (b_{i1} + b_{i2} \times X_i + b_{i3} \times X_i^2) \quad [5]$$

where:  $a_{ij}$  and  $b_{ij}$  = coefficients given in Table 6;  
 $X_i$  = Variables defined in Table 7.

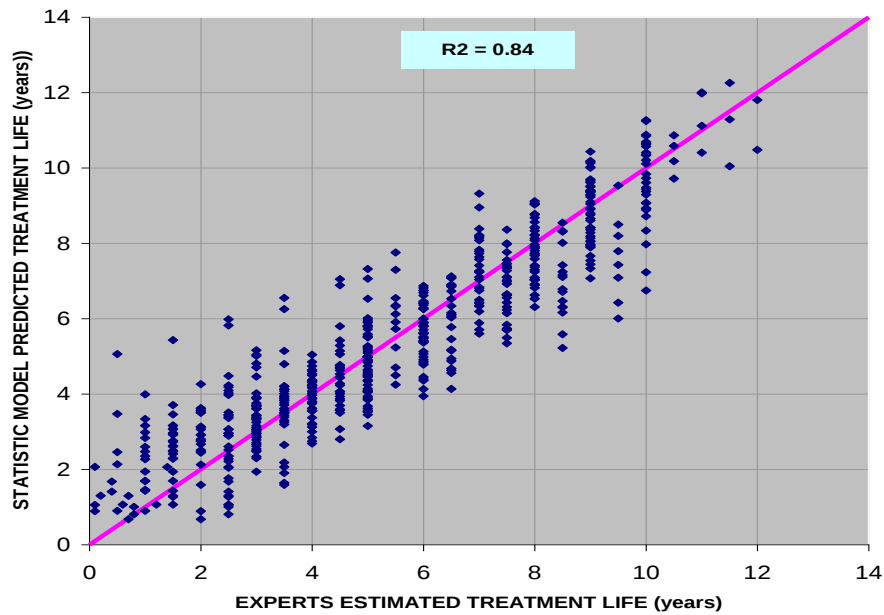
**Table 6.** Statistical coefficients for the life model (Equations 2 and 3) [R2=0.844]

| $i$ | $a_{i1}$   | $a_{i2}$   | $a_{i3}$   | $b_{i1}$   | $b_{i2}$   | $b_{i3}$   |
|-----|------------|------------|------------|------------|------------|------------|
| 1   | -1.029E+02 | 3.826E+00  | -5.381E-02 | -1.269E+02 | -8.601E-01 | 3.199E-02  |
| 2   | 3.223E-02  | -1.646E-03 | 3.354E-05  | -8.063E-01 | 6.716E-02  | -2.350E-03 |
| 3   | -1.708E+00 | 9.926E-03  | 1.342E-03  | 7.147E-02  | -3.076E-03 | 7.195E-05  |

**Table 7.** Variables defining the pavement conditions in Equations 4 and 5

| $i$ | $X_i$                                                                | Minimum | Maximum |
|-----|----------------------------------------------------------------------|---------|---------|
| 1   | RCT - Temperature defined by:<br>Air Mean Monthly – Minimum Air (°C) | 20      | 45      |
| 2   | PC – Percent Cracking                                                | 0       | 18      |
| 3   | TI – Traffic Index                                                   | 3       | 15      |

All variables show statistical significance and the correlation of the model is 0.84 as demonstrated in Figure 6.



**Figure 6.** Best fit between expert estimated treatment life and corresponding estimations from statistical model

Based on this new model, the expected analytically derived treatment lives of the four California regions are shown in Table 8 through Table 11. It can be observed that the values predicted for Coastal and Valley are slightly different but vary more from Mountain and Desert regions due to temperature effects.

