ESTIMATING LIVES AND COST EFFECTINESS OF MAINTENANCE TREATMENTS ON FLEXIBLE PAVEMENTS

By

Jorge B. Sousa, Ph.D,
George Way, PE
Gary Hicks, PhD, PE.
Shakir Shatnawi, PhD, PE.

December 20, 2007

EXECUTIVE SUMMARY

The California Department of Transportation (Caltrans) employs a variety of pavement preservation treatments to maintain and preserve their network of paved highways. The primary purpose of the proactive pavement preservation program is to delay the need for costly pavement rehabilitation or reconstruction. History has shown that reducing such costly repairs is enhanced by preventive maintenance treatments sealing out moisture which adds to the structural integrity and endurance of almost every pavement and reduces the deleterious action of water.

Historically the degree of structural reinforcement of these thin maintenance treatments (less than one inch) has been difficult to estimate in a rational manner. The purpose of this study is to estimate the pavement treatment life and pavement life extension. In addition, this study is being conducted to help establish the cost effectiveness of pavement preservation treatments using the information on treatment lives and life extension associated with applying a given treatment. Life extension is defined as the time the treatment delays the need for rehabilitation. Treatment life does not necessarily equal life extension; it is often less depending when the treatment is placed.

This study is a continuation of a previous study entitled "CONSIDERATIONS FOR ESTIMATING PAVEMENT TREATMENT LIVES AND PAVEMENT LIFE EXTENTION ON FLEXIBLE PAVEMENTS," (Sousa 2007) and it is recommended that it be reviewed before reading this report. As a result of this previous study, several new objectives were recognized and are addressed in this report. For reasons of continuity, there is some overlap between this report and the previous study report. There were four study objectives. As best as practical, this report addresses each of the objectives listed as follows:

1- Develop tables (which can be readily used by practitioner) that estimate treatment lives and life extension for the 23 asphalt based treatments.
2- Develop a model to determine treatment duration as a function of asphalt treatment characteristics, pavement location, pavement condition and traffic for flexible pavements.
3- Determine the optimal time for treatment application and provide an assessment of cost effectiveness of each type of treatment in terms of its own duration and its contribution to pavement life extension.
4- Improve and, if possible provide validation, on the life extension tables for flexible pavements created in the previous research phase completed earlier in 2007.

The degree of difficulty in satisfactorily completing each objective was often referred to by the researchers as a mission impossible. Although there are many studies on structural pavement rehabilitation greater than one inch in thickness, comprehensive research on thin maintenance treatments is more difficult to obtain. In addition, little if any objective maintenance performance data and associated materials properties and aging were very hard to obtain in California. Even with these difficulties, the authors have compiled a new and innovative way at examining each of the study objectives. The authors were very ably assisted by Dr. Gary Hicks of Chico State University , Dr. Shakir Shatnawi of Caltrans, Dr. Kamil Kaloush of Arizona State University, and Dr. Jorge Pais of the University of Minho in Portugal,

From the sum total of the body of work reported on in this study, it was found that that the better asphalt treatments are those that have higher Treatment Performance Capacity (TPC), which simply indicates, what is intuitively known by most pavement engineers, that asphalt treatments perform better if they have more binder, are made with better binder and are thicker (i.e. more long lasting and more waterproofing).

A model was developed to relate asphalt 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 region), 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 (i.e. 621 observations) with only 4 variables, with a remarkably high R^2 of 0.84.

Using the TPC values for each treatment and the price of each treatment, the cost effectiveness for all treatments was developed (*simply dividing the TPC of a treatment by its cost per square yard*). 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**.

Structural and reflective cracking analyses indicate that the optimum time to apply a treatment is when the pavement cracking levels are in the range of 1% to 2%. There are significant structural benefits (structural pavement life extension) when a pavement has a waterproofing treatment applied by the time it reaches 4 to 5% cracking. Preventive maintenance treatments, if applied at the correct time, with long lasting 100% waterproofing capabilities, can provide structural life extensions for the underlying pavement of about 4 years.

From these findings, it is recommended that prior to the application of a treatment that the cost effectiveness of each possible and available treatment in the region be made. It should be noted that all treatments investigated in this study contribute to pavement preservation. However, some appear to be more cost effective than others. **It is recommended that the treatment selected should be the one with the highest cost effectiveness in terms of TPC/$.** At this time, with the current price structure in the market, and based on the cost data provided to this project, it appears that CALTRANS should adopt a policy to use treatments with the highest cost effectiveness in terms of TPC/$ as soon as pavement cracking levels reach 1 or 2% levels.

Data are needed to determine the current allocation of maintenance funds for each type of treatment, or what percentage of area is covered with each kind of treatment each year and the annual maintenance budget of Caltrans. This will allow one to better quantify the costs effectiveness of alternative maintenance strategies.

It is further recommended that an investigation be made and quantified, from CALTRANS data, if available, the effect of water penetrating into the pavements in the four different climatic regions in California. Will this require a measure of the permeability of the pavements and FWD data at different cracking levels in a same pavement.

It is also recommended that an investigation be made to determine the relationship between the rate of crack percentage evolution (cracking change from 1% to 5%) as a function of the climatic region, traffic index and pavement type and or overlay.

1 INTRODUCTION

1.1 Background

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 (Maintenance 2003). The primary purpose of the proactive pavement preservation program is to delay the need for costly pavement rehabilitation or reconstruction.

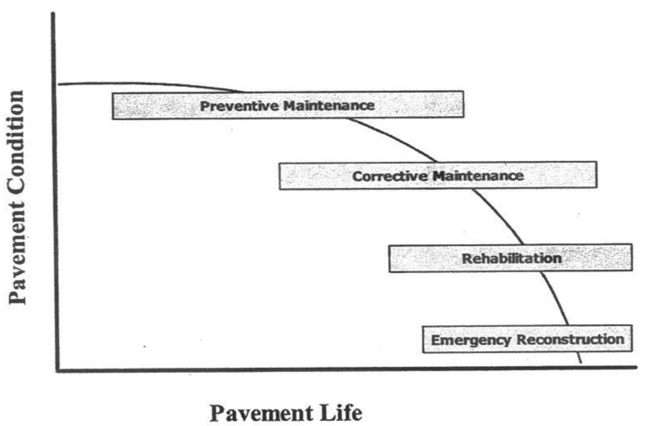

Figure 1 - Pavement Condition vs. Life and Type of Work Required

The history of the use of these various maintenance treatments reaches back as far as 1949 (Hveem 1949) if not earlier. Hveem discussed the purpose of the seal coat, although his discussion can be applied to many different types of maintenance surface treatments. He noted the term "seal coat" was to seal the road surface; that is, to prevent surface water from penetrating the pavement or base. However, all highway engineers will recognize that a surface treatment of asphalt and screenings may be applied to a road to accomplish one or more of several distinct purposes. Distinct purposes enumerated for seal coats are as follows (Hveem 1949):

1. Seal the road to the entrance of moisture

2. Develop a non-skid surface on the existing road
3. Apply fresh coatings of aggregate which will enliven and provide an all weathered surface to improve wear resistance
4. Reinforce and build an adequate pavement surface
5. Provide new stripping between lanes.
6. Improve luminosity.

Hveem identified sealing out moisture as the primary reason for a seal coat application. Later he noted (Hveem 1950) that the structural integrity and endurance of most engineering works are jeopardized by the action of water. He went on to state that in its simplest form then, one of the major problems confronting the civil engineer is the necessity for guarding against or combating the deleterious effects arising from the action of water upon the materials of construction. Thus maintenance surface treatments need to be able to some degree to seal out water (see Figure 2).

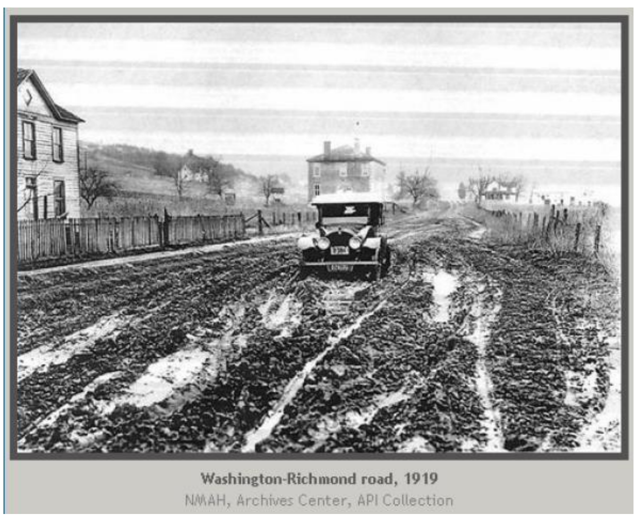

Figure 2 - Effect of too much water in the roadway (API 2005)

1.2 Purpose of Study

Historically, thin pavement preservation surfacing less than one inch in thickness are considered to improve one or more of the distinct purposes enumerated by Hveem, but the degree of structural reinforcement of these thin treatments has been difficult to estimate. The purpose of this study is to estimate in a rational manner the pavement treatment life and the pavement life extension. In addition, this study is being conducted to help establish the cost effectiveness of pavement preservation treatments, information on treatment lives and life extension associated with applying a given treatment. Life extension is defined as the time the treatment delays the need for rehabilitation. Treatment life does not necessarily equal life extension; it is often less depending when the treatment is placed as shown in Figure 3.

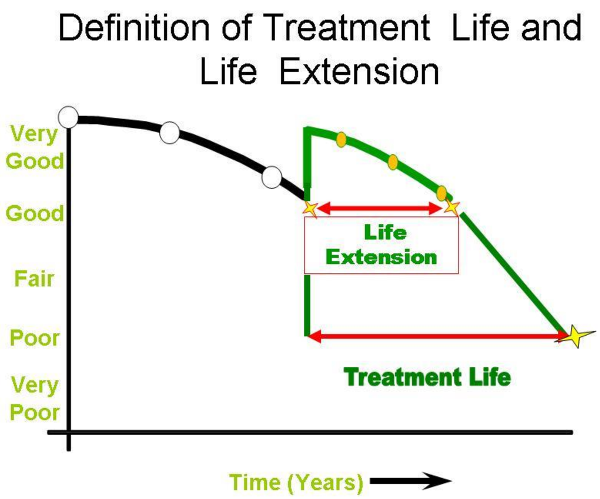

Figure 3- Maintenance Treatment Lives (Hicks 2006)

1.3 Study Objectives

This study is a continuation of a previous study entitled “CONSIDERATIONS FOR ESTIMATING PAVEMENT TREATMENT LIVES AND PAVEMENT LIFE EXTENTION ON FLEXIBLE PAVEMENTS,” (Sousa 2007) and it is recommended that it be reviewed before reading this report. As a result of the previous study, several new objectives were identified and are addressed in this report. For reasons of clarification there is some overlap between this report and the previous study report.

