

# **Application of the Endurance Limit Premise in Mechanistic-Empirical Based Pavement Design Procedures**

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### **Abstract**

Flexible pavements have traditionally been designed to limit load-related cracking. The more traffic – the thicker the hot mix asphalt (HMA) layer to limit the amount of load related cracks. Industry, however, has proposed the use of an endurance limit as a mixture property for HMA layers. The endurance limit is defined as the tensile strain below which no fracture or fatigue damage occurs. Values that have been used vary from 65 to over 100 micro-strains. Most all design and analysis procedures that use the endurance limit concept assume that one value applies to all HMA mixtures and temperatures. This purpose of this paper is to confirm or reject the concept and values suggested for the endurance limit through the use field performance data.

### **Introduction**

Mechanistic-empirical (M-E) based procedures are used to design flexible pavement to limit load related cracking. All M-E based design procedures can be grouped into three types relative to load-induced cracking, which are listed below.

1. Design procedures that use the equivalent axle load and equivalent temperature concepts. The equivalent temperature is determined based on an annual or monthly basis. These procedures typically use the cumulative damage concept to determine the amount of fracture damage over the design period for each structure. The Asphalt Institute's DAMA program falls within this category.
  - a. The equivalent temperature concept simply defines one temperature for which the annual or seasonal damage equals the cumulative damage determined at monthly intervals. The equivalent temperature is used to estimate the dynamic modulus for calculating critical pavement responses (tensile strain at the bottom of the hot mix asphalt [HMA] layer) on an annual or seasonal basis.
  - b. The equivalent axle load concept simply converts all truck traffic into an equivalent number of a specific axle load applications. That axle load is used to calculate the pavement responses required for design.
2. Design procedures that use the equivalent temperature concept and axle load distribution for each axle type. These procedures also use the cumulative damage concept to determine the amount of fracture damage for each pavement structure. The PerRoad program falls within this category.

3. Design procedures that use the axle load distribution and pavement temperature distributions at specific depths over some time interval, generally less than a month. These procedures typically use the incremental damage concept to determine the amount of fracture damage within specific time and axle load intervals at specific depths within the pavement structure. The Mechanistic-Empirical Pavement Design Guide (M-E PDG) falls within this category.

Most M-E based design procedures, regardless of the group, use Minor's hypothesis to calculate fracture damage, and assume that load-related alligator cracks initiate at the bottom of the HMA layer and propagate to the surface with continued truck loadings, with the exception of the M-E PDG. The M-E PDG predicts both bottom and surface initiated cracks. In addition, all M-E based design procedures use the maximum tensile strain at the bottom of the HMA layer as the pavement response parameter for calculating fracture damage and the amount of alligator cracks. Thus, the more traffic the thicker the HMA layer to limit the amount of alligator cracking.

Industry has proposed the use of an endurance limit as a mixture property. The endurance limit is defined as the tensile strain below which no fracture damage occurs; a fatigue resistant pavement. The purpose of this paper is to present field performance data to confirm or reject this design premise.