**Table 8.** Model estimated treatment lives for Coastal Region (years) as a function of traffic and % cracking

| Pavement Condition<br>Cracking<br>Maintenance<br>Treatment | Treatment Lives for Coastal Region (PG 64-10) |     |     |      |     |     |      |     |     |
|------------------------------------------------------------|-----------------------------------------------|-----|-----|------|-----|-----|------|-----|-----|
|                                                            | Traffic Index (TI)                            |     |     |      |     |     |      |     |     |
|                                                            | 5                                             |     |     | 8.5  |     |     | 13   |     |     |
|                                                            | 0                                             | 5   | 15  | 0    | 5   | 15  | 0    | 5   | 15  |
| HMA Crack sealing                                          | 7.9                                           | 5.4 | 3.3 | 7.0  | 4.8 | 2.9 | 6.1  | 4.2 | 2.6 |
| HMA Crack filling                                          | 5.9                                           | 3.8 | 2.4 | 5.1  | 3.3 | 2.1 | 4.4  | 2.9 | 1.8 |
| Fog seals                                                  | 3.5                                           | 2.0 | 1.3 | 2.9  | 1.6 | 1.0 | 2.4  | 1.4 | 0.9 |
| Rejuvenator seals                                          | 3.5                                           | 2.0 | 1.3 | 2.9  | 1.6 | 1.0 | 2.4  | 1.4 | 0.9 |
| Scrub seals                                                | 7.9                                           | 5.4 | 3.3 | 7.0  | 4.8 | 3.0 | 6.1  | 4.2 | 2.6 |
| Slurry seals                                               | 8.3                                           | 5.7 | 3.5 | 7.4  | 5.1 | 3.1 | 6.4  | 4.4 | 2.7 |
| REAS slurry seal                                           | 9.5                                           | 6.6 | 4.1 | 8.5  | 5.9 | 3.7 | 7.4  | 5.2 | 3.2 |
| Micro-Surfacing                                            | 8.1                                           | 5.6 | 3.4 | 7.2  | 5.0 | 3.1 | 6.3  | 4.3 | 2.7 |
| PME chip seals                                             | 8.9                                           | 6.2 | 3.8 | 8.0  | 5.5 | 3.4 | 6.9  | 4.8 | 3.0 |
| PMA chip seals                                             | 8.5                                           | 5.9 | 3.6 | 7.6  | 5.2 | 3.2 | 6.6  | 4.6 | 2.8 |
| AR chip seals                                              | 10.8                                          | 7.7 | 4.7 | 9.8  | 6.9 | 4.3 | 8.6  | 6.1 | 3.7 |
| Cape seals AR<br>(slurry) ½ inch                           | 11.6                                          | 8.2 | 5.1 | 10.5 | 7.5 | 4.6 | 9.2  | 6.6 | 4.0 |
| Cape seals AR<br>(micro) ¾ inch                            | 12.1                                          | 8.7 | 5.3 | 11.0 | 7.9 | 4.8 | 9.6  | 6.9 | 4.2 |
| Conventional HMA,<br>1 inch                                | 10.7                                          | 7.5 | 4.6 | 9.6  | 6.8 | 4.2 | 8.4  | 6.0 | 3.7 |
| OGAC, 1 inch                                               | 10.7                                          | 7.5 | 4.6 | 9.6  | 6.8 | 4.2 | 8.4  | 6.0 | 3.7 |
| PBA HMA, 1 inch                                            | 10.7                                          | 7.5 | 4.6 | 9.6  | 6.8 | 4.2 | 8.4  | 6.0 | 3.7 |
| RAC-G, 1 inch                                              | 12.3                                          | 8.8 | 5.4 | 11.2 | 8.0 | 4.9 | 9.8  | 7.0 | 4.3 |
| RAC-O, 1 inch                                              | 12.3                                          | 8.8 | 5.4 | 11.2 | 8.0 | 4.9 | 9.8  | 7.0 | 4.3 |
| RAC-O (HB), 1 inch                                         | 12.6                                          | 9.0 | 5.5 | 11.4 | 8.2 | 5.0 | 10.0 | 7.2 | 4.4 |
| BWC-Open, ¾ inch                                           | 10.4                                          | 7.3 | 4.5 | 9.3  | 6.6 | 4.0 | 8.1  | 5.8 | 3.5 |
| BWC-Gap, ¾ inch                                            | 10.4                                          | 7.3 | 4.5 | 9.4  | 6.6 | 4.1 | 8.2  | 5.8 | 3.5 |
| BWC-RAC-G, ¾ inch                                          | 11.6                                          | 8.2 | 5.0 | 10.5 | 7.5 | 4.6 | 9.2  | 6.5 | 4.0 |
| BWC-RAC-O, ¾ inch                                          | 11.6                                          | 8.2 | 5.0 | 10.4 | 7.4 | 4.6 | 9.1  | 6.5 | 4.0 |