As best as practical, this report addresses several study objectives listed as follows:

1- Develop tables (which can be readily used by practitioners) to estimate treatment lives and life extension for the 23 asphalt based treatments.

2- Develop a model to determine treatment duration function of asphalt treatment characteristics, pavement location, pavement condition and traffic for flexible pavements.

3- Determine optimal time for treatment application and provide an assessment of cost effectiveness of each type of treatment in terms of its own life and its contribution to pavement life extension.

4- Improve and, if possible provide validation, the life extension tables for flexible created in the previous research phase and completed in 2007.

Achieving all four rather ambitious study objectives is extremely difficult given the lack of objective data in general and in California in particular. The author's have relied on subjective data developed by the Pavement Preservation Task Group (PPTG) and data and numerous studies conducted in Arizona (Kaloush, Sousa, Way and Zborowski).

This report focuses on meeting the study objectives. An integral part of this is to develop estimates of pavement treatment life and life extension in flexible pavements which can readily be used by practitioners for a number of maintenance treatments in flexible pavements. The beginning point to address all the study objectives was a list of 30 Caltrans preservation treatments furnished to the authors by California Pavement Preservation Center, California State University, Chico shown in Table 1.

Table 1 shows the treatments that were considered for this study. In all 30 maintenance treatments were identified to be studied to estimate the treatment life. However, for this report life extension analysis was only conducted for flexible pavements. 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 Equivalent Single Axle Loads (ESAL's).The estimated life information compiled in this document is based on the collective experience of the Pavement Preservation Task Group (PPTG) to which the experience and best engineering judgment of a few experts in the industry were added.

Table 1- Maintenance Pavement Treatments Used by Caltrans (Flexible and Rigid Pavements)

	Maintenance Treatment		Maintenance Treatment		Maintenance Treatment
	Hot Mix Asphalt	14	Conventional HMA, 1 inch		Portland Cement Concrete (PCC)
1	HMA Crack sealing	15	Open Graded Asphalt Concrete (OGAC), 1 inch	24	PCC Crack sealing
2	HMA Crack filling	16	PBA HMA, 1 inch	25	PCC Diamond Grinding
				26	PCC Partial depth Spall Repair
3	Fog seals		Rubberized Asphalt Concrete (RAC)	27	PCC Full depth spall repair
4	Rejuvenator seals	17	RAC-G, Gap Graded, 1 inch	28	PCC Dowel Bar Retrofit
5	Scrub seals	18	RAC-O , Open Graded, 1 inch	30	PCC Random slab replacement
6	Slurry Seals	19	RAC-O (HB), Open Graded High Binder, 1 inch		
7	REAS slurry seal				
8	Micro-Surfacing		Bonded Wearing Course (BWC)		
9	PME chip seals	20	BWC-Open, 3/4 inch		
10	PMA chip seals	21	BWC-Gap, 3/4 inch		
11	AR chip seals	22	BWC-RAC-G, 3/4 inch		
		23	BWC-RAC-O, 3/4 inch		
12	Cape seals AR (slurry) 1/2 inch				
13	Cape Seals AR (micro) 3/4 inch				

As previously stated, 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. Nevertheless, an attempt is made in this report to verify the models as best as the limited data outside of California allows. 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 best as possible given the limited data and information.

The time of placement of the treatments can influence the performance of the treatment that is 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 live 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 prior study first focused on developing tables of the estimated treatment lives (Sousa 2007). The tables in Appendix A in that study show the estimated treatment life for the various treatments. These tables were first developed by the PPTG strategy selection committee, although the original tables provided ranges of average life. As part of this study, it was requested that the PPTG original tables be converted into the average and standard deviation of life for each treatment. The author's (with the assistance of Dr. Kamil Kaloush) made the requested conversion. The author's also considered that the treatment lives should adjusted for different climatic regions. The author's recommended that the asphalt PG grading regions (Figure 4) be 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 author's and Dr. Kaloush, 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, is it hoped that the Caltrans pavement management system will provide definitive measures of treatment life for the various climate regions.

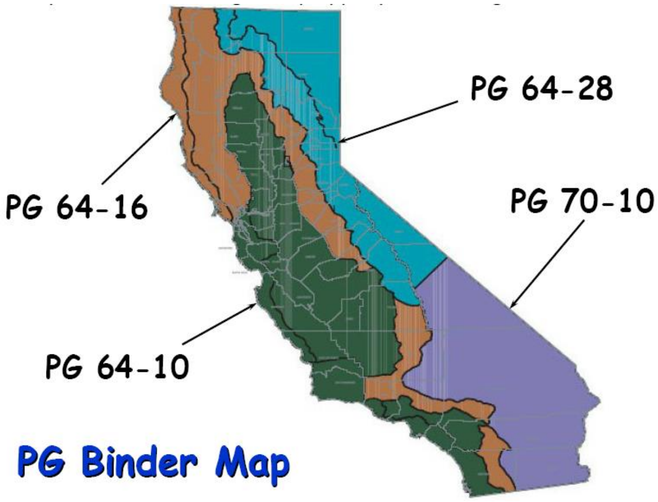

Figure 4- Climate Regions Proposed For California- Coastal, Valley, Mountain and Desert

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

2.2 How to Bring in the Effect of Climate in Life of Treatments?

The first step was to identify significant climate 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 which California has been divided (Figure 4).

2.3 How to Bring in the 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 ESALS.

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 was divided into three categories as follows:

- Low TI < 6 ,
- Intermediate 6 < TI < 12,
- Heavy TI >12

2.4 How to Bring in the 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, Performance Condition Index (PCI) 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 Pavement Condition Index (PCI) of 70 be used as the limits for applying pavement preservation treatments (Zhou and Barrantees, 2007).

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 and life extensions 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 reflective cracking or raveling when the pavement is in good to medium condition and structural when the pavement is in poor condition. It could be either reflective cracking or structural in the medium condition. It should be noted that extending structural pavement life treatments with surface distress oriented treatments such as raveling or bleeding are not directly addressed in this report.

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 water 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 in 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 How to Bring in the 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 simple multiple variable regression over all the data would give directly the life of each treatment. However, that data does not exist yet for most treatments and therefore it is necessary to use a modeling 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 author's experience and they were 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 & mix inch	Asphalt/Oil G/sq. yd on surface	Overall Asphalt/Oil G/sq. yd on surface includes 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) 1/2 inch	0.10	0.56	0.55	0.85	
Cape Seals AR (micro) 3/4 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, 3/4 inch	0.02	0.75	0.11	0.60	6.20
BWC-Gap, 3/4 inch	0.02	0.75	0.11	0.62	5.50
BWC-RAC-G, 3/4 inch	0.02	0.75	0.11	0.62	5.50
BWC-RAC-O, 3/4 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 take strain and not to break. Limited data is 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 when more data is collected. However, Kaloush and others (Kaloush 2002, Kaloush 2003, Zborowski 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 take 5 times the strain (Green et.al. 1977) before breaking, and the results of four point flexural fatigue test where usually the ratio between fatigue live 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 2000, 2003, 2006), the following ratios were adopted as shown in Table 3 (again subjected 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 the previous report (Sousa 2007), the authors developed a conceptual measure of treatment effectiveness called the TREATMENT PERFORMANCE CAPACITY (TPC) and it is defined as follows;

"TREATMENT PERFORMANCE CAPACITY= (BINDER CONTENT PER METER SQUARE - LITER/M2) * (STRAIN ENERGY AT FRAILURE ratio) * THICKNESS OF TREATMENT (mm)"

Obviously a fog seal with a regular emulsion will have a much smaller number in terms of TPC than an AR-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 better STRAIN ENERGY AT FAILURE then 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, **Error! Reference source not found.** was developed. Clearly having a binder that ages less is better, but this factor may be compounded or confounded 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, can see that capacity being "drained" quite fast as compared when it is placed over a low traffic non-cracked pavement. Obviously a treatment with a **low performance capacity** will last even less under the same scenarios. **The TPC is inherent to each treatment. How long it takes to "consume" that capacity depends on the circumstances where the treatment is applied.**

Table 4 – Treatment Performance Capacity for several treatments used in California (mm.l/m2)

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	9.62
REAS slurry seal	32.06
Micro-Surfacing	8.08
PME chip seals	17.81
PMA chip seals	11.88
AR chip seals	128.25
Cape seals (slurry)	274.31
Cape Seals (micro)	473.00
Conventional HMA (30mm)	89.26
OGAC (30 mm)	92.12
PBA HMA (30mm)	89.26
RAC-G (30 mm)	487.78
RAC-O (30 mm)	474.90
RAC-O (HB) (30mm)	639.48
BWC-Open (19 mm)	78.31
BWC-GAP (19 mm)	80.17
BWC-RAC-G (19 mm)	267.24
BWC-RAC-O (19 mm)	261.04

2.9 Chapter Summary

This chapter has been included in this report as an extension of the work performed by Sousa 2007. In its essence introduces the concept that treatment lives are depended on traffic levels (as expressed by the TI), pavement condition (as explained by percent cracking level), weather effects explained by the region defined by the PG grade and some intrinsic qualities of the binder. These intrinsic qualities have been captured, for the mot part, by the TPC of the binder.

3 COST EFFECTIVENESS OF TREATMENTS

Cost effectiveness is defined in this report as a measure of the cost of the treatment in relation to its performance.

Given each treatment has a TPC; it is possible to couple this with the cost of the treatments and determine the cost effectiveness of each treatments. Each year CALTRANS establishes a budget for all maintenance treatments. Therefore, it is reasonable to expect that one of the goals would be to maximize the TPC purchased each year. Some treatments should be more effective than others in a given situation. Table 5 presents typical costs of the various treatments (per square yard) provided by PPTG as a function of the size of the job.

Table 5– Average Price per square yard for treatments in California.

Aug 11 2007	AVERAGE PRICE USD/sq. yd		
Maintenance Treatment	Small	Medium	Large
HMA Crack sealing (10% - 15% cracked)	0.83	0.525	0.375
HMA Crack filling (10% - 15% cracked)	0.78	0.475	0.325
Fog seals	0.30	0.225	0.15
Rejuvenator seals	0.50	0.35	0.2
Scrub seals	2.15	2.15	2.15
Slurry Seals	2.25	2.1	1.8
REAS slurry seal	2.80	2.2	2
Micro-Surfacing	2.65	2.5	2.4
PME chip seals	3.25	2.5	1.9
PMA chip seals	3.25	2.5	2
AR chip seals	4.63	4.375	4.15
Cape seals AR (slurry) 1/2 inch	6.50	6.25	6
Cape Seals AR (micro) 3/4 inch	6.90	6.75	6.5
Conventional HMA, 1.2 inch	12.00	10	8
OGAC, 1.2 inch	12.00	10	8
PBA HMA, 1.2 inch	14.00	12	10
RAC-G, 1.2 inch	14.00	12	10
RAC-O , 1.2 inch	14.00	12	10
RAC-O (HB), 1 inch	15.00	13	11
BWC-Open, 3/4 inch	14.00	12	10
BWC-Gap, 3/4 inch	14.00	12	10
BWC-RAC-G, 3/4 inch	14.00	12	10
BWC-RAC-O, 3/4 inch	14.00	12	10

It has already been determined in the previous report (Sousa 2007), that there is a very good correlation (at times higher then 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 5, these values, for all treatments, can be compared. It can be observed that there is a very wide range of 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 purchased that are more cost effective. The data also indicates that generally the most cost effective treatments follow the 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.