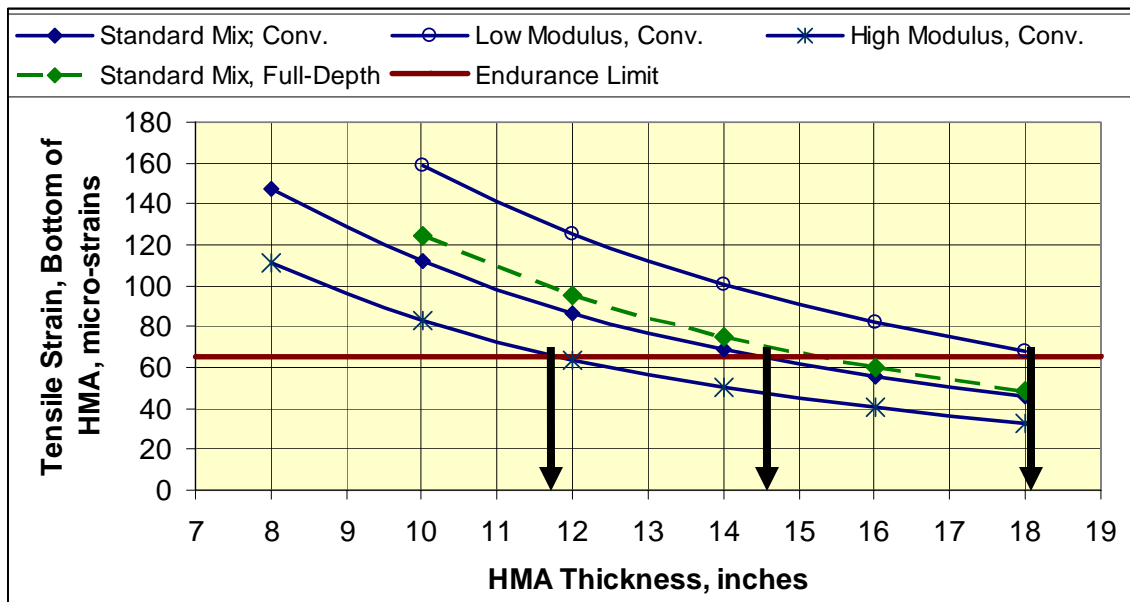
### **Mechanistic-Empirical Design Procedures and the Endurance Limit**

The M-E based design procedures that consider the endurance limit design premise incorporate that concept into the design procedure in one of three methods, which are summarized below.

1. The introduction of the endurance limit design premise into those design procedures that use the equivalent temperature and equivalent axle load concepts is straight forward. Stated simply, the maximum tensile strain is calculated at the equivalent temperature and axle load and compared to the endurance limit. The HMA layer thickness is simply determined for which the maximum tensile strain equals or is less than the endurance limit. Figure 1 illustrates the use of the endurance limit within this method.
2. The introduction of the endurance limit into those design procedures that combine use of the equivalent temperature concept and actual axle load distribution require more computations of pavement response. The maximum tensile strain is calculated at the equivalent temperature for each axle load within the axle load distribution. The axle load distribution for each axle type is used to determine the probability of the tensile strain exceeding the endurance limit. The designer then considers that probability of exceeding that critical value in designing an HMA layer for which no fatigue damage would accumulate over time. Figure 2 illustrates the use of the endurance limit within this method. One concern with this method is that the higher loads result in significantly higher damage indices; an increase in axle load will result in an increase in damage to a power of about 4.

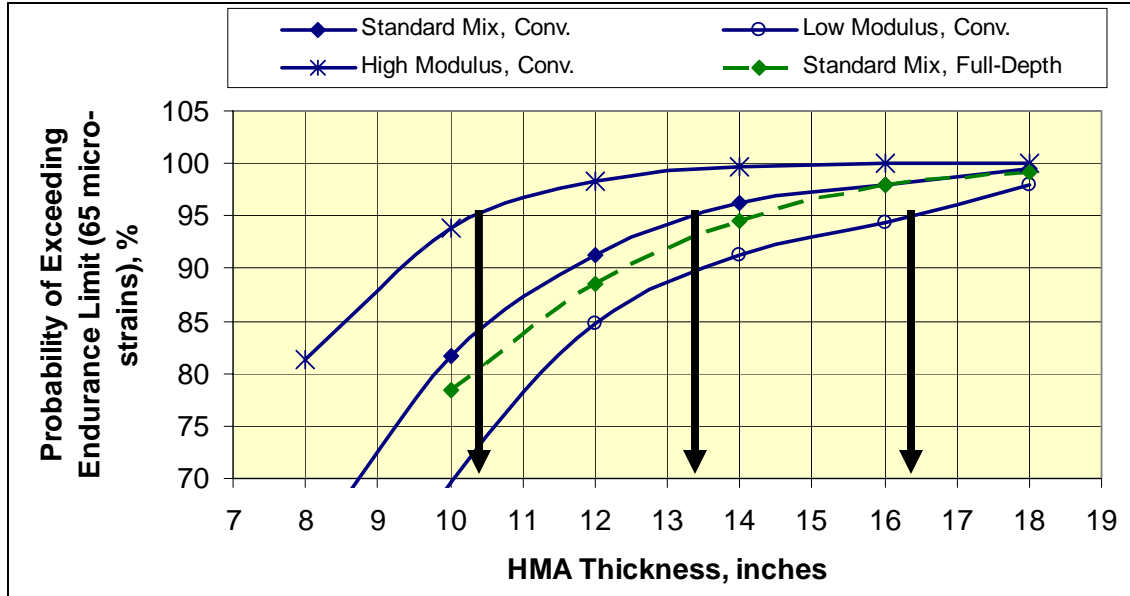
Thus, the probability of cracking is much higher than the probability of a specific tensile strain being exceeded.