**Table 9.** Model estimated treatment lives for Valley Region (years) as a function of traffic and % cracking

|                               | Treatment Lives for Valley Region (PG 64-16) |     |     |      |     |     |     |     |     |
|-------------------------------|----------------------------------------------|-----|-----|------|-----|-----|-----|-----|-----|
|                               | Traffic Index (TI)                           |     |     |      |     |     |     |     |     |
|                               | 5                                            |     |     | 8.5  |     |     | 13  |     |     |
|                               | 0                                            | 5   | 15  | 0    | 5   | 15  | 0   | 5   | 15  |
| Pavement Condition Cracking   |                                              |     |     |      |     |     |     |     |     |
| Maintenance Treatment         |                                              |     |     |      |     |     |     |     |     |
| HMA Crack sealing             | 7.6                                          | 5.2 | 3.2 | 6.7  | 4.6 | 2.8 | 5.9 | 4.0 | 2.5 |
| HMA Crack filling             | 5.8                                          | 3.8 | 2.3 | 5.0  | 3.3 | 2.0 | 4.3 | 2.8 | 1.7 |
| Fog seals                     | 3.6                                          | 2.1 | 1.3 | 3.0  | 1.7 | 1.1 | 2.5 | 1.4 | 0.9 |
| Rejuvenator seals             | 3.6                                          | 2.1 | 1.3 | 3.0  | 1.7 | 1.1 | 2.5 | 1.4 | 0.9 |
| Scrub seals                   | 7.6                                          | 5.2 | 3.2 | 6.8  | 4.6 | 2.8 | 5.9 | 4.0 | 2.5 |
| Slurry seals                  | 8.0                                          | 5.5 | 3.4 | 7.1  | 4.9 | 3.0 | 6.2 | 4.3 | 2.6 |
| REAS slurry seal              | 9.1                                          | 6.3 | 3.9 | 8.1  | 5.7 | 3.5 | 7.1 | 4.9 | 3.0 |
| Micro-Surfacing               | 7.8                                          | 5.4 | 3.3 | 7.0  | 4.8 | 2.9 | 6.1 | 4.2 | 2.6 |
| PME chip seals                | 8.5                                          | 5.9 | 3.6 | 7.6  | 5.3 | 3.3 | 6.6 | 4.6 | 2.8 |
| PMA chip seals                | 8.2                                          | 5.6 | 3.5 | 7.3  | 5.0 | 3.1 | 6.3 | 4.4 | 2.7 |
| AR chip seals                 | 10.3                                         | 7.3 | 4.5 | 9.3  | 6.6 | 4.0 | 8.1 | 5.7 | 3.5 |
| Cape seals AR (slurry) ½ inch | 11.0                                         | 7.8 | 4.8 | 9.9  | 7.1 | 4.3 | 8.7 | 6.2 | 3.8 |
| Cape seals AR (micro) ¾ inch  | 11.5                                         | 8.2 | 5.0 | 10.4 | 7.4 | 4.6 | 9.1 | 6.5 | 4.0 |
| Conventional HMA, 1 inch      | 10.2                                         | 7.2 | 4.4 | 9.2  | 6.5 | 4.0 | 8.0 | 5.6 | 3.5 |
| OGAC, 1 inch                  | 10.2                                         | 7.2 | 4.4 | 9.2  | 6.5 | 4.0 | 8.0 | 5.7 | 3.5 |
| PBA HMA, 1 inch               | 10.2                                         | 7.2 | 4.4 | 9.2  | 6.5 | 4.0 | 8.0 | 5.6 | 3.5 |
| RAC-G, 1 inch                 | 11.7                                         | 8.3 | 5.1 | 10.6 | 7.6 | 4.6 | 9.3 | 6.6 | 4.1 |
| RAC-O, 1 inch                 | 11.7                                         | 8.3 | 5.1 | 10.6 | 7.5 | 4.6 | 9.3 | 6.6 | 4.0 |
| RAC-O (HB), 1 inch            | 11.9                                         | 8.5 | 5.1 | 10.8 | 7.7 | 4.7 | 9.5 | 6.8 | 4.2 |
| BWC-Open, ¾ inch              | 9.9                                          | 6.9 | 4.3 | 8.9  | 6.3 | 3.8 | 7.8 | 5.5 | 3.4 |
| BWC-Gap, ¾ inch               | 9.9                                          | 7.0 | 4.3 | 8.9  | 6.3 | 3.8 | 7.8 | 5.5 | 3.4 |
| BWC-RAC-G, ¾ inch             | 11.0                                         | 7.8 | 4.8 | 9.9  | 7.1 | 4.3 | 8.7 | 6.2 | 3.8 |
| BWC-RAC-O, ¾ inch             | 11.0                                         | 7.8 | 4.8 | 9.9  | 7.0 | 4.3 | 8.7 | 6.2 | 3.8 |