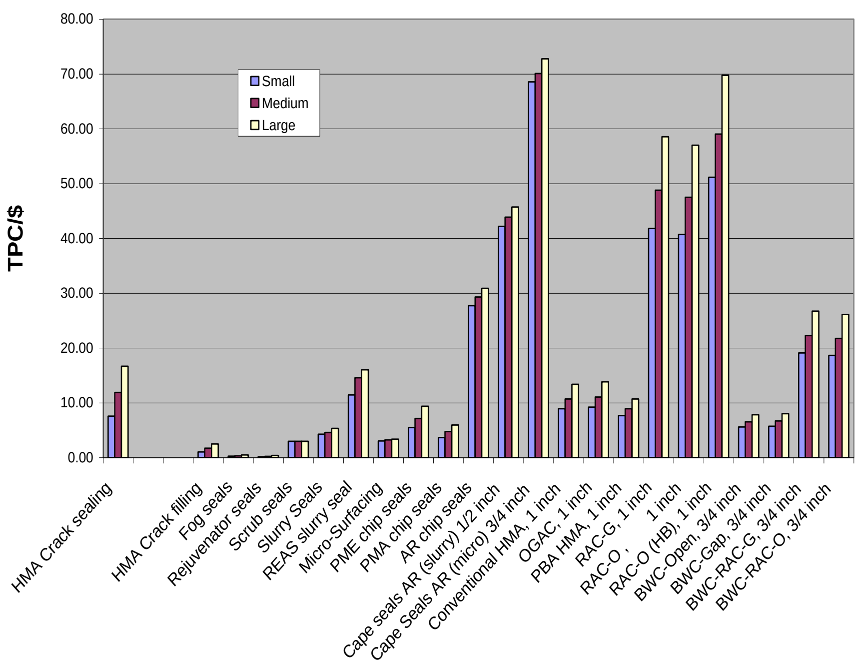

Figure 5 – Cost effectiveness, measured in TPC/$, for California treatments function of job size.

Depending on what are the current maintenance strategies of CALTRANS, 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 are the current allocation of money for each type of treatment, or what percentage of area is covered with each kind of treatment each year and the annual maintenance budget of Caltrans so that a more informed determination, quantifying the costs effectiveness of alternative maintenance strategies, can be made.

4 MODELING THE EFFECT OF TPC ON TREATMENT LIFE

Data from the Appendix A of the (Sousa 2007) report was used to further investigate the effect ot TPC in the life of a treatment.

4.1 General Effect of TPC on Treatment Life

From the analyis of the data presented in Figure 6, Figure 7 and Figure 8 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.

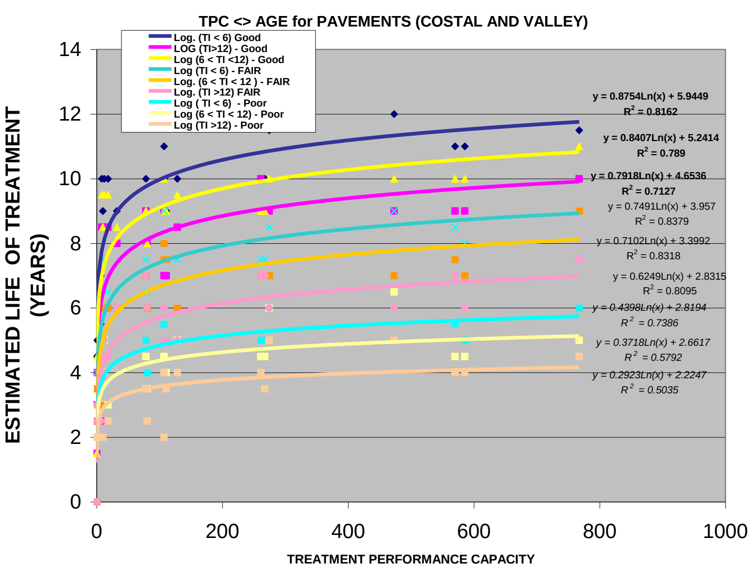

Figure 6 - Influence of TPC on Treatment Life for Coastal and Valley Regions

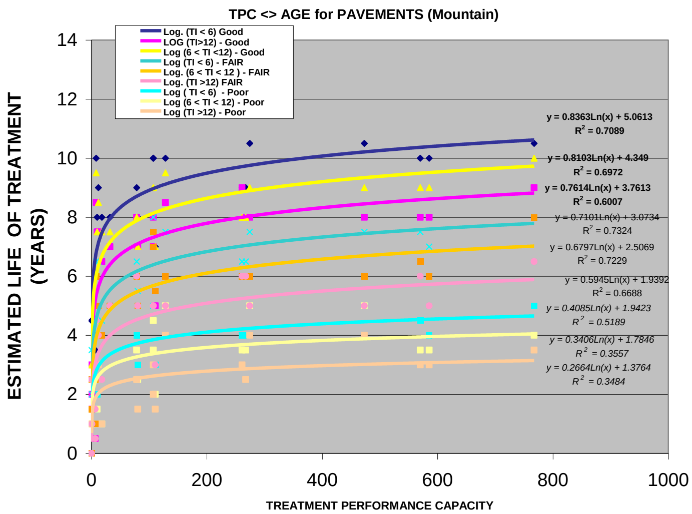

Figure 7 - Influence of TPC on Treatment Life for Mountain Region

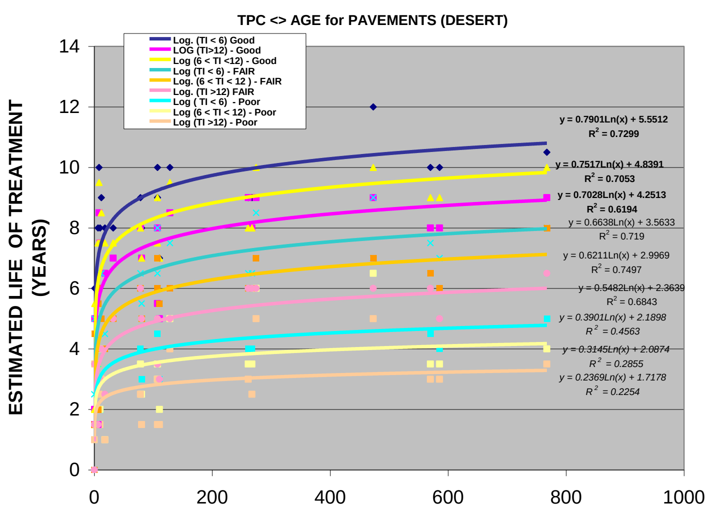

Figure 8 - Influence of TPC on Treatment Life for Desert Region

4.2 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. Appendix B shows Shell procedure for computing the weighted mean annual air temperature and computed values for selected California cities. It is noteworthy to mention that in a totally unrelated project, the reflective cracking study done for the Rubber Pavements Association, Sousa also identified the difference in temperatures as having strong influence in the reflective cracking life of overlays (Sousa, 2001). Analysis of all temperature data as presented in Appendix B is summarized in Table 4.

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 4 - Average Temperatures for the regions in California

	A	B	C	D	B-D	C-D
REGION	Maximum Air Temp. °C	Maximum 7 Day Average Air Temp. °C	**Mean** Annual Air Temp. °C (Shell Design)	**Min**imum Air Temp. °C	Max 7 DayAve - 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

For model calibration, the average of the temperatures and temperature differences (RCT) of Valley and Coastal regions shown in Table 4 were grouped together as the CV statistics since they are so similar.

4.3 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 *STATISTICA for Windows* software by Professor Jorge Pais, from the University of Minho, Portugal. This option allows the user to define a *specified regression* equation which is fitted in the existing data. The use of a suitable estimation method, in the case the *Rosenbrock and quasi-Newton 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:

$$LIFE = K1 \times \log(TPC) + \mathrm{K}2 \,. \quad [1]$$

The inclusion of the other independent variables (Temperature, PC, and TI), is applied in the K1 and K2 coefficients of the logarithmic equation.

Thus, the difficult job of this task is the finding of the equations which best define the influence of Reflective Cracking Temperature (RCT), Percent Cracking, Traffic Index in the logarithmic equation. Among the known equations, the parabolic seems to be the best which produced an interesting fit of the existing data, resulting in the following model:

$$LIFE = K1 \times \log(TPC) + \mathrm{K}2 \quad [2]$$

Where:

$$K1 = \prod_{i=1}^{3} \left(a_{i1} + a_{i2} \times X_i + a_{i3} \times X_i^2 \right) \quad [3]$$

$$K2 = \prod_{i=1}^{3} \left(\mathrm{b}_{i1} + \mathrm{b}_{i2} \times X_i + \mathrm{b}_{i3} \times X_i^2 \right) \quad [4]$$

Where: aij and bij are coefficients given in Table 5.

Variables X are defined in Table 6.

Table 5 - Statistical coefficients for the life model (Equation 2 and 3) [R^2=0.844]

i	a_{i1}	a_{i2}	a_{i1}	b_{i2}	b_{i3}	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 6 - Variables defining the pavement conditions in equation 2 and 3

i	X_I	*Minimum*	*Maximum*
1	RCT - Temperature defined by: Air Mean Monthly – Minimum Air (ºC)	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 (see Figure 9).

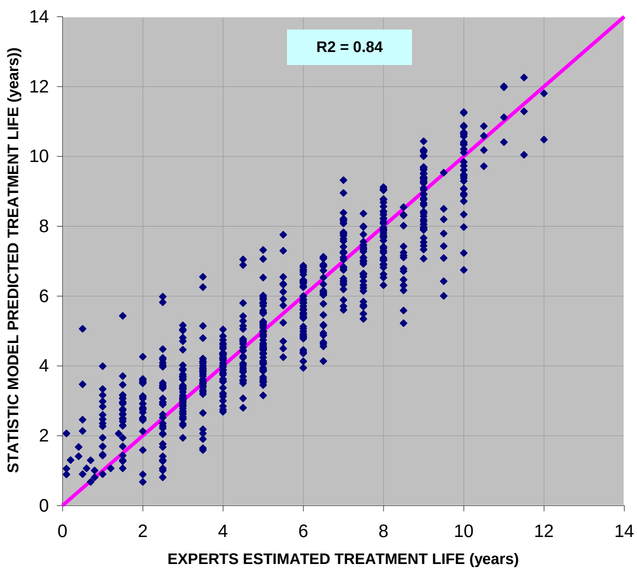

Figure 9 – Best fit between expert estimated treatment life and corresponding estimations from statistical model

Based on this new model, the expected analytically derived treatment lives of the four California regions is shown in Table 7 through Table 10. It can be observed that the values predicted for Costal and Valley are slighly different but valy more from Mountain and Desert regions due to temperature effects.

