QUANTIFICATION OF THE RUTTING AND CRACKING RESISTANCE OF ASPHALT MIXES WITH RAP USING LTPP DATA

J P AGUIAR-MOYA*, F HONGAND JA PROZZI*****

*Research Assistantjpaguiar@mail.utexas.eduDepartment of Civil, Architectural and
Environmental Engineering The University of Texas at Austin ECJ Bldg., Ste. 6.10
(C1761), Austin, TX 78712

*Pavement Specialistsfrank_hongf@yahoo.comPavement Specialists, Construction
Division Texas Department of Transportation4203 Bull Creek Rd., Austin, TX 78731

***Associate Professorprozzi@mail.utexas.eduDepartment of Civil, Architectural and
Environmental Engineering The University of Texas at Austin ECJ Bldg., Ste. 6.10
(C1761), Austin, TX 78712

ABSTRACT

In recent years, there has been a significant increase in the use of RAP for the construction and rehabilitation of flexible pavement structures. There are many advantages that are associated with the use of RAP, including economic benefits due to the reduction in virgin asphalt binder and new aggregates required, environmental benefits associated with the use of a recycled material, significant energy savings, and short-term performance benefits due to increased rutting resistance. However, field observations have raised some concerns in terms of the long-term performance of mixtures containing RAP compared to those of virgin mixes.

In order to address these concerns, the authors used data from FHWA's LTPP SPS-5 experiment in Texas to quantify and compare the field performance of pavement sections containing RAP with those of those that do not contain RAP. Based on the SPS-5 data, simple performance models were developed for rutting and cracking of the pavement structure. The models are then used to statistically quantify the effect of RAP on each type of distress and to estimate the expected pavement life of a given overlay, with and without RAP. As expected, the results indicate that there is a significant gain in rutting resistance when using RAP. However, pavements containing RAP develop cracking earlier, and at a faster rate, so short-term savings may be offset by additional overlays later in the life of the pavement. This raised the following concern: are we saving today to pay later?

The main objectives of this paper are: i) to make pavement designers aware that RAP may not be always the most economical solution, and that ii) life-cycle cost analysis (LCCA) is imperative to assess the real benefits and costs of the various alternatives.

Based on the simple performance models developed, a basic LCCA analysis was performed in order to compare the economic advantages or shortcomings of using RAP in the HMA mix. The interim results indicate that, under particular scenarios, the use of RAP might not be the most economic choice. Where and how much RAP should be used

Proceedings of the 30th Southern African Transport Conference (SATC 2011) 11 - 14 July 2011
Proceedings ISBN Number: 978-1-920017-51-4 Pretoria, South Africa
Produced by: Document Transformation Technologies cc Conference organised by: Conference Planners

should be determined through a case-by-case analysis. In order to do this, accurate field performance data are necessary. While LTPP may provide some initial data, RAP technology has evolved since the inception of LTPP and the use of fractionated RAP is more prevalent now. Therefore, LTPP needs to be updated and new data sources may be needed.

1 INTRODUCTION

Many State DOTs currently allow considerable percentages of Reclaimed Asphalt Pavement (RAP) to be included in most of their surface and base mixtures. This is due to a continued increase in the cost of high-quality aggregates, asphalt binder and energy, a decline in the availability of aggregates meeting specification, strict project-specific requirements, and an overall increase in awareness of the environmental impact of improperly storing and disposing material generated when reconstructing asphalt pavements, This is the case at the Texas Department of Transportation (TxDOT), where up to 30% RAP is allowed on base mixtures and up to 20% RAP is allowed on surface mixtures (TxDOT, 2004).Furthermore, cost saving considerations and the incorporation of warm-mix asphalt (WMA) technologies are other influencing factors that are contributing to increasing RAP usage.

Traditionally, because RAP contains a given percentage of aged asphalt binder, the amount of new asphalt that needs to be added to a mixture containing RAP is reduced. For example, as a rule of thumb, the Asphalt Institute suggests that using 20% RAP (with 5% asphalt content) can be approximately translated to a savings of 1% of new asphalt binder. However, the use of RAP introduces an additional variable to the performance and deterioration of the pavement structure. Characterization and better understanding of the interactions between the aged binder and the new or virgin asphalt is required. Depending on the percentage of RAP to be incorporated into the mixture and, in order to obtain a target PG grade for the asphalt binder in the mixture with RAP, often the PG grade of the new asphalt binder needs to be “dumped” one grade to offset the effect of the aged binder in the RAP (McDaniel and Anderson, 2001; Newcomb et al., 2007).

In addition to the initial economic benefits of using RAP (reduction in the requirement of new aggregate and asphalt binder), an improvement in the performance of the pavement structure can be expected in the initial service years of the pavement structure, particularly in terms of reduction in permanent deformation. This is due to increase in stiffness of the HMA mix resulting from the inclusion of RAP. Therefore, no one can argue with the numerous benefits of using RAP, particularly, when the performance during the early life of the pavement is critical.

1.1 Performance of HMA mixes containing RAP

As previously indicated, an additional argument for the use of RAP is the initial gain in resistance to permanent deformation of the HMA mix. However, it is still unclear how HMA mixes containing high percentages of RAP will perform in the long-term in term of durability and cracking. It has been identified that the initial rate of aging in mixes containing RAP is higher than that of virgin mixes. Therefore, it is important to determine what happens in the long run to the binder in mix containing RAP. If the rate of aging of the binder remains relatively constant, the HMA mix might become very stiff, resulting in other types of pavement deterioration such as cracking.

Abdulshafi et al. (2002) looked into the development of a simple test to assess the optimum RAP content based on the maximum percentage of absorbed energy level. The study showed that indirect tensile strength (ITS) tends to increase with RAP. This result limits the use of ITS to control the maximum percentage of RAP. In addition, this further supports the observation that initial durability of RAP mixes is higher than that of mixes with no RAP after construction.

Ziari and Khabiri (2005) showed that the addition of RAP to a mixture increased the resilient modulus. For instance, at 77°F, adding 40% RAP to a control mixture resulted in a 74% increase in stiffness. Similar results were obtained by Valdés et al. (2010), who showed that mixtures with high RAP content exhibit higher stiffness and modulus as compared to their lower RAP content counterparts.

Watson et al. (2008) also demonstrated that the conditioned and unconditioned tensile strength of mixtures with RAP increased. However, the study also showed that the tensile strength ratio (TSR) did not increase significantly. Furthermore, the researchers indicated that, based on their experimental design (four aggregate sources and four RAP types, blended at four different contents: 0%, 10%, 20%, and 30%), it appears that RAP content did not have a significant impact on rutting performance and thermal cracking. But adding more RAP binder to the mixtures resulted in lower resistance to fatigue cracking; samples with 30% RAP exhibited half the fatigue life of the control samples with no RAP.