**Table 10.** Model estimated treatment lives for Mountain Region (years) as a function of traffic and % cracking

| Pavement Condition<br>Cracking<br>Maintenance<br>Treatment | Treatment Lives for Mountain Region (PG 64-28) |     |     |     |     |     |     |     |     |
|------------------------------------------------------------|------------------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
|                                                            | Traffic Index (TI)                             |     |     |     |     |     |     |     |     |
|                                                            | 5                                              |     |     | 8.5 |     |     | 13  |     |     |
|                                                            | 0                                              | 5   | 15  | 0   | 5   | 15  | 0   | 5   | 15  |
| HMA Crack sealing                                          | 6.5                                            | 4.5 | 2.7 | 5.8 | 4.0 | 2.4 | 5.0 | 3.5 | 2.1 |
| HMA Crack filling                                          | 4.8                                            | 3.1 | 1.9 | 4.2 | 2.7 | 1.7 | 3.6 | 2.4 | 1.5 |
| Fog seals                                                  | 2.8                                            | 1.6 | 1.0 | 2.3 | 1.3 | 0.8 | 1.9 | 1.1 | 0.7 |
| Rejuvenator seals                                          | 2.8                                            | 1.6 | 1.0 | 2.3 | 1.3 | 0.8 | 1.9 | 1.1 | 0.7 |
| Scrub seals                                                | 6.6                                            | 4.5 | 2.8 | 5.8 | 4.0 | 2.5 | 5.1 | 3.5 | 2.1 |
| Slurry seals                                               | 6.9                                            | 4.7 | 2.9 | 6.1 | 4.2 | 2.6 | 5.3 | 3.7 | 2.3 |
| REAS slurry seal                                           | 7.9                                            | 5.5 | 3.4 | 7.1 | 5.0 | 3.1 | 6.2 | 4.3 | 2.7 |
| Micro-Surfacing                                            | 6.7                                            | 4.6 | 2.8 | 6.0 | 4.1 | 2.5 | 5.2 | 3.6 | 2.2 |
| PME chip seals                                             | 7.4                                            | 5.1 | 3.2 | 6.6 | 4.6 | 2.8 | 5.8 | 4.0 | 2.5 |
| PMA chip seals                                             | 7.1                                            | 4.9 | 3.0 | 6.3 | 4.4 | 2.7 | 5.5 | 3.8 | 2.3 |
| AR chip seals                                              | 9.1                                            | 6.4 | 3.9 | 8.2 | 5.8 | 3.6 | 7.2 | 5.1 | 3.1 |
| Cape seals AR (slurry)<br>½ inch                           | 9.7                                            | 6.9 | 4.2 | 8.8 | 6.3 | 3.8 | 7.7 | 5.5 | 3.4 |
| Cape seals AR (micro)<br>¾ inch                            | 10.2                                           | 7.3 | 4.5 | 9.2 | 6.6 | 4.1 | 8.1 | 5.8 | 3.5 |
| Conventional HMA, 1<br>inch                                | 8.9                                            | 6.3 | 3.9 | 8.1 | 5.7 | 3.5 | 7.0 | 5.0 | 3.1 |
| OGAC, 1 inch                                               | 9.0                                            | 6.3 | 3.9 | 8.1 | 5.7 | 3.5 | 7.1 | 5.0 | 3.1 |
| PBA HMA, 1 inch                                            | 8.9                                            | 6.3 | 3.9 | 8.1 | 5.7 | 3.5 | 7.0 | 5.0 | 3.1 |
| RAC-G, 1 inch                                              | 10.4                                           | 7.4 | 4.5 | 9.4 | 6.7 | 4.1 | 8.2 | 5.9 | 3.6 |
| RAC-O, 1 inch                                              | 10.3                                           | 7.4 | 4.5 | 9.4 | 6.7 | 4.1 | 8.2 | 5.9 | 3.6 |
| RAC-O (HB), 1 inch                                         | 10.6                                           | 7.6 | 4.6 | 9.6 | 6.9 | 4.2 | 8.4 | 6.1 | 3.7 |
| BWC-Open, ¾ inch                                           | 8.7                                            | 6.1 | 3.7 | 7.8 | 5.5 | 3.4 | 6.8 | 4.8 | 3.0 |
| BWC-Gap, ¾ inch                                            | 8.7                                            | 6.1 | 3.8 | 7.8 | 5.5 | 3.4 | 6.8 | 4.8 | 3.0 |
| BWC-RAC-G, ¾ inch                                          | 9.7                                            | 6.9 | 4.2 | 8.8 | 6.3 | 3.8 | 7.7 | 5.5 | 3.4 |
| BWC-RAC-O, ¾ inch                                          | 9.7                                            | 6.9 | 4.2 | 8.8 | 6.3 | 3.8 | 7.7 | 5.5 | 3.4 |