Table 7 – Model estimated treatment lives for Coastal Region (years) as a function of traffic and % cracking.

	Treatment Lives for Coastal Region (PG 64-10)								
	TI								
	5			8.50			13		
	Pavement Condition (cracking)								
Treatment	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**
AR Cape seals (slurry) 1/2in.	**11.6**	**8.2**	**5.1**	**10.5**	**7.5**	**4.6**	**9.2**	**6.6**	**4.0**
AR Cape Seals (micro) 3/4 in	**12.1**	**8.7**	**5.3**	**11.0**	**7.9**	**4.8**	**9.6**	**6.9**	**4.2**
Conventional HMA (30mm)	**10.7**	**7.5**	**4.6**	**9.6**	**6.8**	**4.2**	**8.4**	**6.0**	**3.7**
OGAC (30 mm)	**10.7**	**7.6**	**4.6**	**9.6**	**6.8**	**4.2**	**8.4**	**6.0**	**3.7**
PBA HMA (30mm)	**10.7**	**7.5**	**4.6**	**9.6**	**6.8**	**4.2**	**8.4**	**6.0**	**3.7**
RAC-G (30 mm)	**12.3**	**8.8**	**5.4**	**11.2**	**8.0**	**4.9**	**9.8**	**7.0**	**4.3**
RAC-O (30 mm)	**12.3**	**8.8**	**5.4**	**11.2**	**8.0**	**4.9**	**9.8**	**7.0**	**4.3**
RAC-O (HB) (30 mm)	**12.6**	**9.0**	**5.5**	**11.4**	**8.2**	**5.0**	**10.0**	**7.2**	**4.4**
BWC-Open (19 mm)	**10.4**	**7.3**	**4.5**	**9.3**	**6.6**	**4.0**	**8.1**	**5.8**	**3.5**
BWC-GAP (19 mm)	**10.4**	**7.3**	**4.5**	**9.4**	**6.6**	**4.1**	**8.2**	**5.8**	**3.5**
BWC-RAC-G (19 mm)	**11.6**	**8.2**	**5.0**	**10.5**	**7.5**	**4.6**	**9.2**	**6.5**	**4.0**
BWC-RAC-O (19 mm)	**11.5**	**8.2**	**5.0**	**10.4**	**7.4**	**4.6**	**9.1**	**6.5**	**4.0**

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

	Treatment Lives for Valley Region (PG 64-16)								
	TI								
	5			8.50			13		
	Pavement Condition (cracking)								
Treatment	0	5	15	0	5	15	0	5	15
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
AR Cape seals (slurry)	11.0	7.8	4.8	9.9	7.1	4.3	8.7	6.2	3.8
AR Cape Seals (micro) 3/4	11.5	8.2	5.0	10.4	7.4	4.6	9.1	6.5	4.0
Conventional HMA (30mm)	10.2	7.2	4.4	9.2	6.5	4.0	8.0	5.6	3.5
OGAC (30 mm)	10.2	7.2	4.4	9.2	6.5	4.0	8.0	5.7	3.5
PBA HMA (30mm)	10.2	7.2	4.4	9.2	6.5	4.0	8.0	5.6	3.5
RAC-G (30 mm)	11.7	8.3	5.1	10.6	7.6	4.6	9.3	6.6	4.1
RAC-O (30 mm)	11.7	8.3	5.1	10.6	7.5	4.6	9.2	6.6	4.0
RAC-O (HB) (30 mm)	11.9	8.5	5.2	10.8	7.7	4.7	9.5	6.8	4.2
BWC-Open (19 mm)	9.9	6.9	4.3	8.9	6.3	3.8	7.8	5.5	3.4
BWC-GAP (19 mm)	9.9	7.0	4.3	8.9	6.3	3.8	7.8	5.5	3.4
BWC-RAC-G (19 mm)	11.0	7.8	4.8	9.9	7.1	4.3	8.7	6.2	3.8
BWC-RAC-O (19 mm)	11.0	7.8	4.8	9.9	7.0	4.3	8.7	6.2	3.8

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

	Treatment Lives for Mountain Region (PG 64-28)								
	TI								
	5			8.50			13		
	Pavement Condition (cracking)								
Treatment	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
AR Cape seals (slurry)	9.7	6.9	4.2	8.8	6.3	3.8	7.7	5.5	3.4
AR Cape Seals (micro) 3/4	10.2	7.3	4.5	9.2	6.6	4.1	8.1	5.8	3.5
Conventional HMA (30mm)	8.9	6.3	3.9	8.1	5.7	3.5	7.0	5.0	3.1
OGAC (30 mm)	9.0	6.3	3.9	8.1	5.7	3.5	7.1	5.0	3.1
PBA HMA (30mm)	8.9	6.3	3.9	8.1	5.7	3.5	7.0	5.0	3.1
RAC-G (30 mm)	10.4	7.4	4.5	9.4	6.7	4.1	8.2	5.9	3.6
RAC-O (30 mm)	10.3	7.4	4.5	9.4	6.7	4.1	8.2	5.9	3.6
RAC-O (HB) (30 mm)	10.6	7.6	4.6	9.6	6.9	4.2	8.4	6.1	3.7
BWC-Open (19 mm)	8.7	6.1	3.7	7.8	5.5	3.4	6.8	4.8	3.0
BWC-GAP (19 mm)	8.7	6.1	3.8	7.8	5.5	3.4	6.8	4.8	3.0
BWC-RAC-G (19 mm)	9.7	6.9	4.2	8.8	6.3	3.8	7.7	5.5	3.4
BWC-RAC-O (19 mm)	9.7	6.9	4.2	8.8	6.3	3.8	7.7	5.5	3.4

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

	Treatment Lives for Desert Region (PG 70-10)								
	TI								
	5			8.50			13		
	Pavement Condition (cracking)								
Treatment	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
AR Cape seals (slurry)	10.0	7.1	4.4	9.1	6.4	3.9	7.9	5.6	3.4
AR Cape Seals (micro) 3/4	10.5	7.4	4.6	9.5	6.7	4.1	8.3	5.9	3.6
Conventional HMA (30mm)	9.3	6.5	4.0	8.4	5.9	3.6	7.3	5.1	3.2
OGAC (30 mm)	9.3	6.5	4.0	8.4	5.9	3.6	7.3	5.2	3.2
PBA HMA (30mm)	9.3	6.5	4.0	8.4	5.9	3.6	7.3	5.1	3.2
RAC-G (30 mm)	10.6	7.6	4.6	9.6	6.9	4.2	8.4	6.0	3.7
RAC-O (30 mm)	10.6	7.6	4.6	9.6	6.9	4.2	8.4	6.0	3.7
RAC-O (HB) (30 mm)	10.9	7.7	4.7	9.8	7.0	4.3	8.6	6.2	3.8
BWC-Open (19 mm)	9.0	6.3	3.9	8.1	5.7	3.5	7.1	5.0	3.1
BWC-GAP (19 mm)	9.1	6.3	3.9	8.1	5.7	3.5	7.1	5.0	3.1
BWC-RAC-G (19 mm)	10.0	7.1	4.3	9.0	6.4	3.9	7.9	5.6	3.4
BWC-RAC-O (19 mm)	10.0	7.1	4.3	9.0	6.4	3.9	7.9	5.6	3.4

5 AGING AND HEALING OF TREATMENTS

5.1 Effect on reflective cracking

The model proposed by the authors was initially developed for RPA and presented at the Transportation Research Board annual meeting in 2002 (Sousa 2002). The model was also evaluated for the determination of the life of each treatment and as such to give a closer insight to life extension taking into consideration reflective cracking through the treatment.

An example of the proposed approach is described below. Figure 10 describes the relationships obtained for overlay of an average GOOD pavement for a TI of 12 in the Coastal Region. For the same zone it was computed the TPC of four treatments that were used to develop those relationships in Arizona namely 1 and 2 inch thick layers of conventional mix, and 1 and 2 inch thick layers of Asphalt Rubber concrete (gap graded). For those four hypothetical overlays the TPC versus the number of predicted traffic for 10% cracking was related and presented in Figure 11. It should be noted the good relationship between TPC and number of reflective cracking ESALS.

It was initially expected that this correlation would yield, directly for each region and each pavement condition the number of ESALs a treatment would resist in reflective cracking.

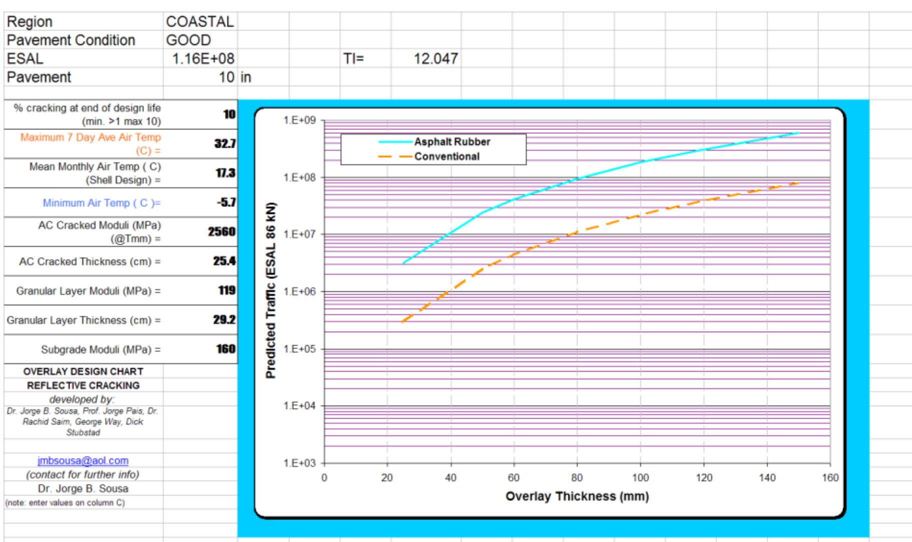

Figure 10 - Reflective Cracking predictions for GOOD pavements in COASTAL region

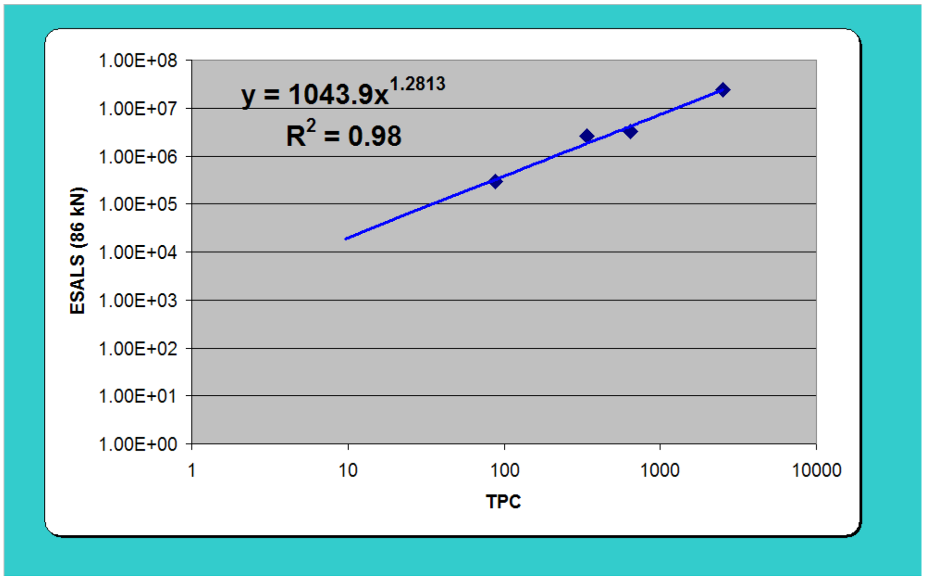

Figure 11 - Relationship for TPC and Reflective Cracking ESALS to reach 10% cracking on a COASTAL zone over a GOOD pavement