Similarly, Sondag et al. (2002) found that there was very little difference in TSR value when RAP content was modified. However, it was found that the addition of RAP to the mix resulted on an increase in resilient modulus and dynamic modulus (E*), especially at higher testing temperatures. Inversely, the phase angle (δ) decreased with RAP content, indicating a decrease of the viscous component of the binder. Based on dynamic modulus and creep compliance testing, Lachance (2002) also showed that the addition of RAP to the mix increases stiffness. Therefore, creep flow time is also increased. Goh and You (2008) have reported that there are no significant differences in dynamic modulus between a control mix and mixes with 15% RAP. However, they also found that the 15% RAP significantly reduced rutting in the Asphalt Pavement Analyzer (APA).

Based on observations at the NCAT test track, West et al. (2009) reported that all test sections (control, 20%, and 45% RAP) performed well in terms of rutting and raveling. However, low to moderate severity cracking has been recorded on the sections with RAP. Hajj et al. (2010) evaluated the performance of mixtures with RAP in several airport runways. The researchers highlighted that the use of RAP in the surface course showed a good resistance to cracking after eight years of service life. However, there was moderate severity transverse and longitudinal cracking in some sections.

There seems to be consensus that the addition of RAP results in an improvement in rutting resistance, but the effects on cracking are not as clear. Tabakovíc et al. (2010) states that introduction of RAP to the HMA mix improved all the mechanical properties of the mix, especially in the case of fatigue cracking. It was found that mix containing 30% RAP developed higher relative fatigue resistance than that of the control mix. On the other hand, Hong and Chen (2009) found that for the case of overlays, the ones that incorporate RAP are more prone to transverse cracking than those containing only virgin asphalt. Due to the lack of consensus, we decided to look for medium- to long-term field performance data in an attempt to settle the discussion.

2 TEXAS SPS-5 SECTIONS

The purpose of the present paper is to evaluate the performance benefits or drawbacks associated with the use of RAP in an HMA mix. In order to do so, it is imperative to have sufficient field performance history so that the deterioration trends of the mixes with RAP can be fully captured. A short observation period may result in the conclusion that the rutting behavior of the mix with RAP was improved because of the increased stiffness associated with using a given percentage of RAP in the mix. It is impossible, in a short time frame, to assess how other types of deterioration, such as cracking, will develop over the long-term. The use of Accelerated Pavement Testing (APT) is also no desirable because the effect of the environment (aging in particular) is not properly accounted for.

Pavement sections with monitoring history of more than 10 years were identified in the State of Texas. The Long Term Pavement Performance (LTPP) SPS-5 sections have a recorded monitoring history of more than 15 years since their original rehabilitation. Therefore, these were selected as the candidate sections to analyze as part of the current study.

Figure 1: Texas SPS-5 Pavement Structures.

The LTPP SPS-5 experiment was designed to examine the effects of climatic region, existing pavement condition, and traffic on pavement sections incorporating different rehabilitation strategies. These strategies consisted of routine preventive maintenance or intensive preparation (cold milling). The experimental design also involved two types of asphalt overlay (virgin and recycled) and two overlay thicknesses (nominally, 2 in and 5 in). The experimental design resulted in eight different strategies. The following SPS-5 sections (Figure 1) were built in Texas, in Kaufman County of Dallas District along US-175: A501 (Control, no treatment), A502 (Thin overlay – recycled HMA mix), A503 (Thick overlay– recycled HMA mix), A504 (Thick overlay, virgin mix), A505 (Thin overlay, virgin mix), A506 (Thin overlay, virgin mix, with milling), A507 (Thick overlay, virgin mix, with milling), A508 (Thick overlay, recycled mix, with milling), and A509 (Thin overlay, recycled mix, with milling).

2.1 Performance of SPS-5 Sections

The field performance of the Texas SPS-5 sections is shown in Figures 2 through 6. As expected, three of the sections containing RAP (thick overlay with and without milling, and thin with milling) outperform the sections with no RAP in terms of rutting resistance. However, it should be highlighted that the average difference in rutting between the sections with RAP and the sections with no RAP is only in the order of 0.07 in. Nonetheless, regardless the difference in rutting magnitude between the sections with RAP and no RAP, it can be noted that there is a statistically significant difference between the performance of the two types of mix.

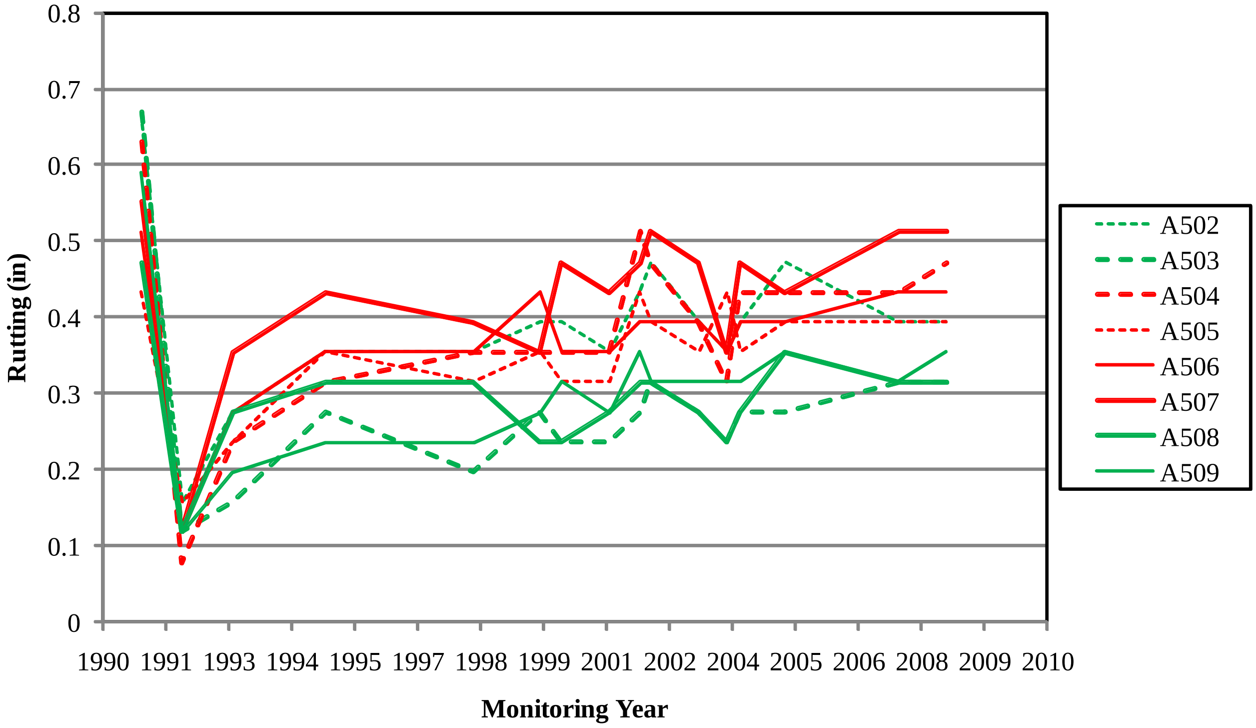

Figure 2: Rutting of Texas SPS-5 Pavement Structures.