**Table 11.** Model estimated treatment lives for Desert Region (years) as a function of traffic and % cracking

| Pavement Condition<br>Cracking<br>Maintenance<br>Treatment | Treatment Lives for Desert Region (PG 70-10) |     |     |     |     |     |     |     |     |
|------------------------------------------------------------|----------------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
|                                                            | Traffic Index (TI)                           |     |     |     |     |     |     |     |     |
|                                                            | 5                                            |     |     | 8.5 |     |     | 13  |     |     |
|                                                            | 0                                            | 5   | 15  | 0   | 5   | 15  | 0   | 5   | 15  |
| HMA Crack sealing                                          | 7.0                                          | 4.8 | 2.9 | 6.2 | 4.2 | 2.6 | 5.4 | 3.7 | 2.3 |
| HMA Crack filling                                          | 5.4                                          | 3.5 | 2.2 | 4.7 | 3.1 | 1.9 | 4.1 | 2.6 | 1.6 |
| Fog seals                                                  | 3.5                                          | 2.1 | 1.3 | 2.9 | 1.7 | 1.1 | 2.5 | 1.4 | 0.9 |
| Rejuvenator seals                                          | 3.5                                          | 2.1 | 1.3 | 2.9 | 1.7 | 1.1 | 2.5 | 1.4 | 0.9 |
| Scrub seals                                                | 7.0                                          | 4.8 | 3.0 | 6.3 | 4.3 | 2.6 | 5.4 | 3.7 | 2.3 |
| Slurry seals                                               | 7.4                                          | 5.0 | 3.1 | 6.6 | 4.5 | 2.8 | 5.7 | 3.9 | 2.4 |
| REAS slurry seal                                           | 8.3                                          | 5.8 | 3.6 | 7.5 | 5.2 | 3.2 | 6.5 | 4.5 | 2.8 |
| Micro-Surfacing                                            | 7.2                                          | 4.9 | 3.0 | 6.4 | 4.4 | 2.7 | 5.6 | 3.8 | 2.4 |
| PME chip seals                                             | 7.9                                          | 5.4 | 3.3 | 7.0 | 4.9 | 3.0 | 6.1 | 4.2 | 2.6 |
| PMA chip seals                                             | 7.5                                          | 5.2 | 3.2 | 6.7 | 4.6 | 2.8 | 5.8 | 4.0 | 2.5 |
| AR chip seals                                              | 9.4                                          | 6.6 | 4.1 | 8.5 | 6.0 | 3.7 | 7.4 | 5.2 | 3.2 |
| Cape seals AR (slurry)<br>½ inch                           | 10.0                                         | 7.1 | 4.4 | 9.1 | 6.4 | 3.9 | 7.9 | 5.6 | 3.4 |
| Cape seals AR (micro)<br>¾ inch                            | 10.5                                         | 7.4 | 4.6 | 9.5 | 6.7 | 4.1 | 8.3 | 5.9 | 3.6 |
| Conventional HMA, 1<br>inch                                | 9.3                                          | 6.5 | 4.0 | 8.4 | 5.9 | 3.6 | 7.3 | 5.1 | 3.2 |
| OGAC, 1 inch                                               | 9.3                                          | 6.5 | 4.0 | 8.4 | 5.9 | 3.6 | 7.3 | 5.2 | 3.2 |
| PBA HMA, 1 inch                                            | 9.3                                          | 6.5 | 4.0 | 8.4 | 5.9 | 3.6 | 7.3 | 5.1 | 3.2 |
| RAC-G, 1 inch                                              | 10.6                                         | 7.6 | 4.6 | 9.6 | 6.9 | 4.2 | 8.4 | 6.0 | 3.7 |
| RAC-O, 1 inch                                              | 10.6                                         | 7.6 | 4.6 | 9.6 | 6.9 | 4.2 | 8.4 | 6.0 | 3.7 |
| RAC-O (HB), 1 inch                                         | 10.9                                         | 7.7 | 4.7 | 9.8 | 7.0 | 4.3 | 8.6 | 6.2 | 3.8 |
| BWC-Open, ¾ inch                                           | 9.0                                          | 6.3 | 3.9 | 8.1 | 5.7 | 3.5 | 7.1 | 5.0 | 3.1 |
| BWC-Gap, ¾ inch                                            | 9.1                                          | 6.3 | 3.9 | 8.1 | 5.7 | 3.5 | 7.1 | 5.0 | 3.1 |
| BWC-RAC-G, ¾ inch                                          | 10.0                                         | 7.1 | 4.3 | 9.0 | 6.4 | 3.9 | 7.9 | 5.6 | 3.4 |
| BWC-RAC-O, ¾ inch                                          | 10.0                                         | 7.1 | 4.3 | 9.0 | 6.4 | 3.9 | 7.9 | 5.6 | 3.4 |

Cost effectiveness is defined in this report as a measure of the cost of the treatment in relation to its performance. Given that each treatment has a TPC; it is possible to couple this with the cost of the treatments and determine the cost effectiveness of each treatment. Table 12 presents typical costs of the various treatments (per square yard) provided by PPTG as a function of the size of the job.

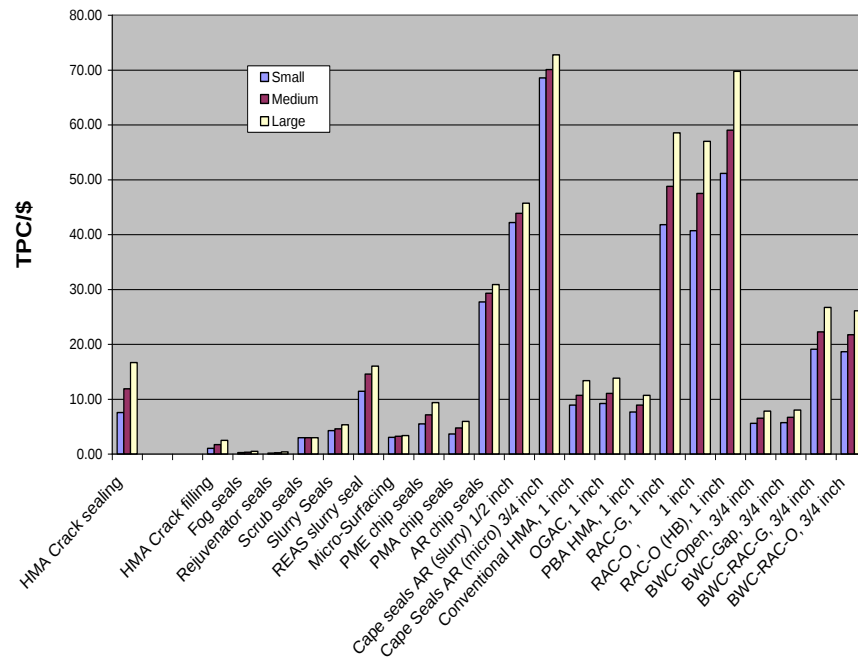
**Table 12.** Average price per square yard for treatments in California