However, as the model was extended to all the treatments (with TPC varying from 0.07 to 600), it was realized that the predictions were EXTREMELY off the mark. It was found that the lower the TPC the higher the "error" (see Figure 12). Note that the pink line in this figure is the same line as in Figure 11. Two major conclusions can be derived from the graph. Life of the treatment is a function of TPC. However the capability to resist reflective cracking for lower TPC treatments is in reality much higher than predicted by the reflective cracking model. However, that difference is a direct function of the TPC. This is attributed to the fact that the model is not able to predict the healing factor of treatments that last a short time (in actual years) but that can take higher number of ESALS while they do not age and become brittle.

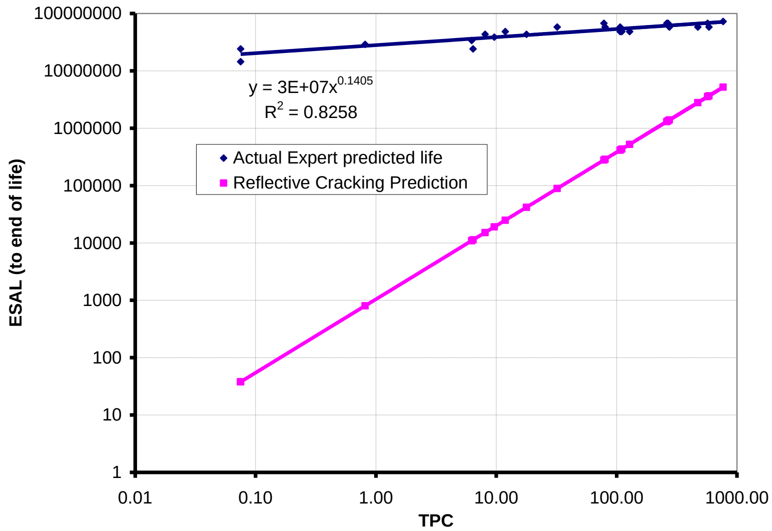

Figure 12 - Comparison between the "actual" treatment lives as per expert opinion and predictions given by the reflective cracking model function of TPC

Actually it was found that there was a very clear relationship, for each region and for each pavement type, between the value predicted using the TPC determined reflective cracking ESALS and the ESALS computed using the number of years the experts expected a treatment to last.

As it can be observed in Figure 13 the reflective cracking model relationship is undeniable. Actually if this relationship is used the reflective cracking model, developed for RPA, can actually be used to predict the reflective cracking life of each treatment based only on its TPC, location and type of pavement where it is being placed. This empirical-mechanistic approach could replace the statistical model present in this report (see Chapter 4.3) with a similar R^2. The kind of predictive capability of this model is presented in Figure 14.

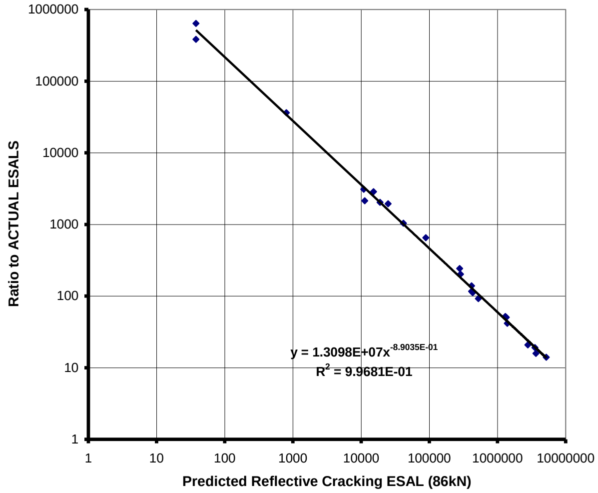

Figure 13 - Relationship between Ratio to Actual ESALS and Reflective Cracking ESALS predicted based on the TPC of the treatments

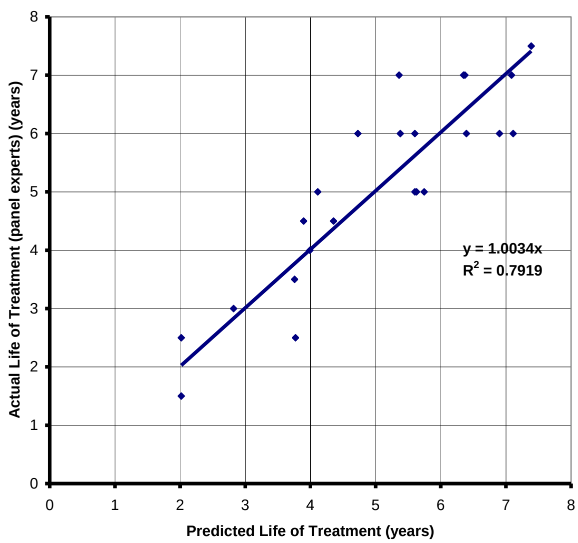

Figure 14 - Comparison between actual (expert based) and predicted (model and TPC) years a treatment lasts

What this exercise clearly demonstrates is that low TPC treatments actually do not have much resistance to reflective cracking. However, experts and observation clearly show that in the first year or so they do perform. What is probably happening is that during the early stages, cracks develop but heal rapidly. As soon as the material ages, the healing capability is lost and cracks develop. The model developed for RPA does not take account healing/aging and therefore it does not capture this aspect however it appears to be very directly correlated with the TPC of a treatment.

The evidence that the life of thinner pavements is affected by something else other then just traffic is clearly recognized in Figure 15. This relationship was obtained from averages of 41514 FWD tests done over many types of pavements designed by ADOT. Pavements thinner then 5 in. (in AC layer thickness) follow design criteria that can take clearly much less traffic then project values (dashed blue line) from design criteria followed for thicker pavements. Yet all pavements are expect to last (if they have 0% cracking) about 12 years. As such this is a clear recognition (evidence) that aging affects severely the expected life of thinner pavements (and by inference with magnified effects of treatments with lower TPC).

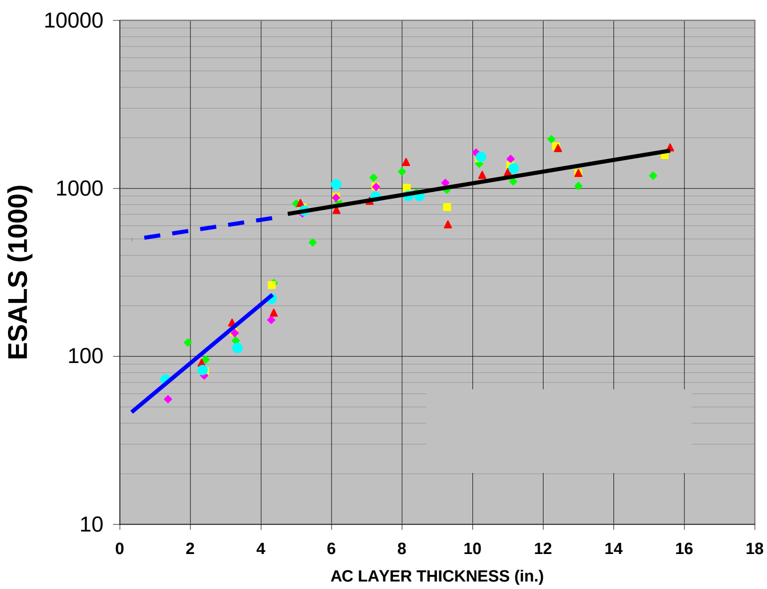

Figure 15 - Traffic Levels function of AC layer thickness in pavements designed by ADOT

6.25.2 Effect of binder aging and TPC on cracking levels

Formatted: Bullets and Numbering

To investigate further into the effect of aging on the cracking tendency of preservation treatments, cracking data was extracted from both the Arizona Pavement Management system (PMS 2004) and from various Arizona studies (Way 1976, 1979, 1980). Considerable data from Arizona cracking inventory and research studies was analyzed and normalized and is summarized in Figure 16 and Table 1Table 11. All the various treatments were normalized to have an ending percent cracking of roughly 12 percent. The treatments include flush coat, seal coat. ACFC (no rubber), 1 inch HMA, 2 inch HMA, AR SAM, ARFC and ARAC at 1.7 inch. The data for AR SAM was stopped at 12 years because virtually all of the projects were overlaid by then. They were overlaid not because they needed the overlay due to cracking but rather to improve the ride or as part of planned reconstruction.

Table 11 - Cracking and Viscosity function of age (years) for several treatments shows cracking levels and binder viscosity levels function of age. Most of the data comes from the reflective cracking study Minnetonka East back in the 1970's (Way 1976, 1979) as well as other ADOT asphalt aging (Way 1980) and seal coat studies (Peters 1979) and City of Phoenix asphalt rubber research (Schnormeier 1985). For each treatment cracking type and curve, there is a corresponding estimate of the 77 °F (25 °C) micro-viscosity in mega-poise. These measurements were taken with the Shell sliding plate micro-viscometer. Micro-viscosity is a measure of the binder stiffness in the temperature zone that is critical for cracking of all types to occur, reflective and fatigue. Figure 16 presents the general trend of cracking propagation with time. To further understand the cause effects related to crack propagation the general trend relating cracking levels with binder viscosity is presented in Figure 17. A R^2 of 64% is indicative of the importance of aging binder viscosity in cracking levels.