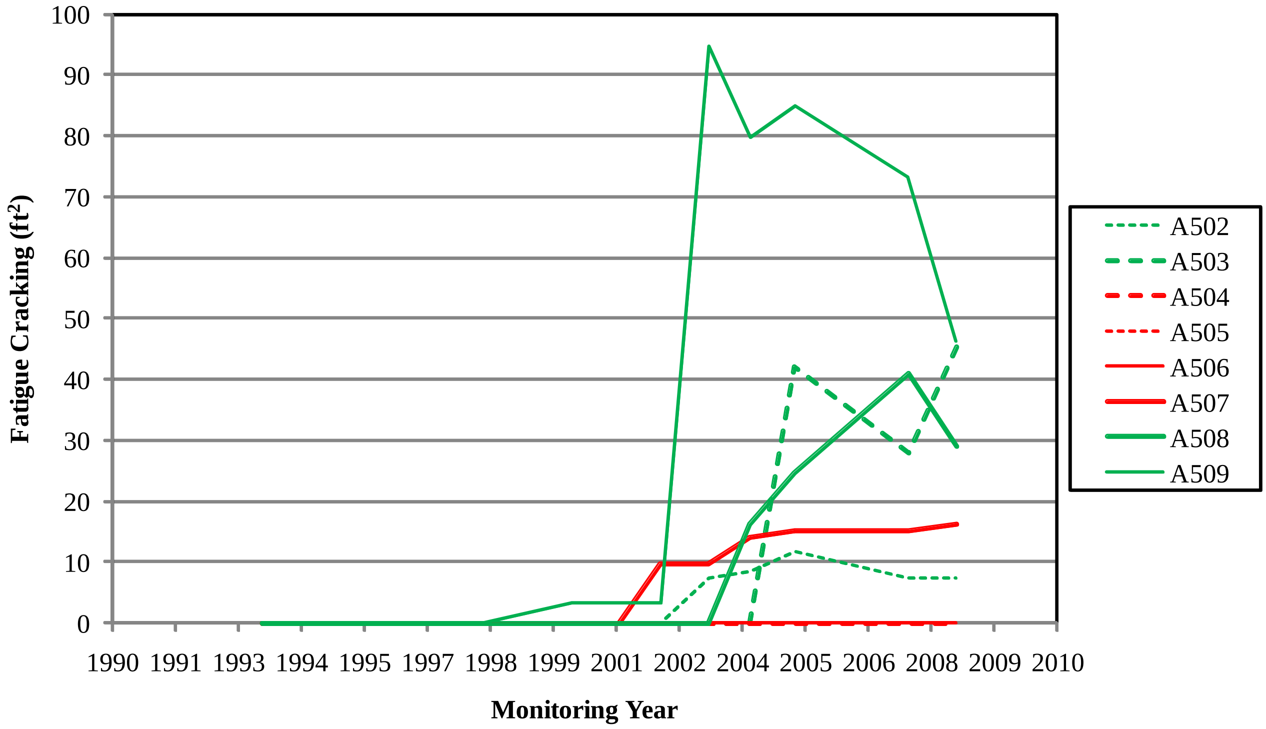

Figure 3: Fatigue Cracking of Texas SPS-5 Pavement Structures.

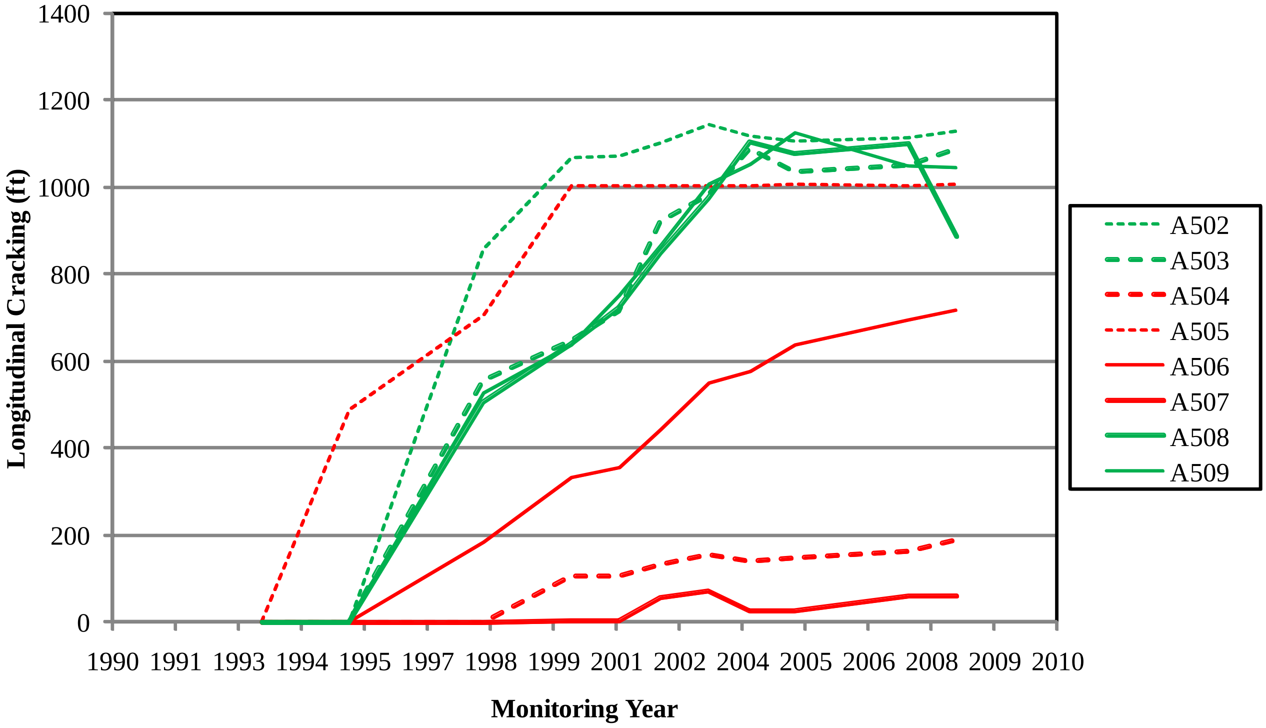

Figure 4: Longitudinal Cracking of Texas SPS-5 Pavement Structures.