| <b>August 11, 2007</b>              | <b>Average Price<br/>USD/sq. yd.<br/>Quantity Used<br/>Small</b> | <b>Average Price<br/>USD/sq. yd.<br/>Quantity Used<br/>Medium</b> | <b>Average Price<br/>USD/sq. yd.<br/>Quantity Used<br/>Large</b> |
|-------------------------------------|------------------------------------------------------------------|-------------------------------------------------------------------|------------------------------------------------------------------|
| <b>Maintenance Treatment</b>        |                                                                  |                                                                   |                                                                  |
| HMA Crack sealing (10%-15% cracked) | 0.83                                                             | 0.53                                                              | 0.38                                                             |
| HMA Crack filling (10%-15% cracked) | 0.78                                                             | 0.48                                                              | 0.33                                                             |
| Fog seals                           | 0.30                                                             | 0.23                                                              | 0.15                                                             |
| Rejuvenator seals                   | 0.50                                                             | 0.35                                                              | 0.20                                                             |
| Scrub seals                         | 2.15                                                             | 2.15                                                              | 2.15                                                             |
| Slurry seals                        | 2.25                                                             | 2.10                                                              | 1.80                                                             |
| REAS slurry seal                    | 2.80                                                             | 2.20                                                              | 2.00                                                             |
| Micro-Surfacing                     | 2.65                                                             | 2.50                                                              | 2.40                                                             |
| PME chip seals                      | 3.25                                                             | 2.50                                                              | 1.90                                                             |
| PMA chip seals                      | 3.25                                                             | 2.50                                                              | 2.00                                                             |
| AR chip seals                       | 4.63                                                             | 4.38                                                              | 4.15                                                             |
| Cape seals AR (slurry) ½ inch       | 6.50                                                             | 6.25                                                              | 6.00                                                             |
| Cape seals AR (micro) ¾ inch        | 6.90                                                             | 6.75                                                              | 6.50                                                             |
| Conventional HMA, 1 inch            | 12.00                                                            | 10.00                                                             | 8.00                                                             |
| OGAC, 1 inch                        | 12.00                                                            | 10.00                                                             | 8.00                                                             |
| PBA HMA, 1 inch                     | 14.00                                                            | 12.00                                                             | 10.00                                                            |
| RAC-G, 1 inch                       | 14.00                                                            | 12.00                                                             | 10.00                                                            |
| RAC-O, 1 inch                       | 14.00                                                            | 12.00                                                             | 11.00                                                            |
| RAC-O (HB), 1 inch                  | 15.00                                                            | 13.00                                                             | 10.00                                                            |
| BWC-Open, ¾ inch                    | 14.00                                                            | 12.00                                                             | 10.00                                                            |
| BWC-Gap, ¾ inch                     | 14.00                                                            | 12.00                                                             | 10.00                                                            |
| BWC-RAC-G, ¾ inch                   | 14.00                                                            | 12.00                                                             | 10.00                                                            |
| BWC-RAC-O, ¾ inch                   | 14.00                                                            | 12.00                                                             | 10.00                                                            |

It has already been determined that there is a very good correlation (at times higher than 80%) between the TPC and expected treatment lives. Based on the above information, the cost effectiveness (TPC/\$) of each treatment was determined by dividing the treatment's TPC by its cost. In Figure 7, these values, for all treatments, can be compared. It can also be observed that there is a very wide range in the cost effectiveness of treatments. Some are as low as 0.25 while some are close to 70.

These values could be used as a criterion to help CALTRANS select its maintenance strategies. What this data is basically suggesting is that treatments with low TPC/\$ should only be used in very special situations. Otherwise, other treatments can be used that are more cost effective. The data also indicates that generally the most cost effective treatments follow this concept: more binder is

better; better binder is also better; and thicker treatment is better - in all cases in generic terms. Asphalt rubber products generally have the best TPC/\$ because they fit the general concept and associated underlying qualities to resist cracking and water intrusion.



**Figure 7.** Cost effectiveness, measured in TPC/\$, for California treatments function of job size

Depending on what the current maintenance strategies of CALTRANS are, it appears that by maximizing treatments with asphalt rubber, the potential for long term savings or increase pavement performance is very high.

Data are needed to determine what pavements the current monetary allocations are of money for each type of treatment, what percentage of area is covered with each kind of treatment each year and the total annual maintenance budget of CALTRANS so that a more informed determination, quantifying the costs effectiveness of alternative maintenance strategies, can be made.