Table 11 - Cracking and Viscosity function of age (years) for several treatments

Treatment	Age Years	Asphalt Viscosity 77 F Mega Poise	% Crk	Treatment	Age Years	Asphalt Viscosity 77 F Mega Poise	% Crk
Flush/Fog Emulsion 0.1	1	65	12	AR SAM	1	0.6	0
				(with rubber)	2	0.75	0
Seal Coat .375 in	1	28	2		3	0.88	0.6
	2	35	7		4	1.16	1.5
	3	60	9		5	0.78	2.2
	4	65	11.5		6	0.91	2.5
					7	1	2.9
0.5" OGFC (No rubber)	1	7	3		8	1.1	3.2
	2	10	5		9	1.2	3.5
	3	20	7.6		10	1.3	3.8
	4	21	9.2		11	1.4	4
	5	23	12		12	1.5	4.5
1" HMA	1	7	1				
	2	10	3.5	ARFC	1	0.6	0
	3	20	4.6	(with rubber)	2	0.75	0
	4	21	6		3	0.88	0
	5	23	8		4	1.16	1
	6	25	12		5	0.78	1
					6	0.91	2
2" HMA	1	7	0.6		7	1	2
	2	10	2		8	1.1	2.5
	3	20	4		9	1.2	2.6
	4	21	5		10	1.3	3
	5	23	7		11	1.4	3.5
	6	25	8		12	1.5	4
	7	33	9		13	1.6	4
	8	60	11		14	1.7	4
	9	90	12.4		15	1.8	4.5

To more directly demonstrate the effect of aging on cracking level the crack rate was determined as a function of the binder viscosity (see Figure 18). So as the treatment ages, it looses the ability to heal and cracks develop allowing water to penetrate into the pavement.

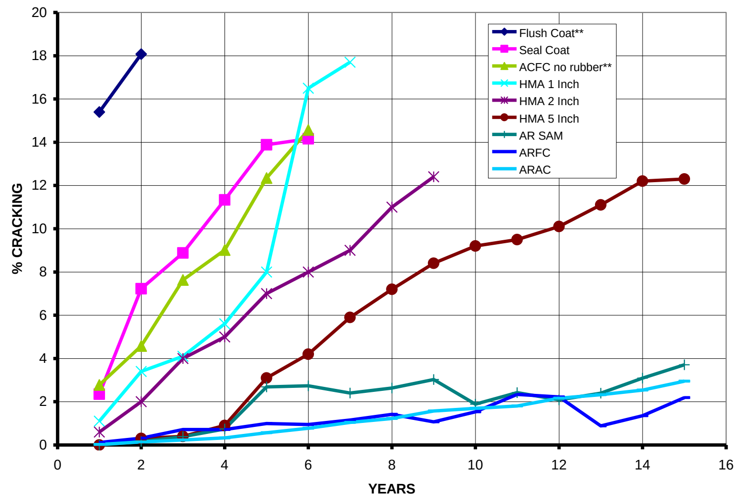

Figure 16 - Cracking levels for several treatments (note data is for several zones and traffic levels)

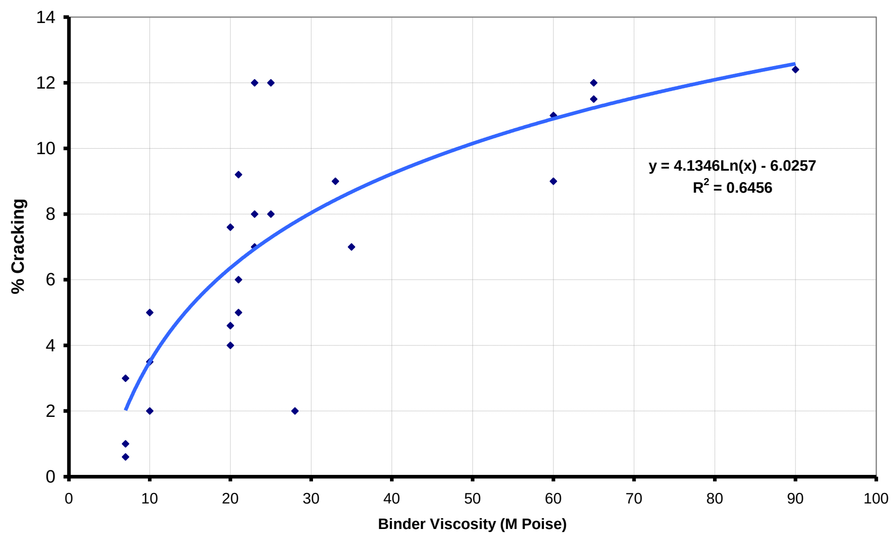

Figure 17 - Effect of Binder Viscosity on % cracking

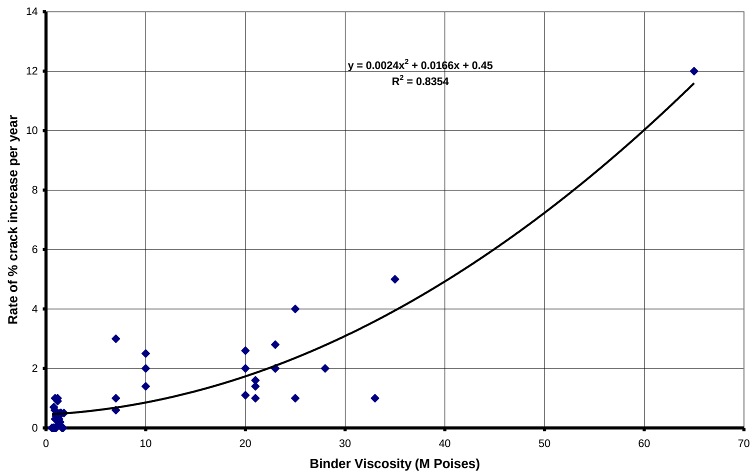

Figure 18 - Rate of % Cracking increase per year function of Binder Viscosity

The rate of aging is to some extent dependent on TPC as expected. Higher TPC treatments lead to lower rates of aging as shown in Table 12 - TPC for several treatments in the aging study. It is noteworthy to mention that AR binders have lower rates of aging for the same TPC levels as shown in Figure 19.

Table 12 - TPC for several treatments in the aging study

	Thickness Inch	Binder Gals/SY	Thickness (mm)	Binder L/m2	Strain at Break Ratio	TPC mm.l/m2	Max Air Temp F	Shell MMAT F	Min Air Temp F	Traffic (*1000)/year
Flush Coat**	0.01	0.070	0.245	0.317	1.000	0.078	116.0	69.0	8.0	2179.9
Seal Coat	0.38	0.270	9.188	1.222	1.000	11.231	107.5	65.8	0.8	243.3
ACFC no rubber**	0.50	0.440	12.250	1.992	1.000	24.402	99.3	54.9	-11.2	244.5
HMA 1 Inch	1.00	0.780	24.500	3.531	1.000	86.517	114.1	69.0	6.0	219.0
HMA 2 Inch	2.00	1.510	49.000	6.836	1.000	334.975	112.2	69.1	4.4	352.0
AR SAM	0.38	0.590	9.310	2.671	5.000	124.340	106.0	63.8	-0.6	1392.0
ARFC	0.50	1.120	12.250	5.071	5.000	310.573	110.2	67.6	2.1	3361.1
ARAC	1.7	1.800	41.650	8.149	5.000	1697.057	104.0	59.9	-6.5	1,737.5

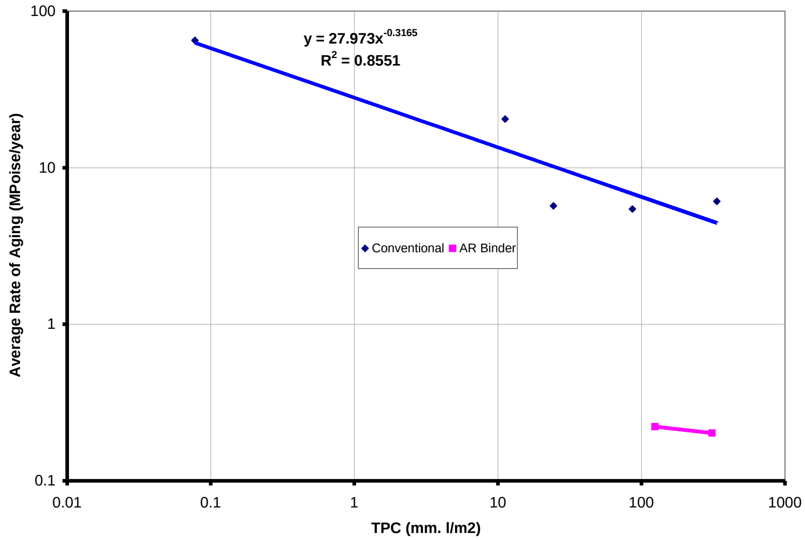

Figure 19 - Average Rate of Aging function of the TPC of each treatment

Figure 20 clearly shows that even for those unrelated treatments (from Figure 16); the TPC plays a major role in the cracking rate increase. This rate was determined as the slope of the best-fit line, in Figure 16, for each treatment up to 10% cracking. Table 12 shows that the weather conditions were these treatments were placed is quite different, even the traffic over them is different, yet, TPC is capable of capturing most of the performance behavior (about 76%).

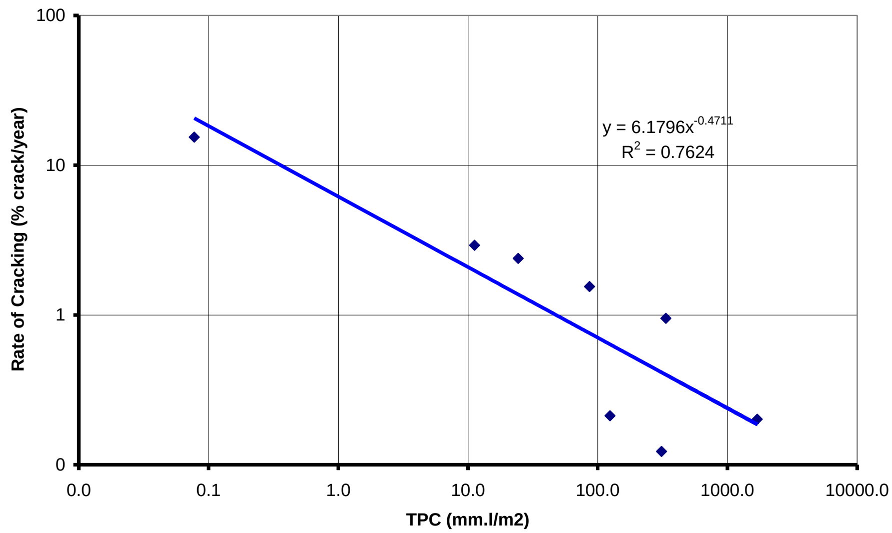

Figure 20 - Effect of TPC on the rate of cracking (% cracking/year) for several treatments

~~6.3~~5.3 Chapter Summary

Formatted: Bullets and Numbering

The research presented in this chapter identifies that reflective cracking through treatments (and treatment life) are controlled by three major factors (beyond the cracking level of the underlying pavement) namely:

a) Traffic levels,
b) Treatment capability to resists aging (function of the region where it is placed),
c) Treatment capability to heal once a crack has developed (function of the region where it is placed).