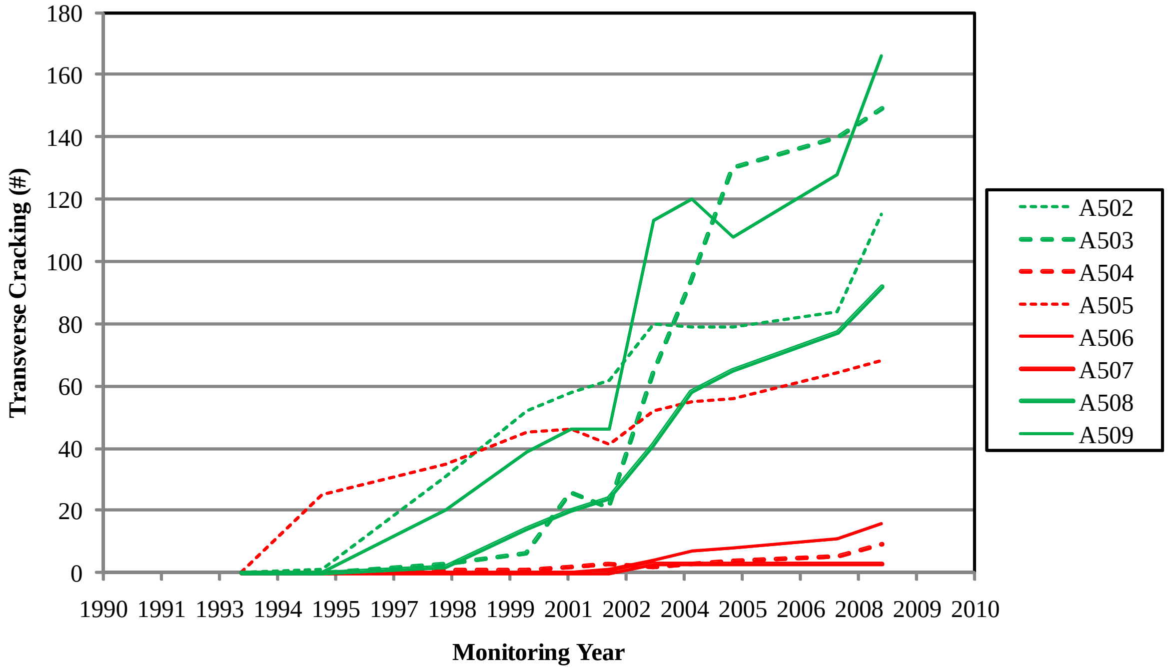

Figure 5: Transverse Cracking of Texas SPS-5 Pavement Structures.

Contrary to the case of rutting, it can be seen from Figures 3 through 5 that the pavement sections with RAP consistently exhibit earlier cracking initiation (alligator, longitudinal, and transverse cracking) plus a faster cracking progression rate, when compared to pavement sections where RAP was not included. In the case of fatigue cracking, two of the pavement sections with no RAP (thin overlay with and without milling) did not develop alligator cracking during the entire observation period. Similarly, in the case of transverse cracking three of the pavement sections with no RAP (thick overlay with and without milling, and thin with milling) have developed very few transverse cracks at a slower rate than the remaining pavement sections that include RAP.

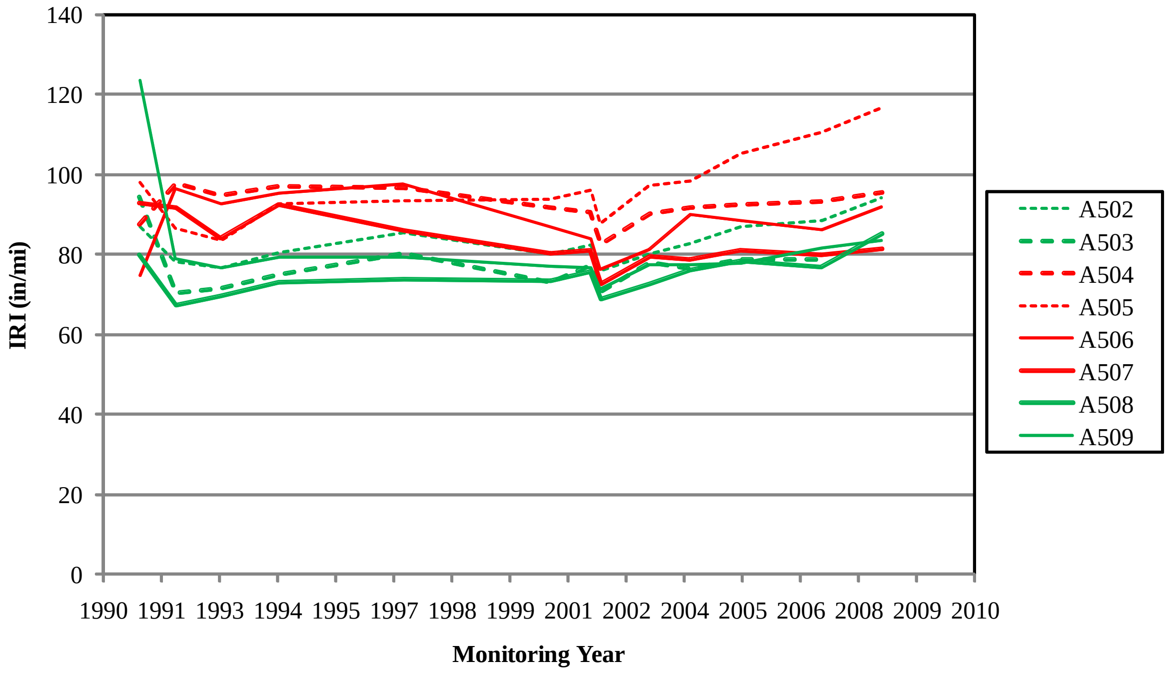

Figure 6: Roughness of Texas SPS-5 Pavement Structures.

Figure 6 shows IRI for the analyzed pavement sections. It can be observed that most of the sections have exhibited very constant roughness during the analysis period. It can be concluded that the pavement sections with RAP have on average an IRI value of approximately 10 in/mi lower than that of the pavement sections with no RAP. The difference is due mainly to the pavement sections with no RAP, where no milling was performed prior to rehabilitation. Higher IRI on the pavement sections with no RAP was somewhat expected because of the significant effect that rutting has on the roughness of the pavement structure, thereby increasing the IRI values of the sections with no RAP.

3 MODELING THE PERFORMANCE OF SPS-5 SECTIONS

When performing economic comparisons and evaluations of HMA overlays with or without RAP, as well as other properties, it is necessary to develop models that can accurately predict the performance of the pavement structures. Two simple models were developed: a rutting model and a transverse cracking model.

