Evaluation of the Performance of Recycled Asphalt Sections in California Environmental Zones

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ABSTRACT
The California Department of Transportation (Caltrans) initiated a study to evaluate the performance of in-service pavements in California, and hence the success of Caltrans' pavement design and rehabilitation procedures. This effort also included the investigation of the field performance of special materials, such as Rubber Asphalt Concrete (RAC), Recycled Asphalt Pavement (RAP), Pavement Reinforcing Fabric (PRF) and many other special materials and treatments.

As part of this study, sixty Recycled Asphalt Pavement (RAP) test sections located in three of California's environmental zones – Desert (DS), Mountain (MT) and North Coast (NC) – along four routes (one in each of Caltrans' Districts 1, 7, 9 and 11) were considered. Deflection, roughness, distress and cores/bores were among the data attributes collected from the test sections. Laboratory tests were also performed on the cores recovered from the field. Analysis was performed on the data collected from these sections to evaluate the performance of RAP in different environmental zones. This analysis was focused mainly on the actual field performance rather than laboratory predicted performance. In this analysis, the field performance was evaluated with respect to the in-situ structural capacity, distress condition, roughness condition and consistency of construction. This paper describes the observed field performance of the RAP sections, as well as the results of the evaluation analysis, and compares the performance of the RAP sections by environmental zone.

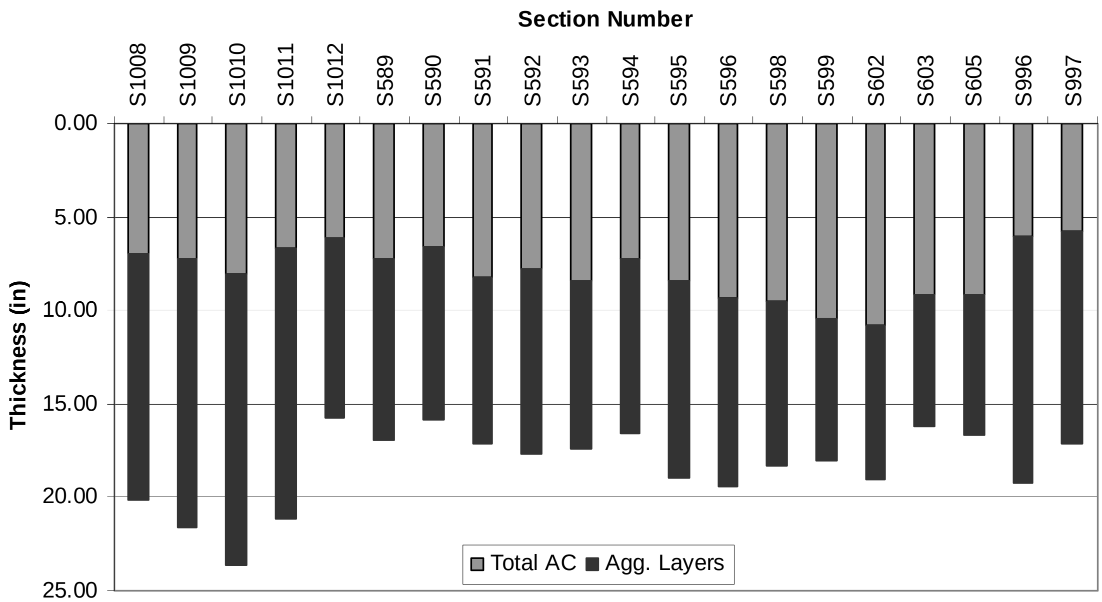
INTRODUCTION

The California Department of Transportation (Caltrans) initiated a study to evaluate the performance of in-service pavements in California, and hence the success of Caltrans' pavement design and rehabilitation procedures. This effort also included the investigation of the field performance of special materials, such as Rubber Asphalt Concrete (RAC), Recycled Asphalt Pavement (RAP), Pavement Reinforcing Fabric (PRF) and many other special materials and treatments. Several test sections were selected and tested as a part of this study. Deflection measured using Falling Weight Deflectometers (FWD), roughness measurements, in terms of the International Roughness Index (IRI), distress surveys, and cores/bores were among the data attributes collected from the test sections. Laboratory tests were also performed on the cores recovered from the field. These laboratory tests included bulk specific gravity, maximum specific gravity (RICE), asphalt content and the gradation aggregate.

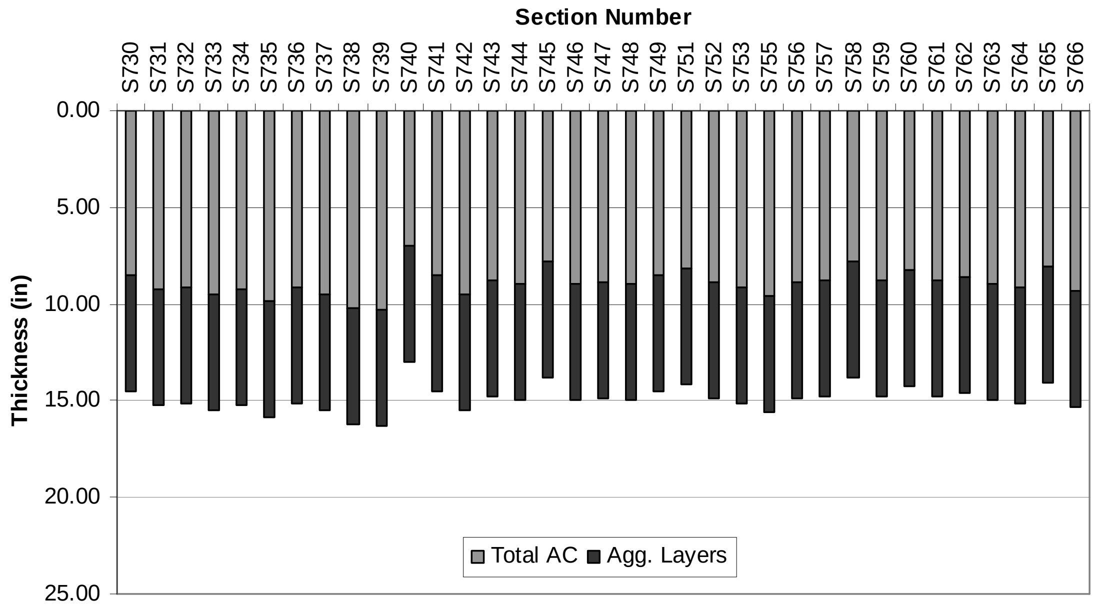
Caltrans' specifications allow the use of 15% reclaimed asphalt pavement as a substitute for virgin aggregate mix in hot asphalt concrete mix. This represents the default case for the RAP sections included in this study. Sixty RAP sections located in three of California's environmental zones – Desert (DS), Mountain (MT) and North Coast (NC) – along four routes (one in each of Caltrans' Districts 1, 7, 9 and 11) were considered in the study. Five of these sections have a Cement Treated Base (CTB), while the rest of the sections have an aggregate base course. Analysis was performed on these sections to evaluate the performance of RAP in different environmental zones. This analysis was focused mainly on the actual field performance rather than laboratory predicted performance. In this analysis, the field performance was evaluated with respect to the in-situ structural capacity, distress condition, roughness condition and consistency of construction. This paper describes the observed field performance of the RAP sections, as well as the results of the evaluation analysis, by environmental zone. The environmental zones referred to in this paper are as defined by University of California, Berkley, in 2000 (*1*).