## 4. Discussion

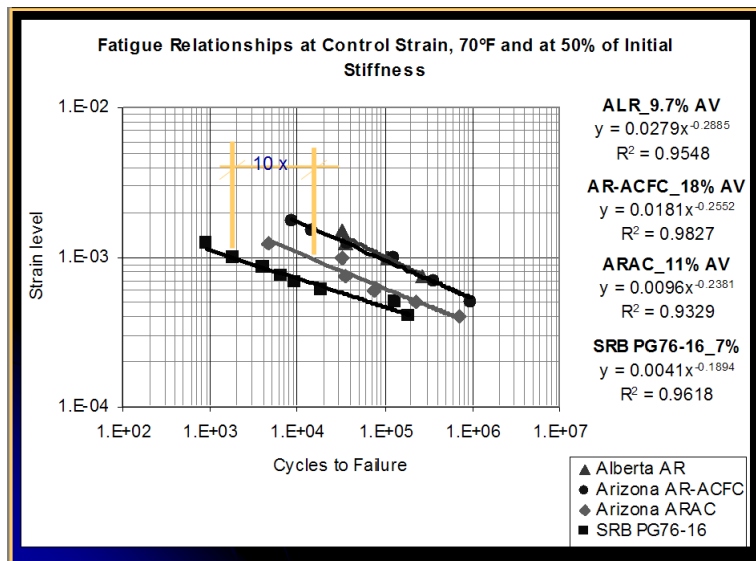
### 4. 1. Strain energy at break ratio

One of the components that have helped the TPC to capture rather well the treatment performance is the Strain at Failure Ratio. The rationale for its introduction into the formula was to bring in the “quality” of the binder that cannot be explained only by its quantity. Several researchers have in the past developed many methods to measure these properties using the Dynamic Shear Rheometer (DSR), Elastic Recovery, Aging methods and many others. Strains at Failure and Total Fracture Energy have been used and the later appears to be better correlated with performance. Table 13 shows some examples of the Strain at Failure Ratio for various mixes. Clearly, not all conventional binder has identical values amongst each other and not all Polymer Modified Binder (PMB) are identical in this regard either. However the data indicate that some differences in the “quality” of the binders affect performance.

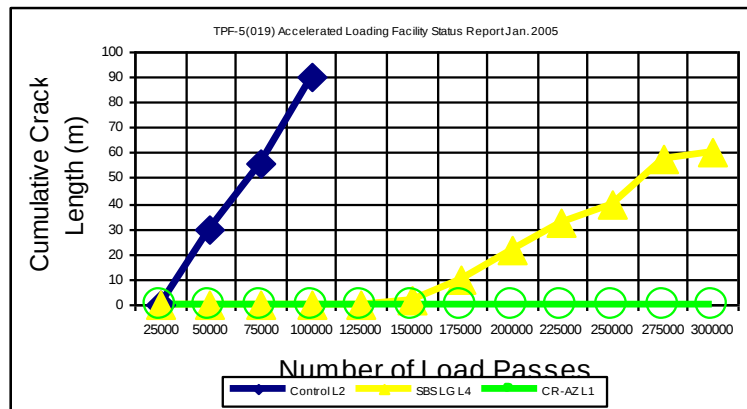
**Table 13.** Strain at Failure Ratio for several treatments in the aging study

| Static Creep Test       | Target Air Voids % | Temp. ° F | $\sigma_3$ (psi) | $\sigma_d$ (psi) | Axial Flow Time (sec) | Axial Strain @ Failure % | Strain @ Failure Ratio |
|-------------------------|--------------------|-----------|------------------|------------------|-----------------------|--------------------------|------------------------|
| <b>Mixture</b>          |                    |           |                  |                  |                       |                          |                        |
| AR-ACFC                 | 18                 | 130       | 10               | 120              | 2                     | 4.24                     | 6.42                   |
| ARAC                    | 11                 | 130       | 10               | 120              | 3                     | 6.15                     | 9.32                   |
| SRB PG64-22             | 7                  | 130       | 10               | 120              | 8                     | 0.66                     | 1.00                   |
| <b>Thermal Cracking</b> |                    |           |                  |                  |                       |                          |                        |
| <b>Mixture</b>          | Air Voids %        | AC %      | Rubber %         | $V_{beff}$       | VMA                   | Pen @ 25°C Tank 0.1mm    | Strain @ Failure Ratio |
| SR ¾" PG64-22           | 7.0                | 4.20      | 0                | 9.0              | 16.0                  | 54                       |                        |
| SRB PG64-22             | 7.5                | 4.55      | 0                | 8.6              | 16.1                  | 54                       |                        |
| ¾" PG64-22              | 6.6                | 4.90      | 0                | 9.9              | 16.5                  | 54                       |                        |
| Base PG64-22            | 7.8                | 5.25      | 0                | 10.5             | 18.3                  | 54                       |                        |
|                         |                    |           |                  |                  |                       | Average                  | 1.89                   |
| SR ¾" PG70-10           | 7.2                | 4.30      | 0                | 9.0              | 16.2                  | 26                       |                        |
| SRB PG70-10             | 7.3                | 4.25      | 0                | 8.9              | 16.2                  | 26                       |                        |
|                         |                    |           |                  |                  |                       | Average                  | 1.00                   |
| ARAC                    | 8.1                | 7.00      | 20               | 12.5             | 20.6                  | 35                       | 5.24                   |
| AR-ACFC                 | 17.9               | 9.40      | 20               | 15.1             | 33.0                  | 35                       | 3.87                   |

In Figure 8 data from flexural fatigue tests indicate that AR binder does perform better, at least by a factor of 10 (Kaloush et al, 2003). Clearly the amount of binder can capture some of those increases but not them. Also, as shown in Figure 9, the data from ALF-FHWA (Qi et al, 2006) and the analyses reported in Sousa et al (2006) demonstrated that AR binder outperformed all other binders in the study in terms of reflective cracking resistance.