It was interesting to identify that one of the major aspects controlling factors b) and c) is the TPC of a treatment. To a high TPC corresponds generally high resistance to aging.

~~7~~6 DISCUSSION

Formatted: Bullets and Numbering

~~7.1~~6.1 *Strain Energy at Break Ratio*

Formatted: Bullets and Numbering

One of the components that have helped the TPC to capture rather well the treatment performance is the Strain Energy at Break Ratio. The rational for its introduction into the formula was to bring in the “quality” of the binder that cannot be explained only by its quantity. Several 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 15 shows some examples of Strain of Energy at Break Ratio for various mixes. Clearly not all conventional binder has identical values amongst each other and clearly not all Polymer Modified Binder (PMB) are identical in this regard either. However the data indicted that some difference in the “quality” of the binders are affecting performance.

Table 13 - TPC for several treatments in the aging study

Static Creep Test

Mix	Target AV%	Temp °F	σ_3 (psi)	σ_d (psi)	Axial Flow Time (sec)	Axial Strain @ failure (%)	Creep Modulus @ failure (psi)	Inst. Compl. D_O x10^{-3} (1/psi)	Intercept a x10^{-3} (1/psi)	Slope m	STRAIN AT FAILURE RATIO
AR-ACFC	18	130	10	120	2	4.24	2,550	0.076	0.207	0.55	6.42
ARAC	11	130	10	120	3	6.15	1,570	0.08	0.27	0.82	9.32
SRB PG64-22	7	130	10	120	8	0.66	21,780	0.008	0.014	0.59	1.00

THERMAL CRACKING

Mixture	Va %	AC %	Rubber %	Vbeff %	VMA %	VFA %	Pen 25 Tank 0.1mm	Total Fracture Energy [kN*mm] Meas.	Predict.	STRAIN AT FAILURE RATIO
Salt River 3/4" PG64-22	7	4.2	0	9	15.998	56.286	54	26.5	25.6	
Salt River Base PG64-22	7.5	4.55	0	8.58	16.073	53.401	54	26.3	27.6	
Bidahouchi 3/4" PG64-22	6.6	4.9	0	9.89	16.468	60.044	54	28	25.3	
Bidahouchi Base PG64-22	7.8	5.25	0	10.46	18.274	57.242	54	33.1	33.6	
								Average	28.0	1.89
Salt River 3/4" PG70-10	7.2	4.3	0	9	16.216	55.517	26	15.6	14.6	
Salt River Base PG70-10	7.3	4.25	0	8.89	16.162	54.997	26	11.1	15	
								Average	14.8	1.00
Two Guns ARAC	8.1	7	20	12.52	20.618	60.715	34.7	77.4	77.6	5.24
Two Guns AR-ACFC	17.9	9.4	20	15.11	33.005	45.766	34.7	57.3	57.3	3.87

In Figure 33 data from flexural fatigue tests indicate the AR binder does perform better, at least by a factor of 10 (Kaloush 2003). Clearly the amount of binder can capture some of those increases but not all of it. Also as shown in Figure 34 the data from ALF-FHWA (Qi 2006) and the analyses reported in Sousa 2006 demonstrated that AR binder out performed all other binders in the study in terms of reflective cracking resistance.

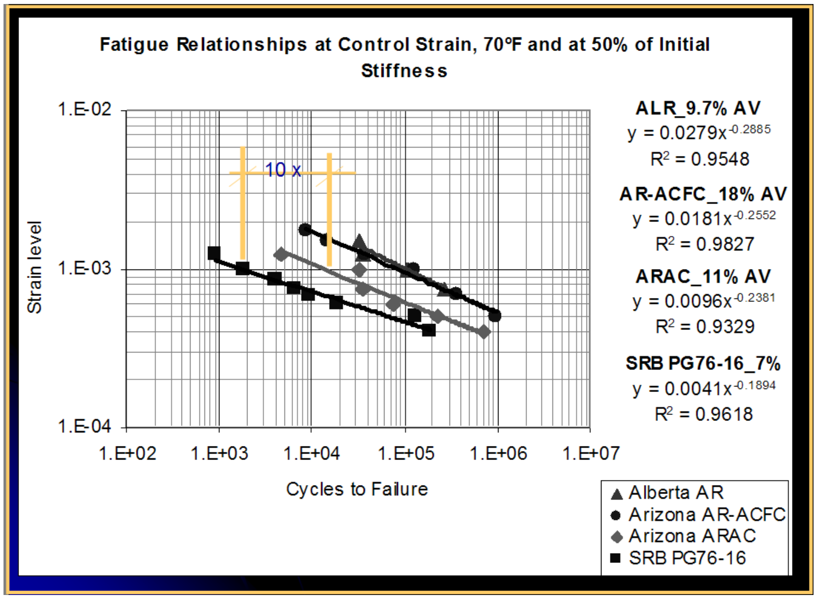

Figure 21 – Comparison of flexural fatigue lives under strain control for conventional and asphalt rubber binder.

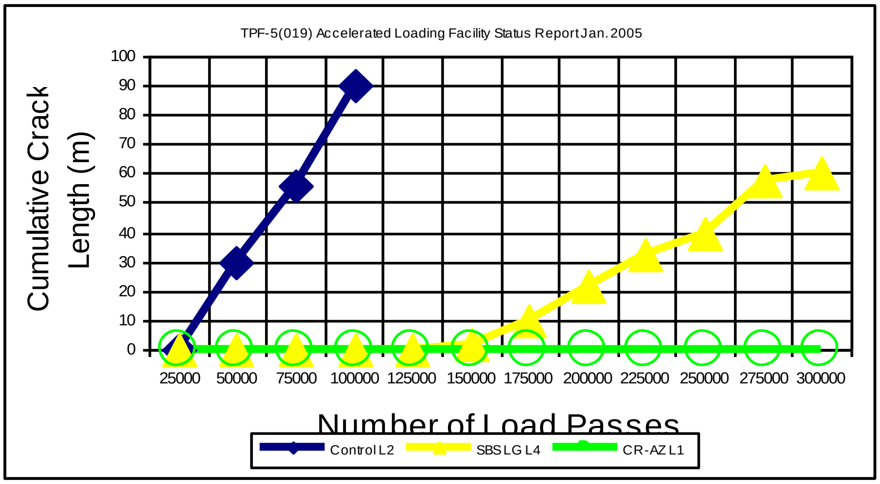

Figure 22 – ALF-FHWA data relating number of passes and cracking level for three pavements with the same thickness (10 cm control- conventional, 10cm SBSLGL4- PMB binder and CR-AZL1- with 5 cm of asphalt rubber binder over 5 cm of conventional.

Figure 35 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.

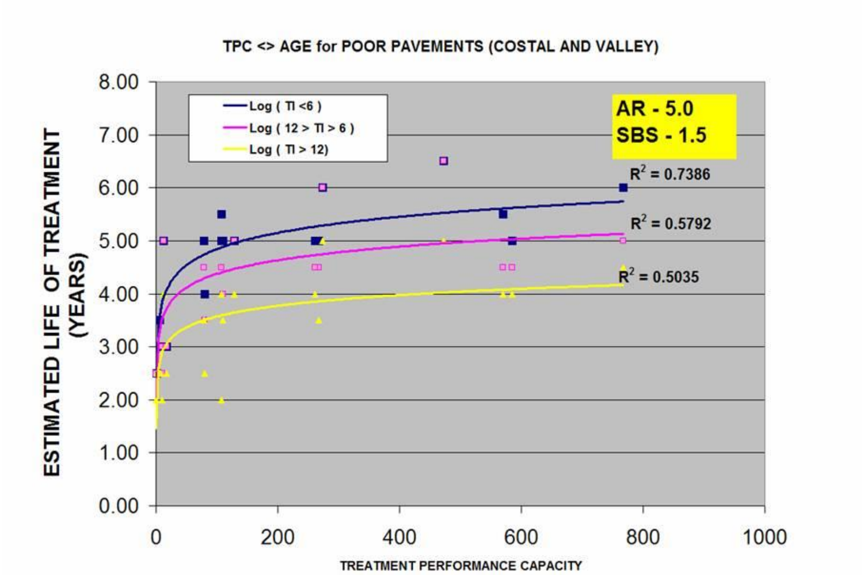

Figure 23 - Influence of TPC on Treatment Life for Coastal and Valley Regions for POOR Pavements

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

	A	B	C	D
SEBR - AR	**5.0**	**5.0**	**5.0**	**5.0**
SEBR - PMB	**1.5**	**2.0**	**5.0**	**1.0**
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

It can be observed in Table 16 (see columns A, B and C) that with the assumption that the Strain Energy at Break Ratio is 1.5 the R^2 is higher than if it is assumed to be 2 or even 5. Interestingly enough for the case of POOR pavements a better 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 for the 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 2006) also showed some cracking improvement with a PMB albeit it was not as great as that for AR.

7.26.2 Optimum time for treatments

Formatted: Bullets and Numbering

The determination of the optimum time for overlay is essential when it is necessary to optimize budgets while guarantying acceptable levels of road serviceability. In this report it was determined that treatments with high Treatment Performance Capacity (TPC) will outperform treatments with low TPC in every pavement condition and region. Treatments with low TPC will not last as long and will age faster and thus be more prone to cracking and consequently allow more water to penetrate into the pavement structure (if it is already cracked).

As a pavement is subjected to traffic and aging factors it will go through several stages of degradation. During a first phase the pavement structure is intact and the pavement surface layers will age (become more hard and brittle) while consuming fatigue life. As the fatigue life reaches the end of its capability the pavement sections with lower compaction levels and least amounts of asphalt will first exhibit cracking which will allow water to penetrate into the pavement. As the water penetrates into the asphalt structure, aggregate base and subgrade it will reduce their moduli and will cause a “softer” foundation to induce higher strains in the asphalt layers leading to accelerated fatigue damage.

If at any point in time a treatment is placed on the pavement to the extent it is waterproofing it will lead to reversal of the softening of the base and subbase thus promoting a more sound foundation and leading to an increase in pavement life. However the treatment itself is subject to aging. As it ages and is subjected to traffic loads it will also crack and allow water to penetrate again into the base and subgrade.

If a treatment that has a low TPC is applied while the pavement has no cracks it is likely that it will age before it can perform its function. It is possible to conceive that a treatment with a low TPC may last 3 years and that treatment is placed when a pavement as 0% or 1% cracked. By the time the pavement develops 4 or 5% cracks (when water does start to seriously affect subgrade moduli) the treatment is already wasted (too brittle and prone to cracking to actually be effective.) In this sense this was a premature treatment.

However if a high TPC treatment is placed instead it may be able to function well at the outset of the cracking thus providing some water penetration mitigation and extending the pavement life. In this case some of the capabilities of the treatment were "wasted" but because it was a long lasting treatment by the time the pavement needed the treatment it still had performance capacities enough left to perform most of its function.