RECYCLED ASPHALT PAVEMENT (RAP) SECTIONS

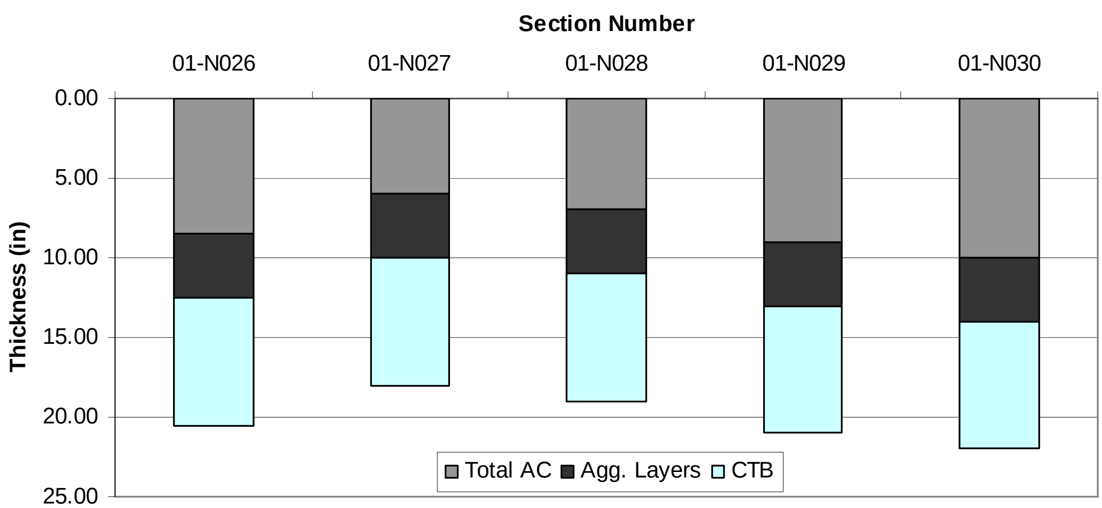
Figures 1 a to c show the in-situ layer thickness, as determined from the cores/bores, for the RAP test sections located in the DS, MT and NC environmental zones, respectively. As can be seen, these sections cover a wide range of layer thicknesses. The total Asphalt Concrete (AC) thickness ranges from 5.76" to 10.8", while the total aggregate thickness ranges from 4" to 15.6". The total pavement thickness above the subgrade ranges from 13" to 24". The age of the RAP sections considered in this study ranged from 5 to 9 years. As such, age adjustment was applied to bring all sections to the same age, 5 years, to allow fair comparisons.



a) Desert environmental zone.



b) Mountain environmental zone.



c) North Coast environmental zone.

FIGURE 1 In-situ layer thickness of RAP sections.

PERFORMANCE EVALUATION CRITERIA

A comprehensive evaluation of the field pavement performance was conducted in this study. This evaluation included both the structural and functional performance of the sections, as well as the construction consistency. For the purposes of the evaluation presented in this paper, the following four performance indices were utilized:

- Structural Adequacy Index (SAI)
- Roughness Index (RI)
- Distress Index (DI)
- Construction Consistency Index (CCI)

Structural Adequacy Index (SAI)

The structural capacity of a pavement describes its ability to support the applied loads. During the design process of a pavement section, the section's structural capacity is selected such that it is sufficient to carry the expected cumulative traffic. In this project, the in-situ structural capacity of the test sections was evaluated through FWD measured deflections. Backcalculation analysis was performed to evaluate the in-situ pavement properties from the measured deflections and the core/bore layer thickness. These mechanical properties were subsequently used to evaluate the structural adequacy of the existing pavement sections and to compare different sections. The backcalculated properties include:

- The subgrade Resilient Modulus (M_R)
- The pavement Effective Elastic Modulus (E_p)
- The Effective Structural Number (SN_{eff}) and effective Gravel Equivalent (GE_{eff}) of the pavement structure.

In general, pavement sections subjected to higher traffic volumes have a higher rate of deterioration. Consequently, thicker pavements with higher quality materials are required for high traffic facilities. Therefore, it is not feasible to compare the structural capacity of two pavement sections subjected to different traffic levels, such as a major interstate highway (e.g. I-5) and a low volume rural road, without taking the traffic effects into consideration.

A Structural Adequacy Index (SAI) was developed to account for the difference in designed pavement structures that results from the differences in expected traffic. This index was developed by normalizing the effective structural capacity from the backcalculation analysis with respect to the design structural capacity. As the expected traffic is used as input in the design process of any given pavement section, normalizing the structural capacity using the design capacity creates a relative index for evaluating the deterioration of the structural capacity of the pavement sections.

SAI was developed by normalizing the effective Gravel Equivalent (GE_{eff}), which evaluates the in-situ structural capacity of the pavement section in its current condition, with respect to the gravel equivalent calculated based on the as-built pavement structure ($GE_{as\text{-}built}$). The GE_{eff} is backcalculated from FWD testing. The $GE_{as\text{-}built}$ is calculated from core/bore results by summing the product of each layer thickness and its corresponding equivalent gravel factors (G_f). SAI allows pavement sections subject to different traffic loads to be compared, as each section is evaluated relative to its design conditions. SAI is calculated using the following equation:

$$SAI = \frac{GE_{eff}}{GE_{asbuilt}} \quad [1]$$

The key benefit of using the SAI is that it eliminates the effect of the difference in the designed pavement structure, which is based on the expected traffic, on the pavement actual structural performance. Therefore, SAI can be used to evaluate the deterioration of the layers' material properties by normalizing them with respect to the design conditions in terms of the design gravel equivalency factors. SAI uses a scale of 0.0 to 1.0, with a value of 1.0 representing the expected SAI value for a new pavement section. As time passes, pavement sections start to deteriorate due to traffic and environmental effects. For the purposes of the current analysis, a pavement section is assumed to be triggered for rehabilitation when its SAI reaches a value of 0.5. A typical SAI age deterioration model is represented by the upper curve in Figure 2. This curve was developed during the first phase of the California pavement performance study using data from around 1,000 test sections (*2*).

Distress Index (DI)

Although detailed distress data was collected in this project, for the purposes of this study a single index representing the overall distress condition of a section was needed to allow sections with different distress types, severities and extents to be compared. The Pavement Condition Index (PCI) is the index most commonly used to evaluate overall distress condition. However, in this study a re-scaled version of PCI, Distress Index (DI), was used to be consistent with other performance indices. DI uses a 0.0 to 1.0 scale, with 1.0 being a perfect section and 0.5 being the value used as a trigger for rehabilitation. Age deterioration models similar to that shown in Figure 2 for SAI were also developed for DI.

Roughness Index (RI)

Ride quality, which is highly correlated with longitudinal roughness, is the most important performance parameter in the user opinions. Traditionally, roughness used to be evaluated in terms of a Pavement Serviceability Index (PSI).

However, more recently, the Federal Highway Administration (FHWA) adopted IRI as their roughness index. IRI data was collected from all sections considered in this study. However, using IRI in its current form in this study was not possible because of the uniqueness of its scale. To ensure consistency with other performance indices used in this study, IRI data was re-scaled to fit a 0.0 to 1.0 scale, with 1.0 being a perfect section and 0.5 being the value used as a trigger for rehabilitation. An exponential formula was used for these purposes, in the form of:

$$RI = (a)e^{IRI^{(b)}} \quad [2]$$

where a and b are constants.

This re-scaling resulted in a Roughness Index (RI), which is used in this study. Age deterioration models similar to that shown in Figure 2 for SAI were also developed for RI.

Construction Consistency Index (CCI)

Evaluating the overall construction quality of a pavement section with respect to performance is not an easy task as a large number of parameters can affect the quality of constructed pavement sections, such as material properties (air voids, binder contents, gradation, compaction, etc.) and layers' thickness. All these parameters have an impact on the overall pavement performance. A Construction Consistency Index (CCI) that evaluates the variability in the in-situ structural capacity was developed and used in this study. CCI utilizes FWD data and is based on the variation along the project. CCI is a function of Deflection 1, Deflection 7, the pavement remaining structural life as determined from the FWD results and the backcalculated subgrade Resilient Modulus (M_R). CCI is not impacted by the values of these parameters, but rather by the consistency of the values along a section. For example, a section with relatively high deflection that is consistent along its length will have better CCI than a section with relatively low deflection that shows large variability along its length. CCI uses a scale of 0.0 to 1.0, where 1.0 indicates the highest possible construction quality.