3. Those design procedure that use the incremental damage concept establish a threshold value for the tensile strain, below which the fracture damage is assumed to be zero. In other words, the procedure simply ignores tensile strains that equal or is less than the value set as the endurance limit for determining the incremental damage within a specific time period and depth. Successive runs have been made with the M-E PDG to determine the difference in calculated fracture damage with and without using the endurance limit as a HMA mixture property. Based on limited runs, little difference was found between the two conditions. The reason for this finding is that most of the damage occurs for the higher strain levels and higher temperatures. Figure 3 illustrates the increasing tensile strains at the bottom of the HMA layer for increasing single axle loads applied to different dynamic modulus values.

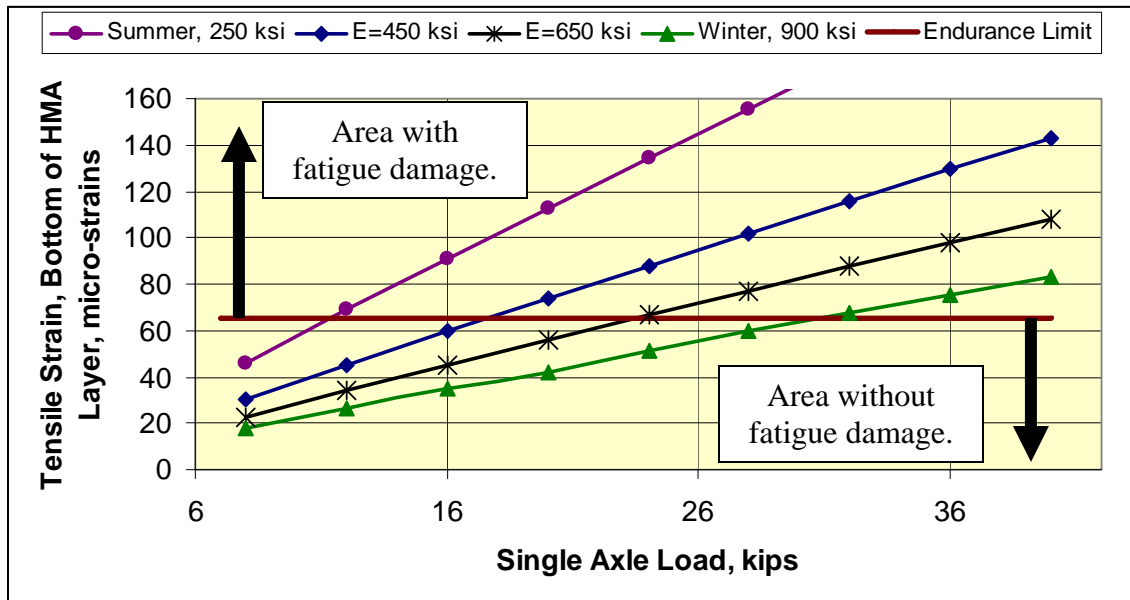


**Figure 1 Tensile strains calculated for an 18-kip single axle load for the equivalent annual temperature for different HMA mixtures.**

All M-E based design methods that consider the endurance limit design premise assume that the endurance limit is independent of the mixture and temperature. The endurance limit being the tensile strain below which no fracture damage occurs. This assumption implies that the endurance limit is not a mixture property – one value applies to all HMA mixtures. Thus, the questions become, is the endurance limit a mixture property and what value should be used as the endurance limit?