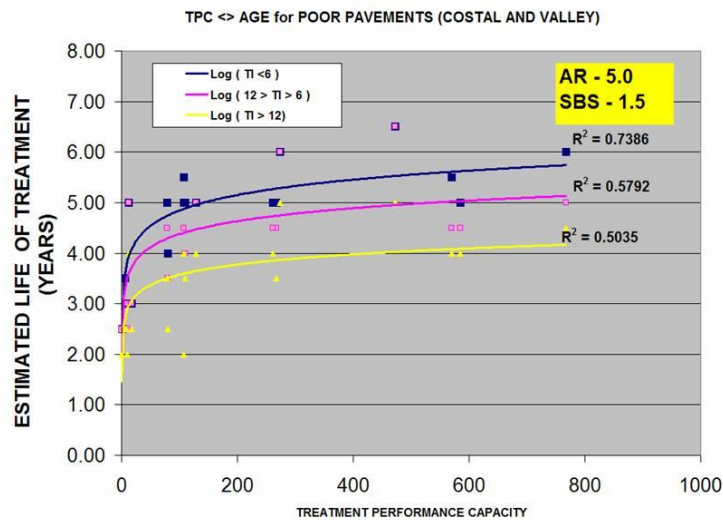


**Figure 8.** Comparison of flexural fatigue lives under strain control for conventional and asphalt rubber binder



**Figure 9.** ALF-FHWA data relating number of passes and cracking level for three pavements with the same thickness (10 cm control- conventional, 10cm SBSLGL4-PMB binder and CR-AZL1- with 5 cm of asphalt rubber binder over 5 cm of conventional).

Figure 10 shows the strain energy at break ratio of 5 for AR binder against 1.5 for PMB and 1 for conventional in order to help address the “extra quality” question.



**Figure 10.** Influence of TPC on Treatment Life for Coastal and Valley Regions for Pavements in POOR condition.

It can be observed in Table 14 (see columns A, B and C) that with the assumption that the Strain Energy at Break Ratio is 1.5 the correlation  $R^2$  is higher than if it is assumed to be 2 or even 5.

**Table 14.** Influence of the value of the STRAIN ENERGY AT BREAK RATIO (SEBR) on the correlation  $R^2$  between predicted life and expert estimated life (for POOR pavements in the COASTAL and VALLEY Regions)

|                   | A          | B          | C          | D          |
|-------------------|------------|------------|------------|------------|
| <b>SEBR - AR</b>  | <b>5.0</b> | <b>5.0</b> | <b>5.0</b> | <b>5.0</b> |
| <b>SEBR - PMB</b> | <b>1.5</b> | <b>2.0</b> | <b>5.0</b> | <b>1.0</b> |
| TI<6              | 0.7386     | 0.7157     | 0.6233     | 0.7650     |
| 12>TI>6           | 0.5792     | 0.5588     | 0.4795     | 0.6033     |
| TI>12             | 0.5035     | 0.4800     | 0.3948     | 0.5329     |

Interestingly enough for the case of POOR pavements, a better correlation  $R^2$  is obtained with the assumption that the strain energy at break ratio is 1.0 (just like the one used for conventional materials). This appears to indicate that over badly cracked pavement PMB materials do not out-perform conventional materials. Nevertheless for the overall maximization of the correlation  $R^2$  of the regression, a

value of 1.5 was found to yield better correlations when FAIR and GOOD pavements are considered and thus was selected for this study. In addition, the ALF experiment (Qi et al, 2006) also showed some cracking improvement with a PMB albeit not as great as that for AR.

## 5. Conclusions

This research made clear that better treatments are those that have higher Treatment Performance Capacity (TPC), which indicates, (and what is intuitively known) that preservation treatments perform better if they have more binder, are made with better binder and are thicker (i.e. more long lasting and more waterproof).

A model was developed to relate treatment life function in terms of TPC, pavement condition, traffic level and location temperatures (actually only the reflective cracking temperature given by the difference between the Shell mean weighted average temperature and the lowest temperature representative of each climatic region), for all asphalt based treatments. This model is able to explain the performance of 23 treatments, in 3 climatic zones, three pavement conditions levels and three traffic magnitudes (i.e. 621 observations), with only 4 variables, with a remarkably high correlation  $R^2$  of 0.84.

Using the TPC values for each treatment and the price of each treatment a cost effectiveness table for all treatments was developed (by simply dividing the TPC of a treatment by its cost per square yard). A meaningful approach would be to evaluate how much TPC /square yard CALTRANS realizes for each 1 USD spent on a given treatment. The results indicate that there are huge differences in values between treatments currently used in California and that there appears to exist a great opportunity for Caltrans to optimize (i.e. minimize) its annual budget by applying only treatments with highest cost-effectiveness at the correct time.

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## Disclaimer

The contents of this report reflect the only the views of the authors. The authors do not endorse specific products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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