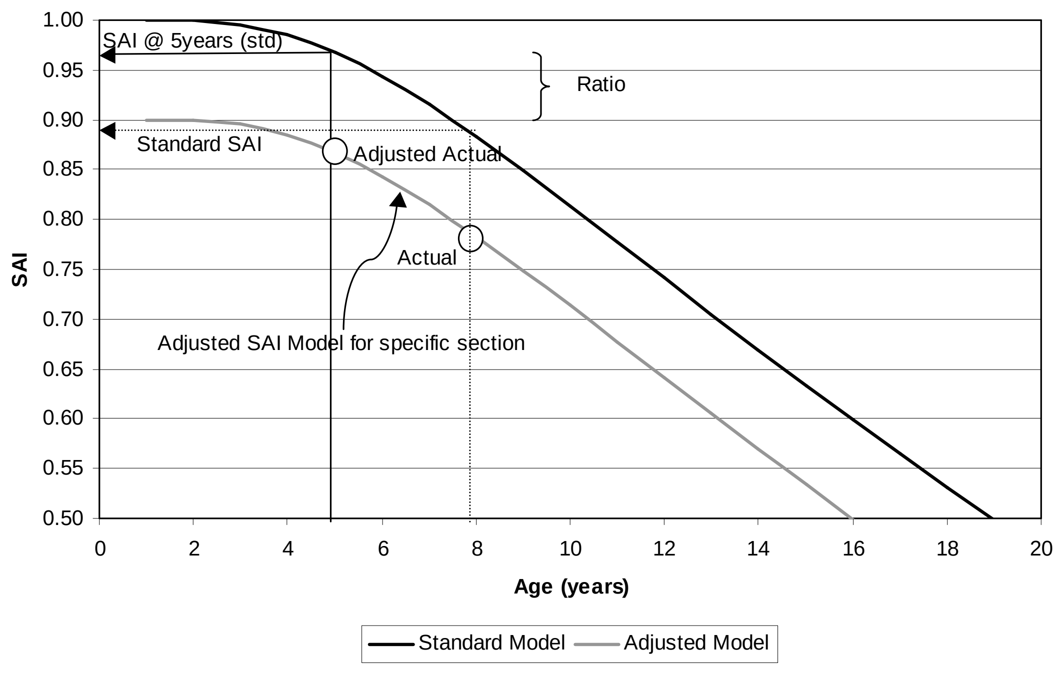


FIGURE 2 Age adjustment for SAI.

EVALUATION OF THE RAP SECTIONS

As mentioned above, the 60 RAP sections considered in this study had been in service for 5 to 9 years. Since the sections had different ages and since pavements deteriorate with time, an age adjustment was required to allow a fair comparison of their performance. The age adjustment was performed on the SAI, RI and DI measurements of different sections to estimate their values at age 5 years. An assumption was made that construction consistency is not expected to change with time. Therefore, no age adjustment was applied to the CCI data. The main difference between the age adjustment performed on the SAI and RI data and that performed on the DI data is that a new pavement may start with less than perfect SAI or RI, i.e. as-built SAI or RI < 1.0. However, this is not the case for DI. An assumption was made that any new pavement will be distress free, i.e. the as-built DI = 1.0.

Adjustment for Age Differences for SAI and RI

Measured SAI and RI were adjusted for all sections and estimated at age 5 years. Figure 2 shows how this adjustment was applied to SAI. A similar approach was followed for RI. The steps followed to account for the age differences among sections can be summarized as follows:

- An assumption was made that the section under consideration was built with adequate initial in-situ structural capacity (SAI_i), i.e. SAI at age 0 = 1.0 (follow the standard SAI curve – upper curve in Figure 2).
- The actual SAI calculated for the section was plotted on the SAI graph (white circle titled "Actual" in Figure 2).
- As can be seen, the "Actual" SAI for the section presented in Figure 2 lies below the standard SAI curve, i.e. this section was built with SAI_i less than 1.0 (standard SAI_i). Therefore, the actual deterioration of this section is expected to be different from that of the standard deterioration.
- A shift was made to the standard SAI deterioration curve to match the actual observed in-situ SAI. The shifted model follows the same shape of the standard SAI deterioration model, but passes through the measured SAI ("Actual"). This shifted model is titled "Adjusted SAI Model for specific section" in Figure 2.
- Using this adjusted model, the SAI at age 5 years was determined, titled "Adjusted Actual" in Figure 2.
- The same procedure was applied for all the sections considered in this study and for both SAI and RI indices.

Adjustment for Age Differences for DI

Similarly to SAI and RI, DI also deteriorates over time. The main difference between the SAI/RI and DI deterioration models is that in case of DI, pavements always start in distress-free condition. Therefore, the initial DI has to be 1.0 at age zero (as-built condition). Age adjustment was applied to all sections to estimate their DI at age 5 years, to be compatible with the adjusted SAI and RI. Figure 3 shows how the age adjustment was applied to DI. The steps followed to account for the age differences among sections can be summarized as follows:

- The standard DI age deterioration curve was plotted on the graph (upper curve in Figure 3)
- The actual DI calculated for the section was then added to the graph (white circle titled "Actual Performance" in Figure 3)
- As can be seen, the "Actual Performance " DI for the section presented in Figure 3 lies below the standard DI curve. However, an assumption is made that the pavement was built with no distresses. Therefore, the actual deterioration of this section is expected to be different from that of the standard deterioration, but still go through DI = 1.0 at age "0". This revised model is titled "Adjusted Model" in Figure 3.
- Using this adjusted model, the DI at age 5 years was determined.

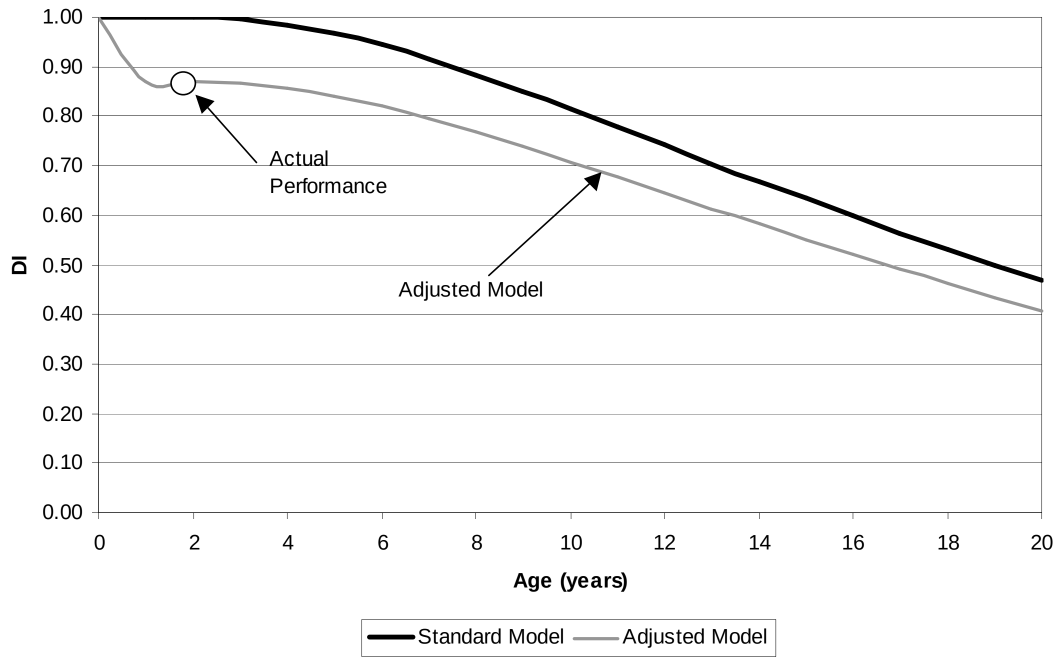


FIGURE 3 Age adjustment for DI.