The rutting model that has been proposed in the current study is similar to that developed by Hong et al. (2010). The model corresponds to a rutting progression model that is intended to capture the incremental rutting after the initial observation (rutting at time t = 0). The functional form of the model is as follows,

$$Rut - Rut_0 = (\beta_1 + \beta_2 Mill + \beta_3 TH)t^{\beta_4 + \beta_5 RAP} \qquad \text{Eq. 1}$$

Where:

Rut : rutting at time t = T (in)
Rut_0 : rutting at time t = 0 (in)
Mill : 1 if milling was performed, Mill = 0 otherwise
TH : 1 if the overlay is thick, TH = 0 otherwise
RAP : 1 is RAP was used in the HMA mix, RAP = 0 otherwise
t : time (years)
β_1-β_5 : regression parameters.

The model parameters have been estimated by means of non-linear least squares (NLS) using Matlab based on the SPS-5 dataset. The model estimates are shown in the following table.

Table 1: Rutting Model Parameter Estimates

Parameter	Mean	Standard Error	t - Statistic
β_1	0.124	0.0129	9.6
β_2	0.0096	0.0060	1.6
β_3	0.0176	0.0061	2.8
β_4	0.309	0.0419	7.4
β_5	-0.178	0.0199	-8.9

From the model estimates it can be concluded that the effect of milling is not significant at the 95% level of confidence. The effect of the thickness of the overlay is significant, based on the previous level of confidence. However, based on the model estimates, the use of RAP has the highest effect on the rutting progression of the pavement structure. Figure 7 shows a comparison of the average performance predicted by the model for all the pavement sections, with and without RAP.

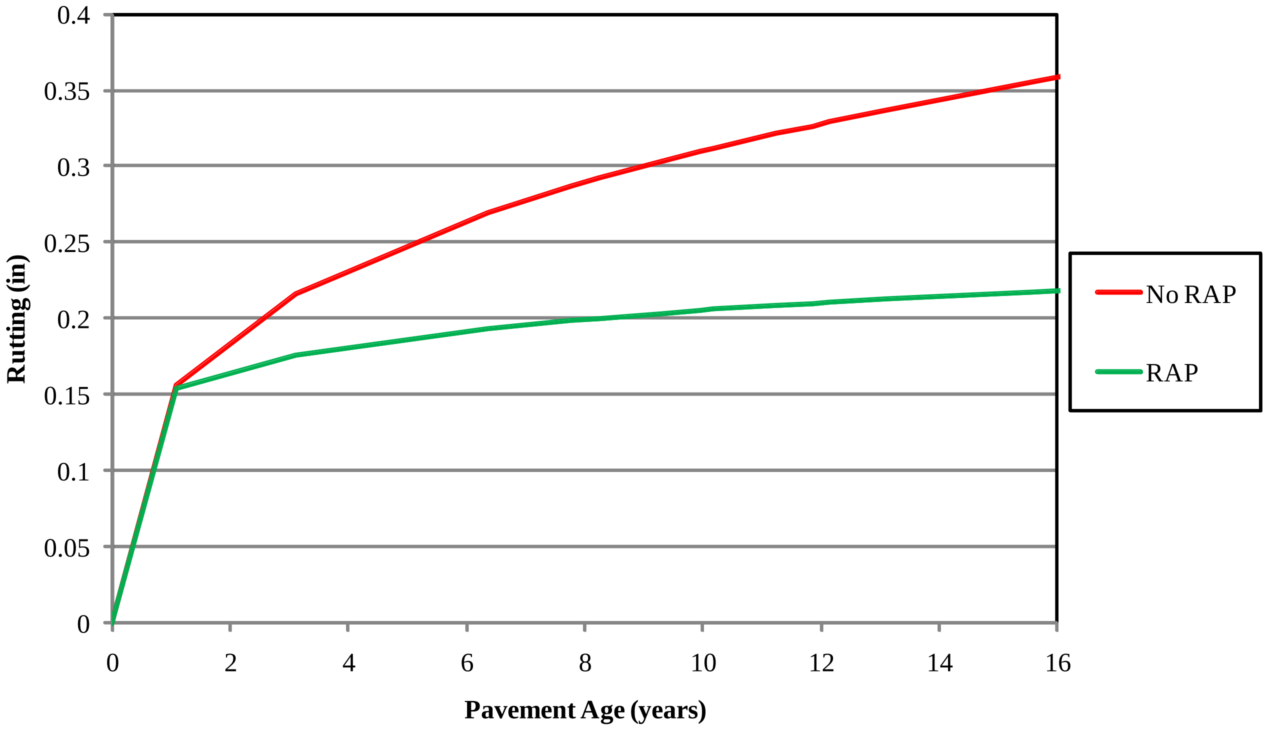

Figure 7: Rutting Progression on a Pavement with a Thick Overlay (with Milling Prior to Overlaying).

The transverse cracking model proposed for the present analysis is a Heckit-type model that consists of two separate models or components: a crack initiation model and a crack progression model. The functional form of the model is the following,

$$Prob(Crack?|Mill, TH, RAP, T) = \Phi(\alpha_1 + \alpha_2 Mill + \alpha_3 TH + \alpha_4 RAP + \alpha_5 t) \quad \text{Eq. 2}$$

$$Crack = \gamma_1 + \gamma_2 Mill + \gamma_3 TH + \gamma_4 RAP + \gamma_5 t \quad \text{Eq. 3}$$

Where:
Crack?: 1 if transverse cracking has occurred, Crack? = 0 otherwise
$\Phi(\cdot)$: normal cumulative density function.
Crack : number of transverse cracks
Mill : 1 if milling was performed, Mill = 0 otherwise
TH : 1 if the overlay is thick, TH = 0 otherwise
RAP : 1 is RAP was used in the HMA mix, RAP = 0 otherwise
t : time (years)
α_1-α_5 : regression parameters
γ_1-γ_5 : regression parameters

In the above model, Equation 3 or the amount of cracking is conditional on whether cracking has initiated or not, which is defined by Equation 2. Equation 2 represents the probability that a given pavement structure has cracked, and for the modeling specification has been assumed to follow a normal distribution. The previous type of joint model is usually referred to as a Heckit model. It is estimated in a two-step procedure which involves initially estimating the crack initiation model (Equation [2]), and then using information from the initial estimation ($\lambda(\alpha_i \mathrm{X}_i) = \frac{\phi(\alpha_i \mathrm{X}_i)}{\Phi(\alpha_i \mathrm{X}_i)}$, where $(\alpha_i \mathrm{X}_i) = \alpha_1 + \alpha_2 \mathrm{Mill} + \alpha_3 \mathrm{TH} + \alpha_4 \mathrm{RAP} + \alpha_5 \mathrm{t}$ and $\phi(\cdot)$ is the normal density function) in the estimation of the crack progression model. For more details on the Heckit model, please refer to Heckman (1976).The estimation procedure was coded in Matlab and was used to estimate the model parameters shown in Table 2.