The treatment may be placed after the pavement reaches 10 or 12% cracking. By that time structural damage has reached such an extent that even if a 100% water proof treatment is placed with high TPC there is little opportunity to recover from all the lost.

Data appear to indicate that the maximum beneficial effects of a high TPC treatment are obtained when the treatment is placed as soon as it reaches a cracking level of 1 or 2%. At the most such treatment should be placed before the pavement reaches 4 to 5 % so that the highest benefits in terms of pavement life extension can be derived. In this case a structural life extension can reach 3 years.

Low TPC treatments should be placed very close to the time the pavement reaches 3 or 4% cracking to ensure that they are at their peak of performance when they are most needed.

There is no great benefit in delaying application of treatments past 4% cracking. From that point on for each percent cracking level reached structural life extension is always less even for very high TPC treatments.

It was not possible from the available data to determine how much time it takes for a pavement at the 1 or 2% level to deteriorate to the 4 or 5% level (function of region, pavement and traffic). This clearly would help CALTRANS in the definition of trigger values to plan interventions for the years ahead. This aspect has been noted in the recommendations for further research.

Preventive maintenance strategies based on the concepts collected in this report should follow an approach similar to this:

A) Determine when a pavement reaches 1 to 2 % cracking and apply the treatment. It is noteworthy to consider that if treatment trigger values are set at higher values, (say 5%) it is very likely that by the time treatments are actually performed the pavement has already further deteriorate to 7 or 8% levels. Also at these levels the pavement structural layers experience accelerated rates of damage affecting the AC layers due to the much higher strain/deformation levels existing when the pavement is at 4 to 5% cracking levels).
B) Apply the treatment with the most cost effective TPC/$ (see Figure 5) depending on what type of road it is.
C) If delayed maintenance is require all efforts show be made so that maintenance takes place before cracking levels reach 4% (i.e. pavements should be sealed form water penetration BEFORE they reach 4 to 5% cracking levels)

7.36.3 Cost effectiveness of treatments

Formatted: Bullets and Numbering

At the time of application of the treatment evaluation of the cost effectiveness of each possible and available treatment in the region should be made. The treatment selected should be the one with the highest cost effectiveness in terms of TPC/$. At this time, with the current price structure in the market, and based on the cost data provided to this project, it appears that CALTRANS should adopt a policy to use preferentially the treatments with the highest cost effectiveness in terms of TPC/$ as soon as pavement cracking levels reaches 1 to 2% levels.

~~8~~7 CONCLUSIONS AND RECOMMENDATIONS

Formatted: Bullets and Numbering

~~8.1~~7.1 Conclusions

Formatted: Bullets and Numbering

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

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 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 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 (*simply dividing the TPC of a treatment by its cost per square yard*). Actually the concept to adopt is to start evaluating how much TPC /square yard does CALTRANS get for each 1 USD spent in 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**.

Structural and reflective cracking analyses indicate that the optimum time to apply a treatment is when the pavement cracking levels are in the range of 1% to 2%. There are significant structural benefits (structural pavement life extension) when a pavement has a waterproofing treatment applied by the time it reaches 4 to 5% cracking. Preventive maintenance treatments, if applied at the correct time, with long lasting 100% waterproofing capabilities, can provide structural life extensions for the underlying pavement of about 4 years.

~~8.2~~7.2 Recommendations

Formatted: Bullets and Numbering

It is recommended that at the time of application of a treatment evaluation of the cost effectiveness of each possible and available treatment in the region should be made. It is recommended that the treatment selected should be the one with the highest cost effectiveness in terms of TPC/$. At this time, with the current price structure in the market, and based on the cost data provided to this project, it appears that CALTRANS should adopt a policy to use treatments with the highest cost effectiveness in terms of TPC/$ as soon as pavement cracking levels reach 1 or 2% levels.

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

It is further recommended that an investigation be made and quantified, from CALTRANS data, if available, the effect of water penetrating in the pavements in the four different climatic regions in California.

It is also recommended that an investigation be made to determine the relationship between the rates of crack evolution (cracking change from 1% to 5%) as a function of the climatic region, traffic index and pavement type and or overlay.

~~9~~8 ACKNOWLEDGEMENTS

Formatted: Bullets and Numbering

The author thanks Dr. Gary Hicks and Dr. Shakir Shatnawi for their assistance on this project. In addition, thanks go to Dr. Kamil Kaloush of Arizona State University who assisted in reviewing the project and assembling data and Dr. Jorge Pais of the University of Minho, Portugal who helped with the modeling.

~~10~~9 REFERENCES

Formatted: Bullets and Numbering

Cedergren, H.R., Arman, J.A., and O'Brien, K.H. (1973). *Development of Guidelines for the Design of Subsurface drainage Systems for Highway Pavement Structural Sections.* FHWA-RD-73-14. Federal Highway Administration, Washington, DC.

Cedergren, H.R. (1974). *Drainage of Highway and Airfield Pavements*. John Wiley & Sons, Inc., New York.

Cedergren, H.R. (1994). "America's Pavements: World's Longest Bathtubs," *Civil Engineering*, American Society of Civil Engineering, September, pp. 56-58.

Christopher, B.R. and V.C. McGuffey (1997). *NCHRP Synthesis of Highway Practice 239: Pavement Subsurface Drainage Systems.* TRB, National Research Council, Washington,

FWD, "Falling Weight Deflectometer Deflections," Arizona DOT FWD Data Base, 2002

Green, E. L. and William J. Tolonen, "The Chemical and Physical Properties of Asphalt-Rubber Mixtures," Arizona Department of Transportation, ADOT-RS-14(162), July, 1977.

Hicks, R. G. and Rob Marsh, "Pavement Preservation Sub-Group on Strategy Selection & Evaluation," Power Point Presentation, April 25, 2006.

Hveem, F. N., Lovering, W.R., and G.B. Sherman, "The Design of Seal Coats and Surface Treatments," State of California Department of Public Works Division or Highways, Materials and Research Department, 1950.

Hveem, F.N. (1950)). "WATER IN HIGHWAY SUBGRADES AND FOUNDATIONS," State of California Department of Public Works Division or Highways, Materials and Research Department, Prepared for National Research Council
American Geophysical Union, South Pacific Meeting, Sections of Hydrology and Meteorology, University of California, Davis, California, February 3 and 4, 1950.

Kaloush, K., Witczak, M., Way, G., Zborowski, A., Abojaradeh, M., and Sotil, A., "Performance Evaluation of Arizona Asphalt Rubber Mixtures Using Advanced Dynamic Material Characterization Tests", Final Report Submitted to FNF Construction and the Arizona Department of Transportation, July 2002.

Kaloush, K., Zborowski, A., Sotil, A., Abojaradeh, M., and Way G. "Material Characteristics of Asphalt Rubber Mixtures". Proceedings Asphalt Rubber 2003 Conference, ISBN 85-903997-1-0, p129-145, Brasilia, Brazil, December 2003.

Maintenance, "Maintenance Technical Advisory Guide (TAG)," Caltrans, Office of Pavement Preservation, Division of Maintenance, October, 2003.

Irwin, L. H., "MODCOMP5," Cornell University Local Roads Program, October, 1999.

Peters, Rowan and David Stephens, "Properties of Asphalts in Seal Coat Emulsions Field Test Status Report," Arizona DOT, Presented at Annual Asphalt Emulsion Manufacturers Association Meeting, San Francisco, California, March 1979.

PMS, "Arizona Pavement Management System Cracking Data," Arizona DOT, 2004.

Qi, Xicheng, Aroon Shenoy, Ghazi Al-Khateeb, Terry Arnold, Nelson Gibson, Jack Youcheff and Tom Harman, "Laboratory Characterization and Full-scale Accelerated Performance Testing of Crumb Rubber Asphalts And Other Modified Asphalt Systems," Proceedings of the Asphalt Rubber 2006 Conference, Pages 39-65, Palm Springs, California, October 25-27, 2006, ISBN 962-405-091-0.

Schnormeier, Russell, "Fifteen-Year Pavement Condition History of Asphalt Rubber Membranes," City of Phoenix, Arizona, 1985.

Shell, "1985 Addendum to 1978 Shell Pavement Design Manual," Shell International Petroleum Company, Limited, London, 1985.

Sousa, Jorge, Jorge C. Pais and Rachid Saim, "The Effect of Mode of Loading on the Comparison Between Asphalt Rubber and Traditional Hot Mixes Laboratory Performance," Proceedings of the Asphalt Rubber 2000 Conference, Pages 259-272, Vilamoura, Portugal, November 14-17, 2000, ISBN 972-95240-9-2.

Sousa, Jorge, Jorge C. Pais, Rachid Saim, George Way, and Richard N. Stubstad, "Development of a Mechanistic Overlay Design Method Based on Reflective Cracking Concepts," Rubber Pavements Association, Tempe, Arizona, July, 2001.

Sousa, Jorge, Jorge C. Pais, George B. Way, Rachid Saim and Richard N. Stubstad, "A Mechanistic-Empirical Overlay design Method for Reflective Cracking," Transportation Research Record 1809, TRB National Research Council, Washington D.C., 2002, pp. 209-217.

Sousa, Jorge, Jorge C. Pais and George B. Way, "A Mechanistic-Empirical Based Overlay Design Method for Reflective Cracking," Proceedings of the Asphalt Rubber 2003 Conference, Pages 85-110, Brasilia, Brazil, December 1-4, 2003,
ISBN 85-903997-1-0.

Sousa, Jorge, George B. Way, Shakir Shatnawi and Catia Dantas, "Asphalt Rubber in New Pavement Design and Construction," Proceedings of the Asphalt Rubber 2006 Conference, Pages 67-98, Palm Springs, California, October 25-27, 2006, ISBN 962-405-091-0.

Sousa, Jorge, George B. Way**, "**Considerations for Estimating Pavement Treatment Lives and Pavement Life Extension on Flexible Pavement", Report for California Department of Transportation and California Pavement Preservation Center, August 22, 2007

Way, George, "Prevention of Refection Cracking in Arizona Minnetonka-East (A Case Study)," Arizona DOT, Report Number 11 HPR-1-13(224), May, 1976.

Way, George, "Prevention of Refection Cracking Minnetonka-East," Arizona DOT, Report Number 1979GWI, August, 1979.

Way, George, "Prevention of Reflective Cracking in Arizona," TRB, National Academy of Sciences, TRB, National Academy of Sciences, Transportation Research Record 756, pp. 29-32, 1980.

Way, George, "Environmental Factor Determination from In-Place Temperature and Moisture Measurements Under Arizona Pavements," Arizona DOT, Report Number FHWA/AZ 80/157, September, 1980.

Zborowski, Aleksander and Kamil E. Kaloush "Predictive Equations to Evaluate Thermal Fracture of Asphalt Rubber Mixtures", Pages 177-192, Proceedings of the Asphalt Rubber 2006 Conference, ISBN 962-405-091-0.