EVALUATION OF THE PERFORMANCE OF RAP SECTIONS

This section provides an overview of the performance of the 60 RAP sections across the three environmental zones in terms of the 4 performance indicators that were used for the purposes of this evaluation: SAI, DI, RI and CCI. SAI provides information about the in-situ structural capacity relative to the designed structural capacity. DI provides information about the observed surface distresses and their severity and extent. RI provides information about the longitudinal roughness and the ride quality of the section. CCI provides information about the consistency of the construction along the section.

In-situ Structural Performance of RAP Sections - Structural Adequacy Index (SAI)

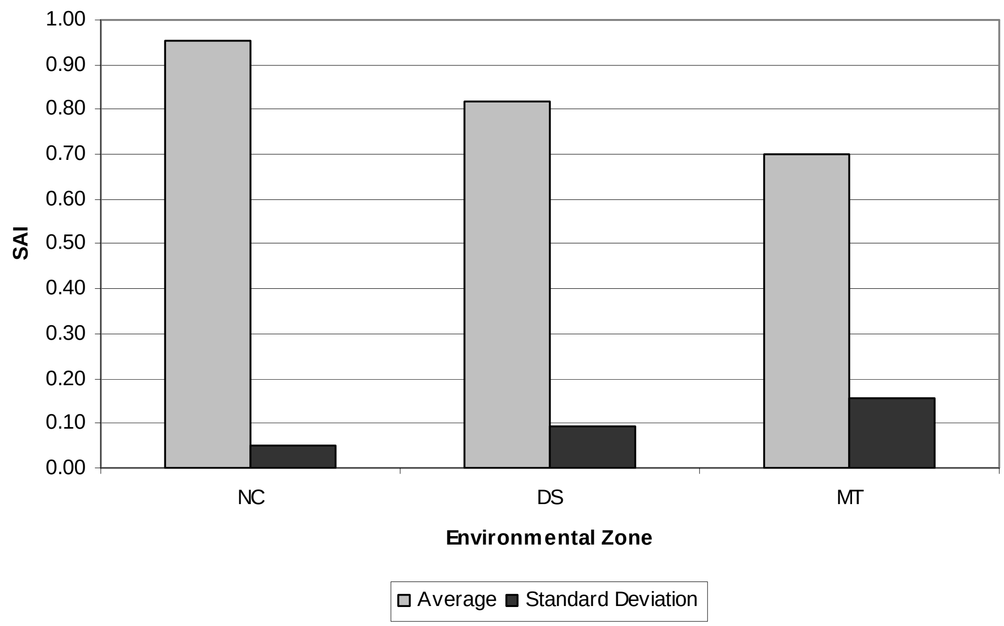
As mentioned above, the SAI at age 5 years (SAI_5) was calculated for all sections and used to compare their structural performance. Figure 4a shows a summary of the SAI_5 values of the 60 RAP sections grouped by environmental zone. As can be seen, the RAP sections in the NC zone are showing higher SAI_5 and less variability than the sections in the other two environmental zones. It should be noted that this observation is not a direct result of the fact that the RAP sections in NC have a CTB base course because SAI takes into account the as-built pavement structure, as explained earlier.

The expected (desired) SAI_5, based on a 20-year design life for a typical pavement built with virgin asphalt, is about 0.97 (it should be noted that this is an ideal scenario and that such standards are not usually met, even for virgin asphalt). The average SAI_5 of the NC sections is 0.95, which means that these sections are performing as would be expected for a section built with virgin asphalt. On the other hand, the average SAI_5 values for the RAP sections in DS and MT environmental zones are 0.82 and 0.7, respectively. These numbers are significantly lower than the typical SAI for a pavement section built with virgin asphalt. Figure 4b classifies the average SAI_5 values, by environmental zone, in terms of performance. In this figure, the RAP sections are shown in one of four performance classes that were used within this study, as listed below. The boundaries of each class are shown in the figure.

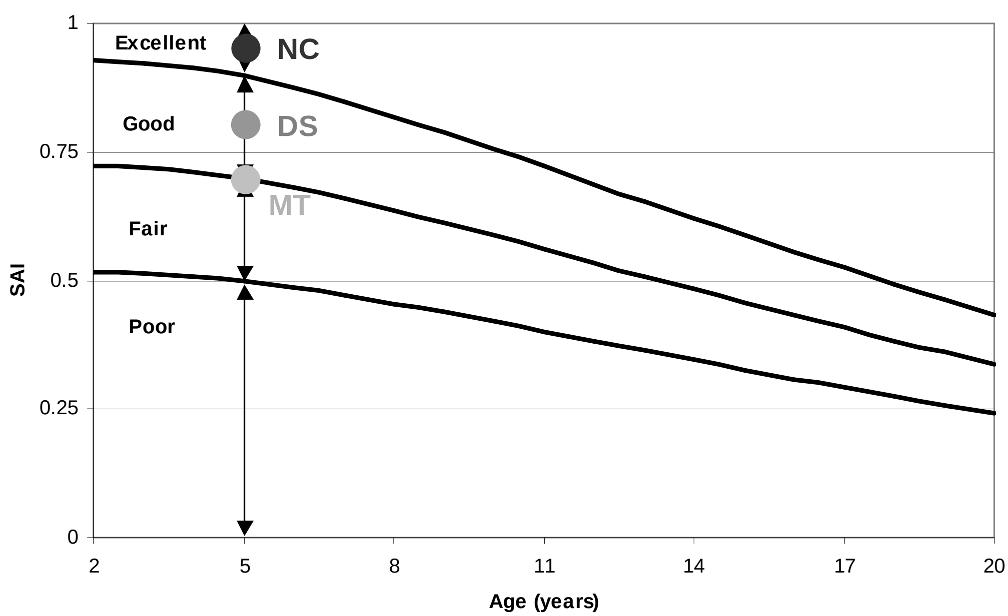
- Excellent $SAI_5 \geq 0.9$
- Good $SAI_5 \geq 0.7$
- Fair $SAI_5 \geq 0.5$
- Poor $SAI_5 < 0.5$

Within this study, a section is considered to be performing to the desired level (based on the ideal scenario for pavements built with virgin asphalt) from the structural point of view if its SAI_5 is greater than or equal to 0.9. Similarly, a section is considered to have a good structural performance if SAI_5 is greater than or equal to 0.7, but less than 0.9. Based on these classifications, and the average SAI_5 of the RAP sections located in the 3 environmental zones, the RAP sections in NC are showing excellent in-situ structural capacity, while those located in DS and MT are showing good and good/fair in-situ structural capacity, respectively.

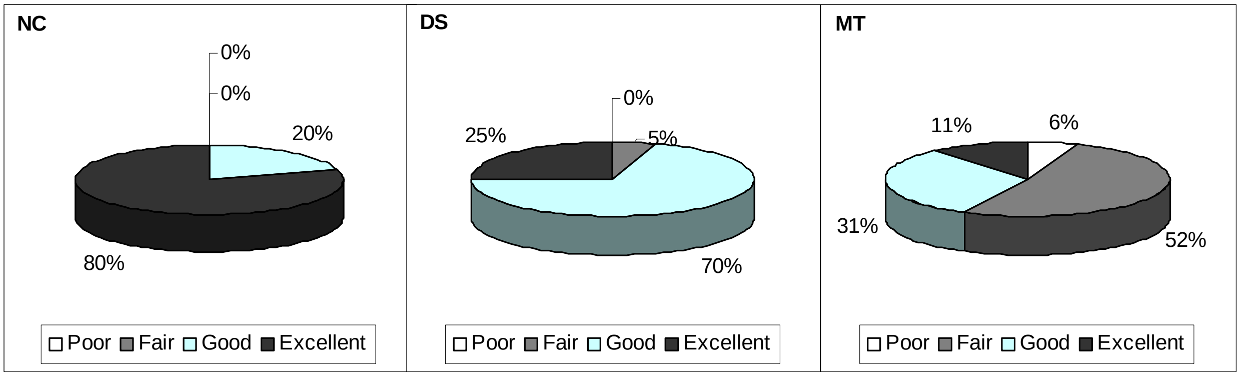
Figure 4c shows the distribution of the RAP sections in the three environmental zones, by structural performance class. As can be seen, 80% of the RAP sections in the NC are in the excellent category (4 out of 5 sections). On the other hand, 25% of the RAP sections in DS (5 out of 20 sections) are in the excellent category and about 95% of the sections are in either the good or excellent categories. The results are not as good for the MT environmental zone: only 11% are in the excellent category (4 out of 35 sections). More than 50% of the RAP sections in MT are in fair category, while 42% are in either the good or excellent categories.



a) Average and standard deviation of SAI_5.



b) Performance classes (average SAI_5).



c) Performance classes (distribution of SAI_5).