Table 2: Transverse Cracking Model Parameter Estimates

Crack Initiation				Crack Progression			
Parameter	**Mean**	**Standard Error**	**t - Statistic**	**Parameter**	**Mean**	**Standard Error**	**t - Statistic**
α_1	-45.8	12.2	-3.7	γ_1	-2.68	1.09	-2.4
α_2	-21.3	6.37	-3.3	γ_2	-3.90	1.47	-2.6
α_3	-27.9	6.04	-4.6	γ_3	-1.23	0.772	-1.6
α_4	56.4	6.24	9.0	γ_4	2.75	1.07	2.6
α_5	8.09	1.06	7.6	γ_5	0.901	0.289	3.1

From the model estimates it can be concluded that, for the case of crack initiation, both milling prior to overlaying and the thickness of the overlay have a significant positive effect (both of the previous factors decrease the probability that the pavement will crack at time t). Inversely, the use of RAP has the highest impact on the crack initiation of the pavement structure (using RAP highly increases the probability of cracking).

Then, based on the estimates from cracking progression model, it can be concluded that milling prior to overlaying results in a lower number of transverse cracks, while adding RAP to the HMA mix increases the number of transverse cracks. Figure 8 shows a comparison of the performance predicted by the model for a pavement section with and without RAP.

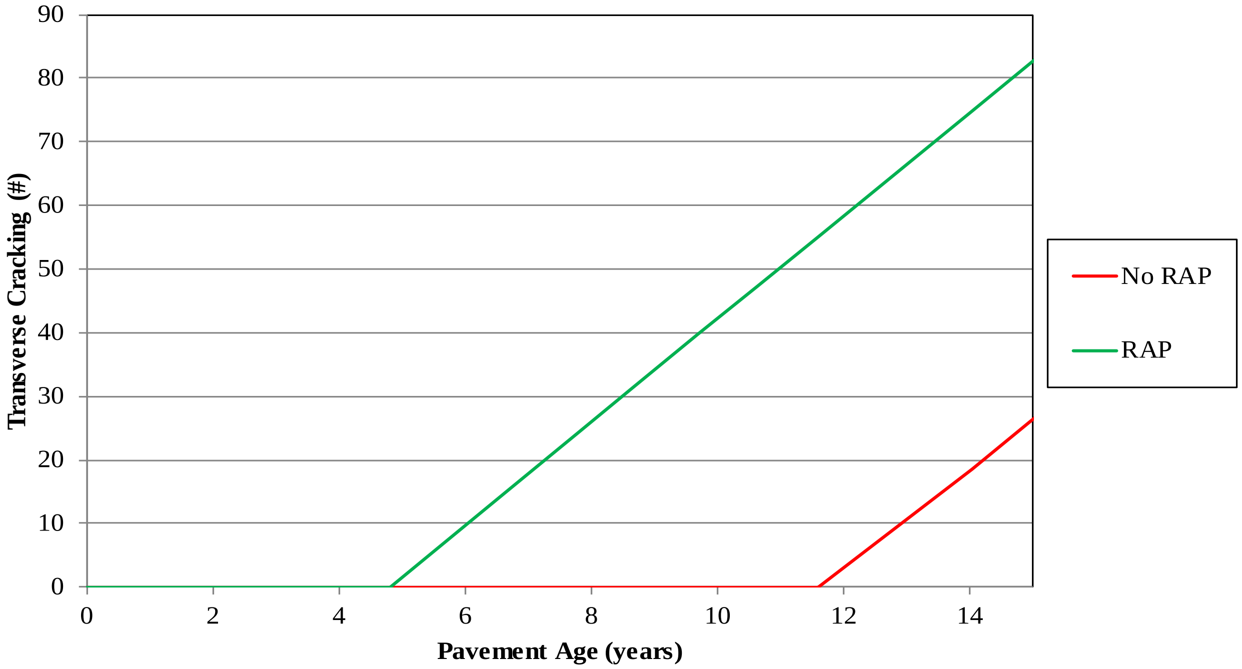

Figure 8: Transverse Cracking Progression on a Pavement with a Thick Overlay(with Milling Prior to Overlaying).

3.1 Predicting Pavement Life

In order to use the previous models to estimate pavement life, it is necessary to previously define what level of deterioration can be considered as failure. This is a fundamental requirement in estimating pavement life, which is very sensitive to changes in the selected failure threshold.

In the case of rutting, the MEPDG recommendation of 0.20 in of rutting of the asphalt layer was adopted as rut depth failure level. Based on this criterion, a pavement structure, whose surface rutting has increased by 0.20 in since initial monitoring of the pavement section, will be considered as failed. With regards to transverse cracking, the criteria that will be selected to define failure is5 cracks per 100 ft station. This can be translated to 25 cracks in a normal LTPP section that measures 500 ft. These two criteria have been selected somewhat arbitrarily but the results and analysis that follows is consistent when other reasonable failure levels are selected. Each agency should select failure according to their practice.

Based on the previously defined deterioration models and failure criteria, the estimated life of the pavement sections of interest can be summarized in Figure 9. It can be observed that milling prior to overlaying increases the life expectancy of the pavement structure when no RAP is used in the mix. In the case where RAP is used, the effect of milling is reversed. Furthermore, the expected increasing trend of pavement life as a function of overlay thickness can be verified for the case of pavement where RAP was used. The reverse trend is observed in pavements with no RAP (However, this trend can be verified by observing the actual field cracking and rutting on the SPS-5 sections in Figures 2 through 5.).