FIGURE 4 SAI for RAP sections by environmental zone.

Additional analysis was performed on the SAI data of the RAP sections to predict the Structural Service Life (SSL). In this analysis, the adjusted SAI deterioration model of each section, similar to that shown in Figure 2, was used to determine the age at which the section's SAI value will reach the trigger value used in this evaluation, SAI = 0.5. Results of this analysis are summarized in Figure 5. As can be seen in this figure, the average SSL for the 5 RAP sections located in NC environmental zone is more than 18 years. The corresponding numbers for the RAP sections located in DS (20 sections) and MT (35 sections) environmental zones are about 15 and 11 years, respectively.

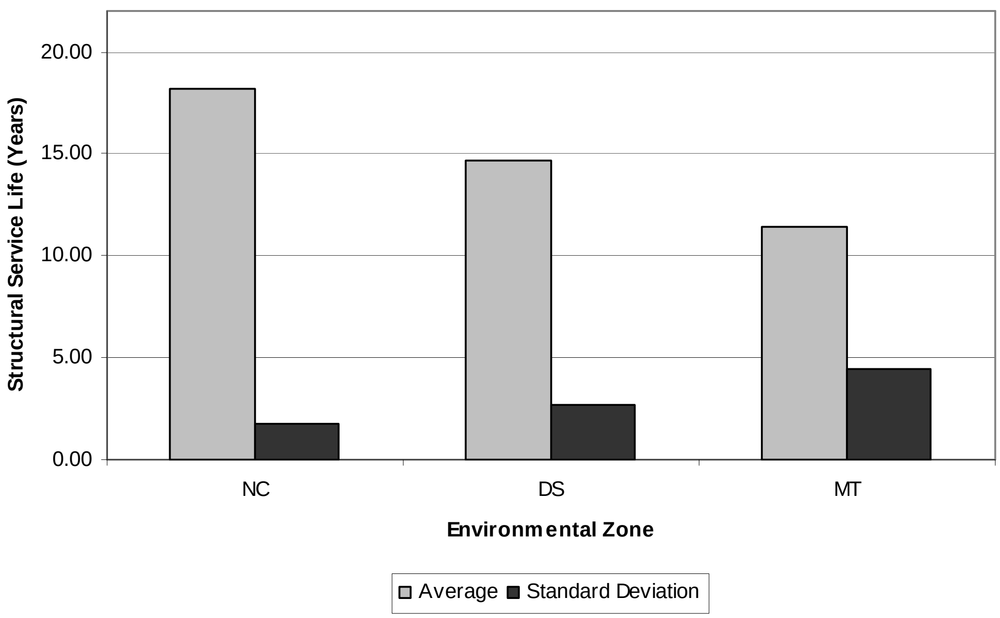
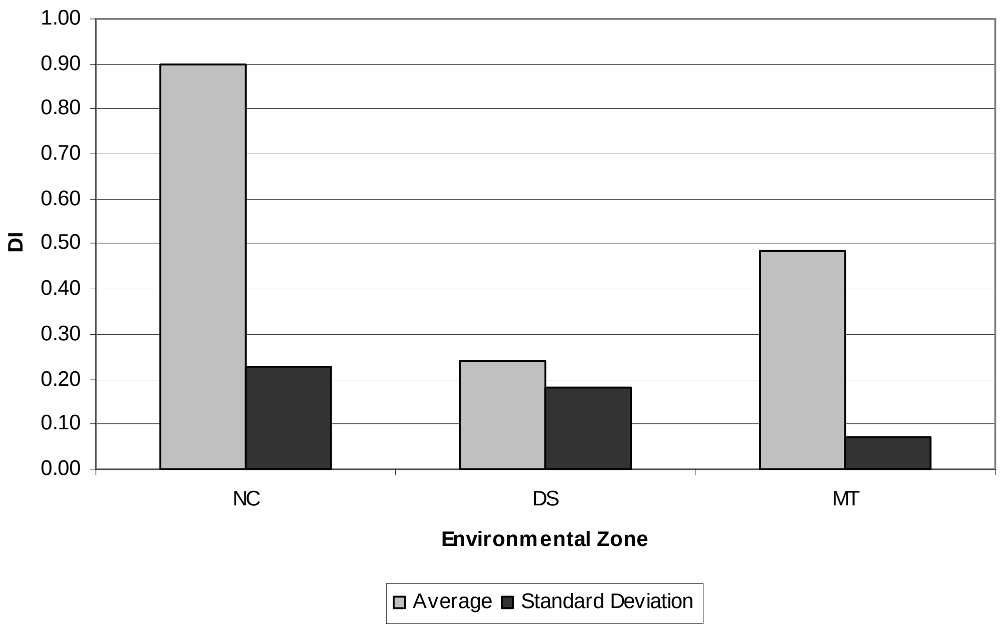


FIGURE 5 Structural Service Life for RAP sections by environmental zone.

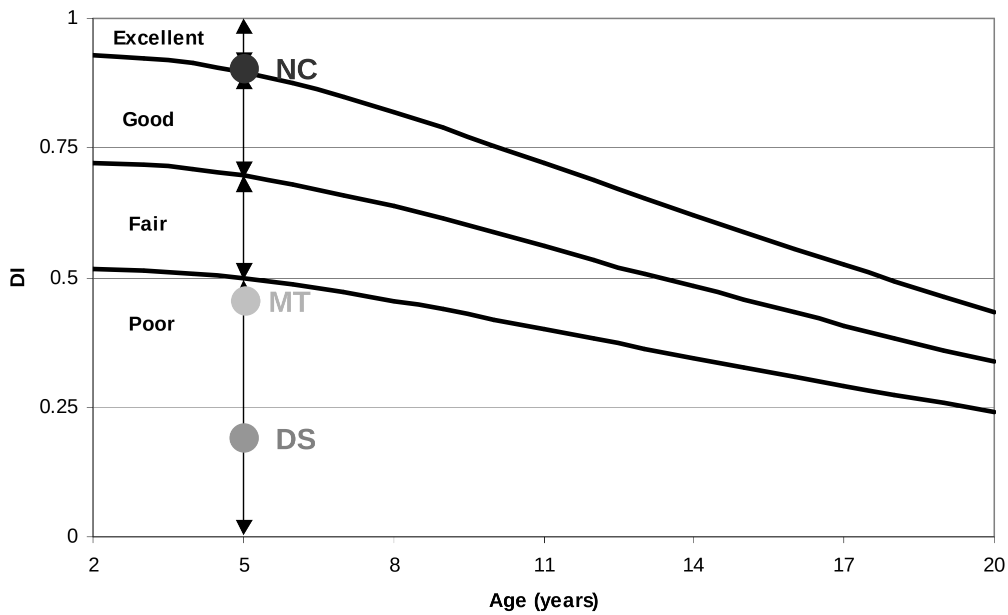
Distress Performance of RAP Sections – Distress Index (DI)

Analysis was performed to evaluate the performance of the RAP sections with respect to surface distresses. This analysis was performed in a manner similar to that performed to evaluate the in-situ structural performance. In this analysis the Distress Index (DI) estimated at age 5 years (DI_5) was used to assess the performance of different RAP sections. Figure 6a shows a summary of the DI_5 values of the 60 RAP sections grouped by environmental zone. As can be seen, the average DI_5 for the RAP sections in the NC zone is about 0.9, while the corresponding numbers for the sections located the DS and MT are less than 0.3 and less than 0.5, respectively. Similarly to SAI_5, DI_5 was classified based on the performance of virgin asphalt pavement in an ideal scenario and shown in Figure 6b. As can be seen, the average distress performance of the RAP sections located in the NC environmental zone is in the excellent category, whereas the average distress performance of the RAP sections located in both the DS and MT environmental zones is in the poor category.