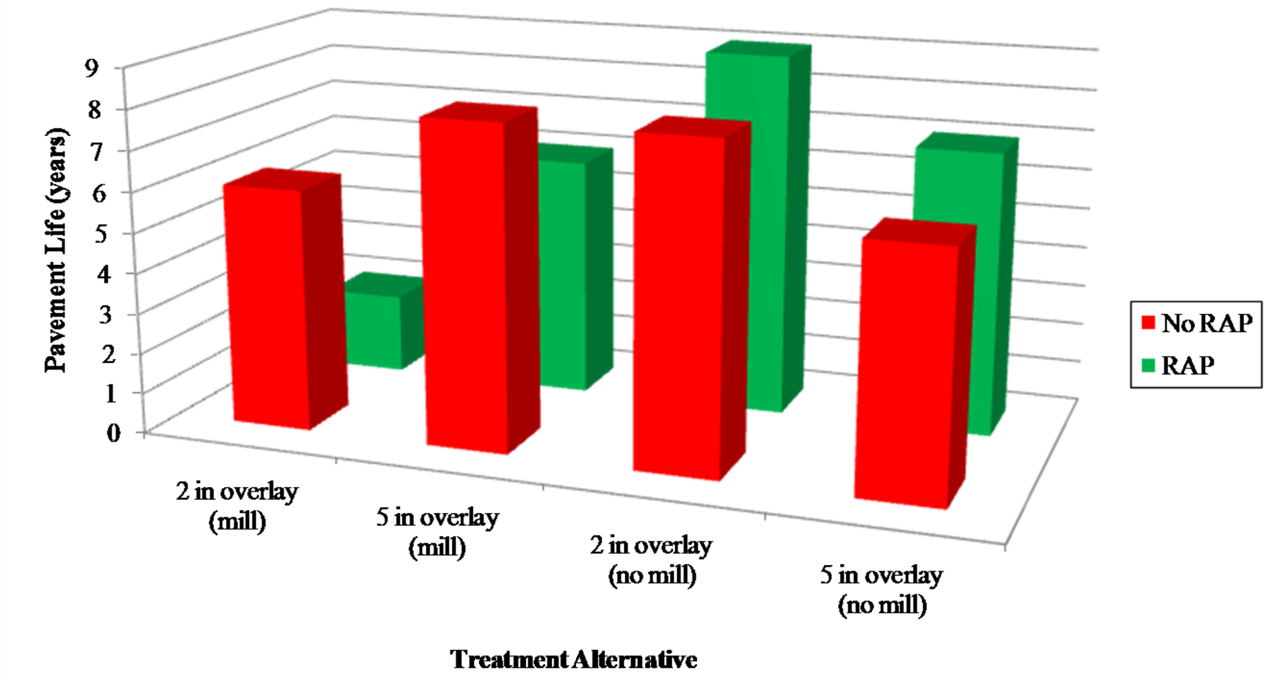

Figure 9: Estimated Pavement Life of Analysis Pavement Sections.

4 ECONOMIC ANALYSIS

In order to perform an economic evaluation of the effect of using RAP in HMA, a life-cycle cost analysis (LCCA) based on Federal Highway Administration recommendations (Walls and Smith, 1998) was performed. The LCCA analysis consists of estimating the net present value (NPV) of a given alternative as follows:

$$\text{NPV} = \text{Initial Construction Cost} + \sum_{k=1}^{N} (\text{Rehabilitation Cost})_k \left[\frac{1}{(1+i)^{n_k}}\right] \qquad \text{Eq. 4}$$

Where:
i : discount rate
n : year in which the given rehabilitation cost is incurred

The present value of the construction and rehabilitation costs should consider both the agency cost and the user costs. The agency costs are directly related to the costs incurred by the agency over the service life of the pavement structure, ranging from the initial engineering design costs to the actual costs of constructing and maintaining the pavement structure. Because all the alternatives are considered mutually exclusive, only the costs that are different between alternatives are considered. There are additional costs that can be incurred by the agency at the end of the service life of the pavement structure, such as the salvage value of the pavement structure. This negative cost will be neglected in the current analysis.

Under the assumption that the underlying structure of the pavements to be analyzed is the same, the only difference in material costs between the different alternatives will be due to the use of RAP on the overlay layer. Based on TxDOT average low bid unit price, a Type C HMA mix with RAP has been assumed to have a cost of approximately $49.60/ton (PG76-22 binder with RAP), while a Type C HMA mix with no RAP has been assumed to have a cost of approximately $57.42/ton (PG64-22 virgin binder) in 2010 US dollars.

The user costs are costs that are directly incurred by and affect the user, such as vehicle operating costs (change in speed, number of stops, additional miles, and hours of idling), user delay costs, and crash costs (Walls and Smith, 1998). The differential user costs are estimated by multiplying the different user costs incurred due to a construction or maintenance / rehabilitation strategy by the unit cost of each of these components. Expressed in 2010 dollars, the following values of time have been assumed based on FHWA's recommendations (Walls and Smith, 1998):

- passenger vehicle: $17.72
- single-unit truck: $28.37, and
- combination truck: $34.13.

Additionally, in order to estimate the remaining costs on the user, the following assumptions (Table 3) of free flow traffic and traffic under the work zone have been used based on Walls and Smith (1998).

The comparison between the pavement sections to be analyzed has been performed for a 20-year design period under the following two assumptions:

- The initial cost of construction of the overlay is equal to the cost of the rehabilitation for a given pavement section.

- The deterioration rates of the subsequent rehabilitation strategies are equal to that of the initial overlay.

Table 3: Traffic Inputs Required for the Estimation of User Costs

Traffic Parameter	Value
AADT Construction Year (two-direction)	9,380
Single Unit Trucks (%)	5.23
Combination Trucks (%)	12,22
Annual Growth Rate of Traffic (%)	3
Speed Limit (mph)	65
Lanes in each direction	2
Free Flow Capacity (vphpl)	2,017 (*)
Queue Dissipation Capacity (vphpl)	1,818 (*)

(*) Based on Highway Capacity Manual recommendations.

Finally, the NPV of the different alternatives has been estimated by means of FHWA's RealCost software. The results are summarized in Figure 10. In the case of thick overlays, the long-term costs of using RAP in the mix appear to be similar to the costs when no RAP is included in the mix. However, in the case of the thin pavement structure there is a clear economic benefit for not using RAP in the long run.

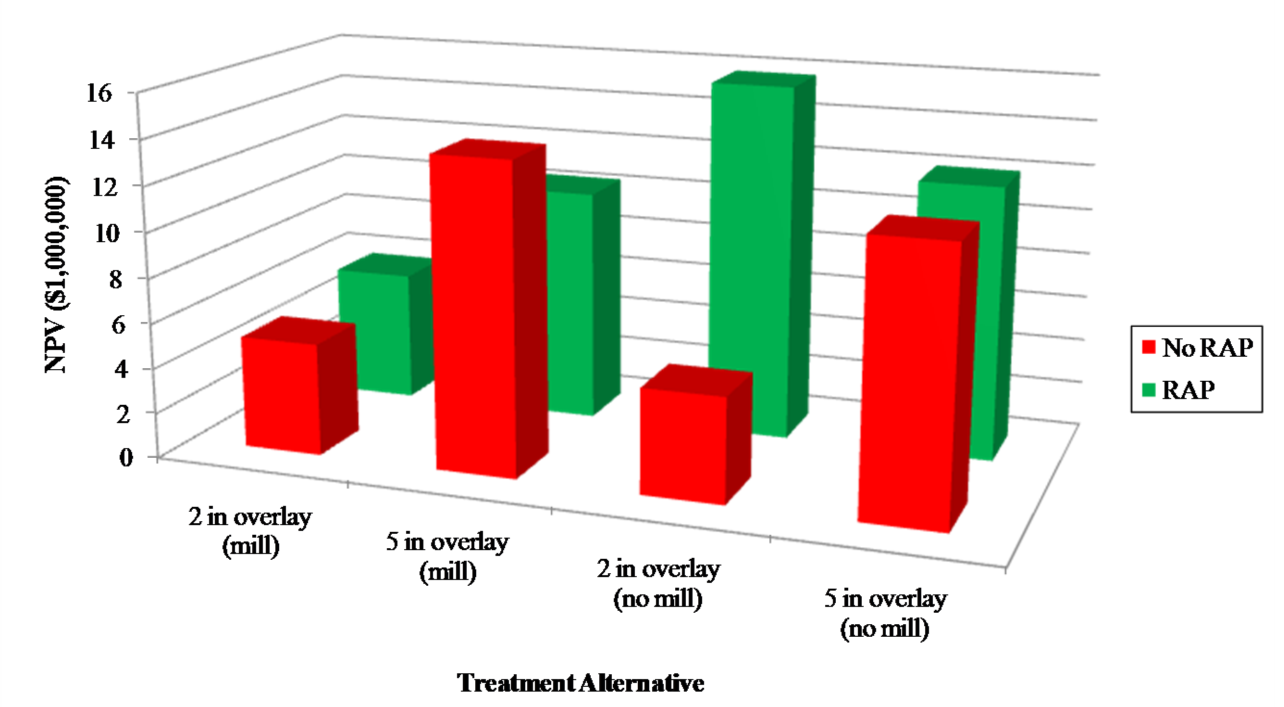

Figure 10: NPV of Total Costs for the Different Alternatives.