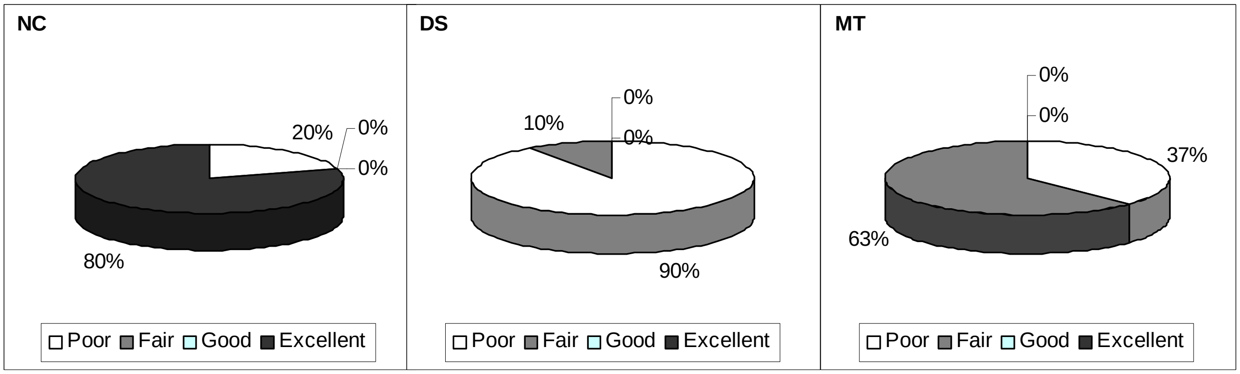
Figure 6c shows the distribution of the RAP sections in the three environmental zones, by DI performance class. As can be seen, 80% the RAP sections in the NC are in the excellent category (4 out of 5 sections). On the other hand, 90% of the RAP sections in DS (18 out of 20 sections) are in the poor category, while 63% of the RAP sections in MT (35 sections) are in the fair category and 37% are in the poor category.



a) Average and standard deviation of DI_5.



b) Performance classes (average DI_5).



c) Performance classes (distribution of DI_5).

FIGURE 6 DI for RAP sections by environmental zone.

Additional analysis was performed on the DI data of the RAP sections to predict the Distress Service Life (DSL). In this analysis, the age adjusted DI deterioration model of each section was used to determine the age at which the section's DI value will reach the trigger level used in this evaluation, DI = 0.5. Results of this analysis are summarized in Figure 7. As can be seen, the expected average DSL for the RAP sections in the NC environmental zone exceeds 20 years, while DSLs for the RAP sections in the DS and MT environmental zones are significantly lower, about 9 and 13 years, respectively. It should be noted that DSLs were calculated based on the assumption that no maintenance will be performed during their service lives. As such, the DSLs can be significantly increased if the appropriate maintenance is performed on these sections. An example of the possible impacts of maintenance on the expected distress performance is shown in Figure 8. As can be seen, the impact of an activity such as crack sealing can be:

1. A slight improvement in DI, because sealed moderate cracks are considered 'low severity', which has less impact on DI, or
2. A temporary prevention of further deterioration in the crack condition, i.e. maintaining the same level of DI, or
3. Deterioration at a slower rate.

In either case, the DSL will be significantly increased as a result of applying appropriate maintenance in a timely fashion.

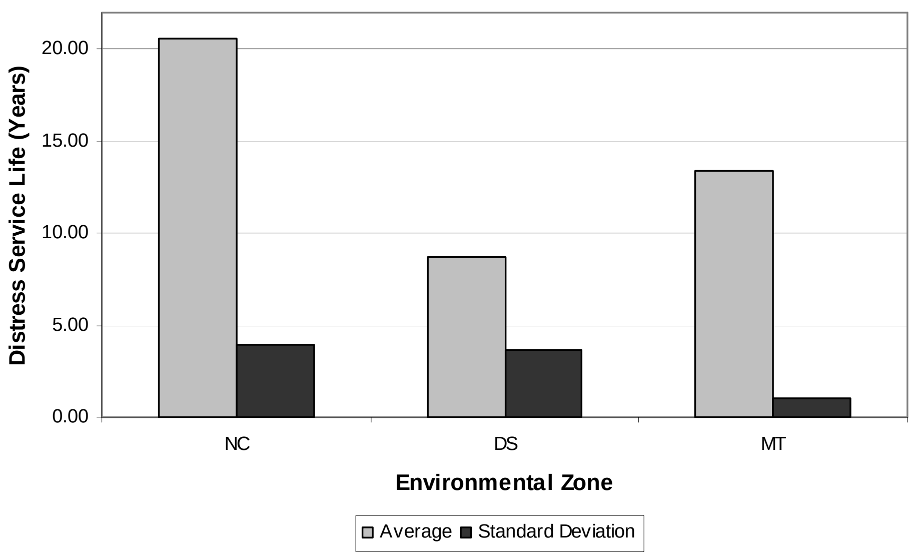


FIGURE 7 Distress Service Life for RAP sections.

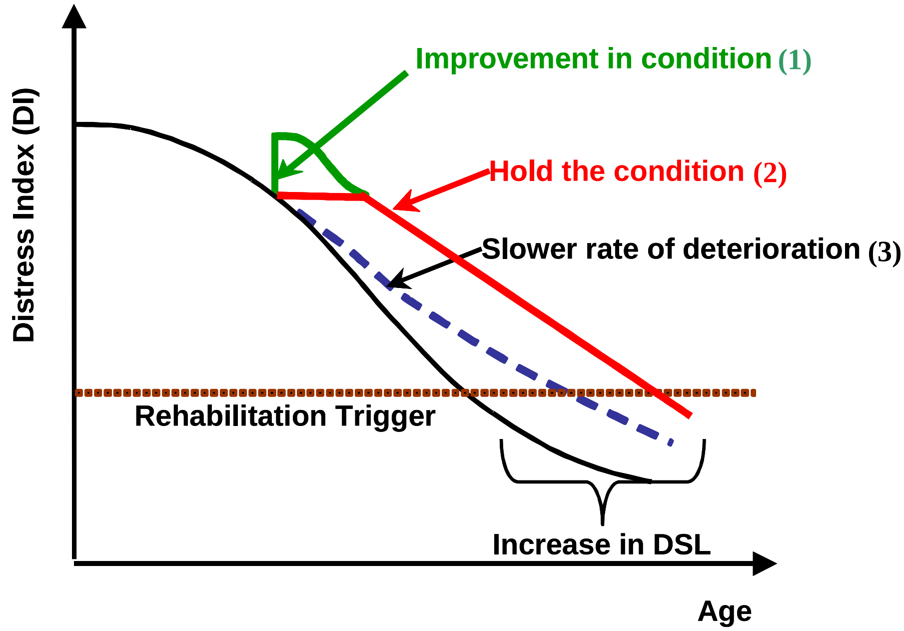
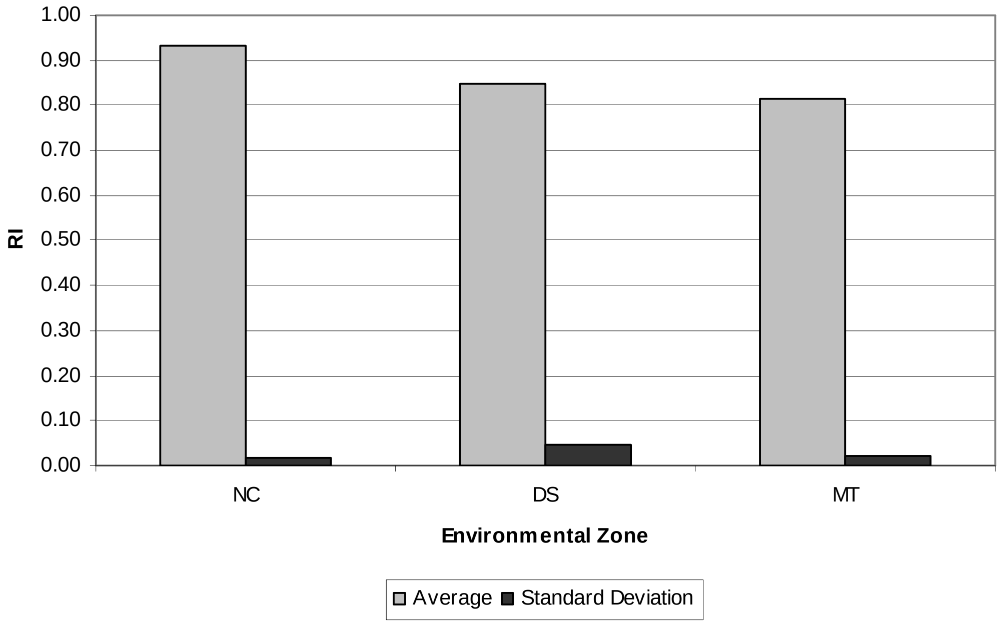