5 CONCLUSIONS

The intention of the paper is not to support the reduction in the use RAP in the construction and rehabilitation of pavements structures. It is clearly established in the literature that there are significant short-term advantages and environmental benefits, in addition, in many cases there are also significant economic advantages. However, we need to better understand and consider the long-term implication of using RAP. In particular, we need to study its effect of pavement cracking.

The authors wish to emphasize that pavement designers need to be cautious with the use of RAP and to take into consideration that pavement structures with RAP might deteriorate faster in the long run, mainly in cases where RAP is used in thin overlays. Increasing RAP percentages is not always the solution. Consequently, it is important that proper deterioration models be developed and calibrated for the different regions where RAP is used so that proper economic analysis is applied for determining whether or not to use RAP in each specific project. Pavement managers should consider that using RAP today may result in initial construction savings, but the long-term maintenance and rehabilitation costs might overshadow these initial benefits.

Although we agree that this analysis was based on a relatively small sample, the authors have seen similar trends on other in-service pavements. With LTPP having reached its 20-year milestone, there is now a large database available to perform similar analyses in other states. Let us use these data to develop stronger statistics and let us use lifecycle cost analysis to decide how much and when RAP should be really used. It should also be emphasized that RAP technology has significantly evolved since the inception of LTPP, therefore, more long-term performance data are needed to validate and verify these results with today’s RAP. In particular, attention should be paid to the use of higher percentages of RAP, the use of fractionated RAP and the use of recycled asphalt shingles (RAS).

As previously mentioned, and as has been demonstrated in this paper, there are definite benefits of using RAP against rutting failure. This practice should be continued. However, there are reliable data indicating that pavements where RAP has been used exhibit shorter pavement lives in terms of cracking. Additionally, the LTPP SPS-5 data for the Texas sections also indicates that the rate of cracking is higher in pavements containing RAP. It is recommended that pavement designers exercise prudence in terms of using RAP while simultaneously lowering PG grades.

REFERENCES

Abdulshafi, O., Kedzierski, B., and Fitch, M.G. (2002).*Determination of Recycled Asphalt Pavement (RAP) Content in Asphalt Mixes Based on Expected Mixture Durability*. Final report submitted to the Ohio Department of Transportation.

Goh, S.W., and You, Z. (2008).*Properties of Asphalt Mixtures with RAP in the Mechanistic-Empirical Pavement Design of Flexible Pavements: A Preliminary Investigation*. Proceedings of the 2008 Airfield and Highway Pavements Conference

Hajj, E.Y., Sebaaly, P., and Kandiah, P. (2010).*Evaluation of the Use of Reclaimed Asphalt Pavement in Airfield HMA Pavements*. Journal of Transportation Engineering, Vol. 136, No. 3, pp. 181 – 189.

Heckman, J. 1976. The *common structure of statistical models of truncation, sample selection, and limited dependent variables and a simple estimator for such models*. Annals of Economic and Social Measurement, Vol. 5, pp. 475 – 492.

Hong, F., and Chen, D.H. (2009).*Effects of surface preparation, thickness, and material on asphalt pavement overlay transverse crack propagation*. Canadian Journal of Civil Engineering, Volume 36, No. 9, pp. 1411 – 1420.

Hong, F., Chen, D., and Mikhail, M. (2010).*Long-term performance evaluation of recycled asphalt pavement based on Texas LTPP SPS5 test sections.* Paper accepted for publication on the Transportation Research Record.

Lachance, M.A. (2002). *Properties of Asphalt Mixtures Containing RAP*. Master's Thesis. University of New Hampshire.

McDaniel, R., and Anderson, R.M. (2001).*Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual*. National Cooperative Highway Research Program, NCHRP Report 452. Washington, DC.

Newcomb, D.E., Brown, E.R., and Epps, J.A. (2007).*Designing HMA Mixtures with High RAP Content. A Practical Guide*. National Asphalt Pavement Association, NAPA Quality Improvement Series 124. Lanham, MD.

Sondag, M.S., Chadbourn, B.A., and Drescher, A. (2002).*Investigation of Recycled Asphalt Pavement (RAP) Mixtures*. Minnesota Department of Transportation MN/RC – 2002-15.

Tabakovíc, A., Gibney, A., McNally, C., and Gilchrist, M.D. (2010).*Influence of Recycled Asphalt Pavement on Fatigue Performance of Asphalt Concrete Base Courses*. Journal of Materials in Civil Engineering, Vol. 22, No. 6, pp. 643 – 650.

TxDOT (2004).*Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges*. Texas Department of Transportation.

Valdés, G., Pérez, F., Miró, R., and Martínez, A. (2010).*Experimental Study of Recycled Asphalt Mixtures with High Percentages of Reclaimed Asphalt Pavement (RAP)*.Proceedings of the Annual Meeting of the Transportation Research Board. Washington, DC.

Walls III, J., and Smith, M. R. (1998). Life-Cycle Cost Analysis in Pavement Design – In Search of Better Investment Decisions. Federal Highway Administration Interim Technical Bulletin No.FHWA-SA-98-079. Washington, DC.

Watson, D.E., Vargas-Nordcbeck, A., Moore, J., Jared, D., and Wu, P. (2008).*Evaluation of the Use of Reclaimed Asphalt Pavement in Stone Matrix Asphalt Mixtures*. Transportation Research Record No. 2051, pp. 64 – 70.

West, R., Kvasnak, A., Tran, N., Powell, B., and Turner, P. *Testing of Moderate and High Reclaimed Asphalt Pavement Content Mixes. Laboratory and Accelerated Field Performance Testing at the National Center for Asphalt Technology Test Track*. Transportation Research Record No. 2126, pp. 100 – 108.

Ziari, H., and Khabiri, M.M. (2005).*Effect of Bitumen and RAP Content on Resilient Modulus of Asphalt Concrete*. Proceedings of the International Symposium on Pavement Recycling. São Paulo, Brazil.