FIGURE 8 Impact of maintenance on DSL.

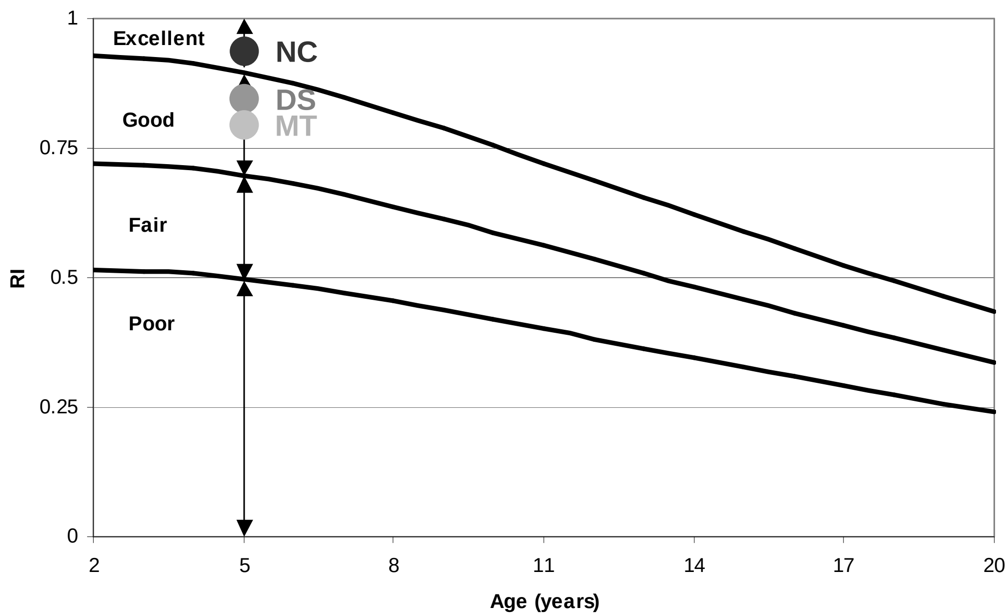
Ride Quality Performance of RAP Sections – Roughness Index (RI)

Analysis was performed to evaluate the performance of the RAP sections with respect to ride quality. This analysis was performed in a manner similar to that performed to evaluate the in-situ structural performance and the distress performance. In this analysis, the Roughness Index (RI) estimated at age 5 years (RI_5) was used to assess the performance of different RAP sections. Figure 9a shows a summary of the RI_5 values of the 60 RAP sections grouped by environmental zone. As can be seen, the average RI_5 for the RAP sections is above 0.8 in all environmental zones. These numbers indicate that the average ride quality performances of the RAP sections located in the 3 environmental zones all fall in the excellent and good categories, when classified using the performance classes utilized in this study, as shown in Figure 9b.

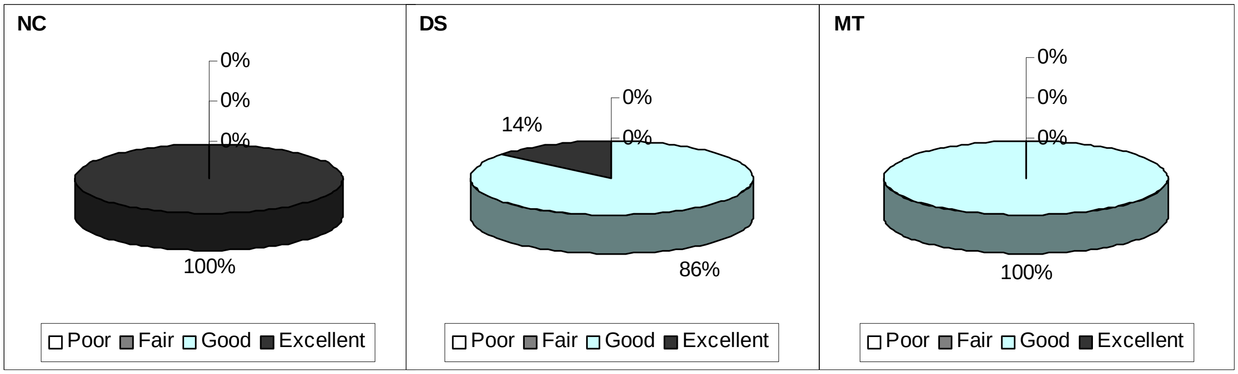
Figure 9c shows the distribution of the RAP sections in the three environmental zones by RI performance class. As can be seen, all the RAP sections in the NC are in the excellent category, while 100% of the sections in the DS are either in the excellent or good category and 100% of the RAP sections in MT environmental zone are in the good category.



a) Average and standard deviation of RI_5.



b) Performance classes (average RI_5).



c) Performance classes (distribution of RI_5).

FIGURE 9 RI for RAP sections by environmental zone.

Additional analysis was performed on the RI data of the RAP sections to predict the Roughness Service Life (RSL) based on the measured deflections. In this analysis, the adjusted RI deterioration model of each section was used to determine the age at which the section's RI value will reach the trigger level used in this evaluation, RI = 0.5. Results of this analysis are summarized in Figure 10. The expected average RSL of the RAP sections located in the NC is about 17 years. For the DS and MT environmental zones the expected average RSL for the RAP sections is approximately 15 years.

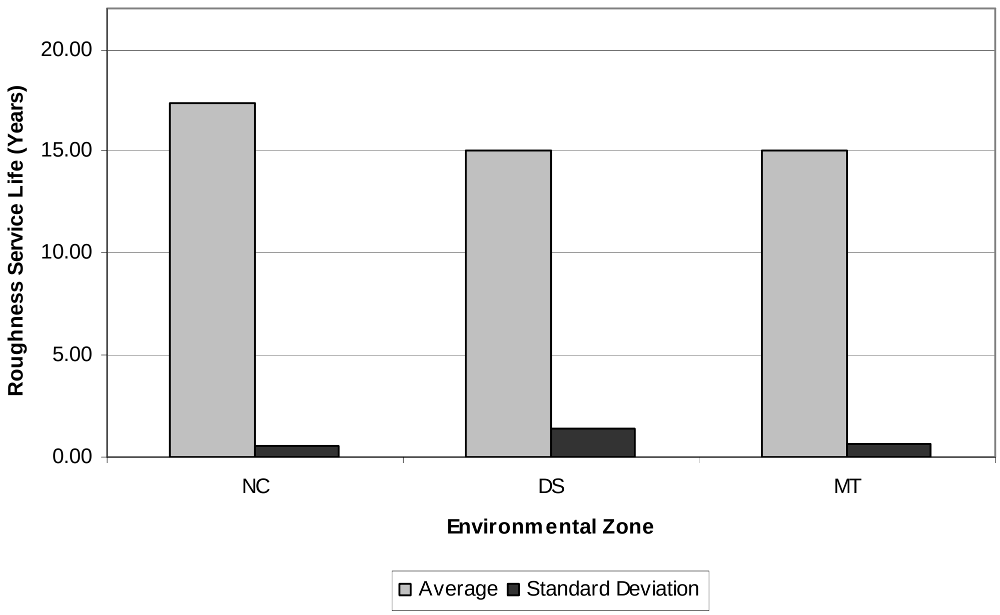
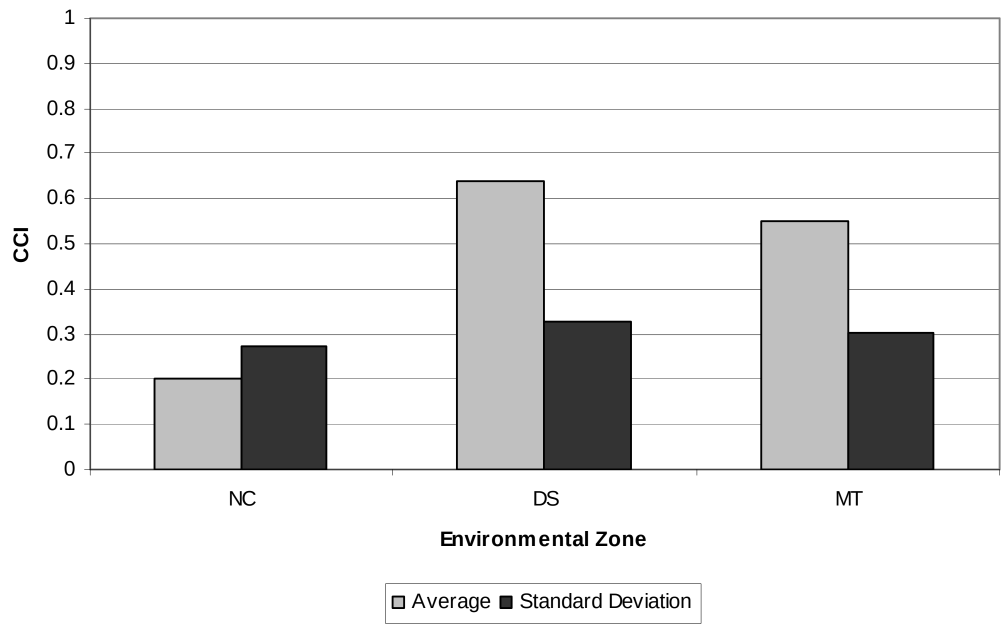


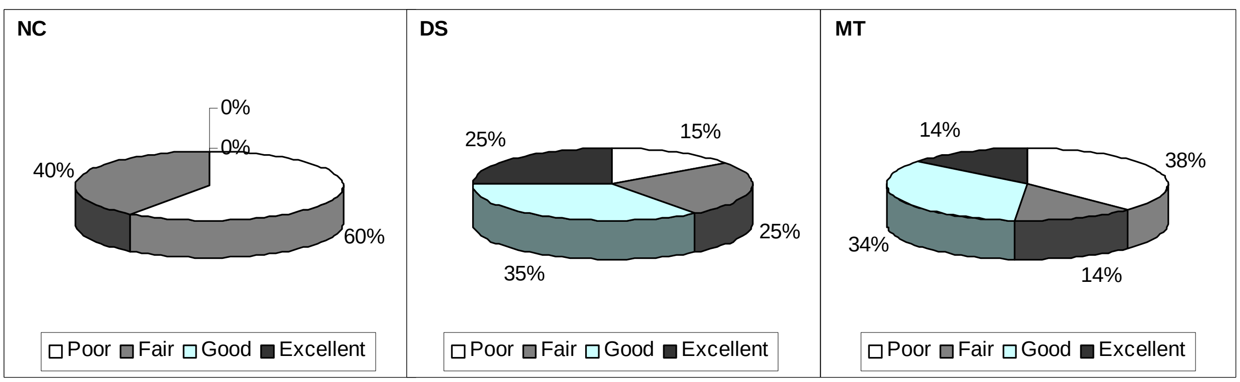
FIGURE 10 Roughness Service Life for RAP sections.

Construction Consistency of RAP Sections – Construction Consistency Index (CCI)

Analysis was performed to evaluate the performance of the RAP sections with respect to construction consistency. Figure 11a shows a summary of the CCI values of the 60 RAP sections grouped by environmental zone. As can be seen, the average CCI values for the RAP sections located in the NC, DS and MT environmental zones are 0.2, 0.64 and 0.55. These numbers indicate that the variability in construction consistency, i.e. variability in the in-situ structural capacity, is high in general with NC sections being the highest. Figure 11b shows the distribution of the RAP sections in the three environmental zones by CCI performance class. As can be seen, 60% of the RAP sections in NC would be categorized as poor according to the performance classes used for the purposes of this evaluation, with no section in the good or excellent categories. On the other hand, only 15% of the RAP sections in DS would be classified as poor, with 60% of the sections in the good and excellent categories, and 38% of the RAP sections in MT would be classified as poor, with 48% of the sections in the good and excellent categories.



a) Average and standard deviation of CCI.



b) Performance classes (distribution of CCI).

FIGURE 11 CCI for RAP sections by environmental zone.

SUMMARY AND CONCLUSIONS

Detailed field testing program was performed on 60 RAP sections located in three California environmental zones (NC, DS, and MT) and four of Caltrans' districts (Districts 1, 7, 9 and 11). Characteristics of these environmental zones are as defined by University of California, Berkley, in 2000 (*1*).

Analysis of the RAP sections was performed with a focus on the actual field performance rather than laboratory predicted performance. In this analysis, the field performance was evaluated with respect to the in-situ structural capacity, distress condition, roughness condition and consistency of construction. Deterioration models were developed and used to estimate the in-situ structural capacity, distress condition and roughness condition for all sections at the same age (5 years) to allow fair comparisons. Also, the expected Structural Service Life (SSL), Distress Service Life (DSL) and Roughness Service Life (RSL) were estimated for each section based on the field observed conditions. The analysis results indicated that:

- The expected service lives for the RAP sections in the NC environmental zone based on structural, distress and roughness performances are 18, 21 and 17 years, respectively. Therefore, the RAP sections will be triggered for ride quality first, after 17 years.

- The expected service lives for the RAP sections in the DS environmental zone based on structural, distress and roughness performances are 15, 9 and 15 years, respectively. Therefore, the RAP sections will be triggered for distress first, after 9 years. However, the distress service life can be significantly increased if the appropriate maintenance activities, such as crack sealing, are applied in a timely fashion. In such a case, it may be expected that the RAP sections in DS environmental zone will last for 15 years, i.e. the lowest of the other two service life values.
- The expected service lives for the RAP sections in MT environmental zone based on structural, distress and roughness performances are 11, 13 and 15 years, respectively. Therefore, the RAP sections will be triggered for structural adequacy first, after 11 years.
- Based on the observed performance of the sections considered in this study, the long-term performance of the RAP sections in NC is expected to be better than that of the RAP sections in DS and MT in terms of SAI, DI, and RI. This may be attributed to the use of CTB, since CTB typically has a higher modulus than an aggregate base course. However, it should be noted that only 5 RAP sections were considered from the NC, compared with 20 and 35 sections from DS and MT, respectively.
- Based on the sections considered in this study, the construction consistency in NC is significantly lower than in DS and MT.

The analysis presented in this paper has compared the performance of RAP in different environmental zones. Further analysis has been initiated to compare the performance of RAP with that of other materials and treatments.

REFERENCES

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