**Figure 2** Probability of exceeding the endurance limit for different HMA mixtures using typical axle load distributions and seasonal temperatures.



**Figure 3** Increasing tensile strains for varying single axle loads for different seasons or dynamic modulus within those seasons (HMA thickness equals 15 inches).

To try and answer these questions, laboratory fatigue testing programs have been sponsored by different agencies within the past decade. The University of Illinois, the Asphalt Institute, and NCHRP have on-gong studies. These studies are basically laboratory test programs to confirm and estimate the tensile strain that would result in an unlimited number of load applications without any fatigue cracking failures of laboratory

prepared flexural beams. Historically, failure in the laboratory has been defined as a reduction in stiffness of the beam test specimens – a 50 percent reduction in stiffness has been used. Results from these laboratory test programs suggest that the endurance limit is a valid design concept. No field studies, however, have been attempted to confirm or reject the endurance limit concept, nor estimate the values for the endurance limit.

## **Field Performance Data**

The Long Term Pavement Performance (LTPP) program was initiated in 1988 to provide pavement data for different materials and pavement performance studies. The program established hundreds of test sections across North America. These test sections vary from thin HMA surfaced pavements to thick or deep-strength HMA surfaced pavements. Many of these sections have HMA layer thicknesses in excess of 15 inches.

For these LTPP sections, distress surveys have been periodically performed to measure the types and extents of load related distresses – including alligator area and longitudinal cracks. As such, the LTPP database was used to evaluate the types of cracks exhibited at the surface of thin to very thick HMA pavements and provide field performance data to confirm or reject the endurance limit hypothesis. Specifically, the LTPP database was used to try and answer three questions related to the endurance limit design premise, as listed below.

1. Do field observations of alligator cracking over a range of pavements and site conditions support the existence of an endurance limit as a HMA mixture property?
2. If the field observations support the endurance limit hypothesis, what is the tensile strain below which no more alligator cracking has been exhibited?
3. Is the endurance limit independent of mixture type and dynamic modulus?

## **Defining the Endurance Limit – A Survivability Analysis**

A survivability analysis was used to try and answer the above questions using the LTPP database. This section of the paper describes the use of survival curves in determining the thickness or level of tensile strain at which no to limited fatigue cracking has occurred over long periods of time.

### **Development and Application of Survival Curves**

Survival or probability of failure analyses have been used for decades in actuarial sciences. They have also been used in the pavement industry to determine the expected service life of pavement structures for use in life cycle cost analysis, and to compare the mean and standard deviation of the expected service life for different design features and site factors in evaluating the adequacy of the design procedure (Gharaibeh and Darter, 2002 and 2003). Survival curves are uniquely useful because every point on the curve represents the probability that a given pavement section will be rehabilitated or exceed a specific level of distress.

Survival analysis is a statistical method for determining the distribution of lives or “Life Expectancy”, as well as the occurrence of a specific distress for a subset of pavements. Since not all of the pavements included in the analysis have reached the end of their service life or a specific level of distress, mean values cannot be used. The age or amount of alligator cracking and probability of occurrence are computed considering all sections in the subset using statistical techniques.

Survival curves are typically based on age but can also be based on traffic loadings or the probability of exceeding a specific level of distress. In either case, the condition at failure must be based on a clearly defined condition. The definition of failure for confirming the endurance limit premise is no alligator cracks. The M-E PDG and other M-E based procedures assume that longitudinal cracks in the wheel path initiate at the surface, while alligator cracks initiate at the bottom of the HMA layer (NCHRP, 2004). This assumption was adopted for this paper.

Mathematical models are best fitted to the points in the survival curves to predict the probability of survival or failure as a function of age, thickness, cumulative traffic, or pavement responses – like tensile strain at the bottom of the HMA layer. A survival analysis can also be completed using a specific level of distress and pavement response value. In other words, the survival curves can be used to define the probability that a specific area of alligator cracking will be less than some specified amount for different HMA thicknesses or tensile strains at the bottom of the HMA layer.

The reliability of a pavement depends on the length of time it has been in service, as well as design features and site factors not properly accounted for in a thickness design procedure. Thus, the distribution of the time to failure of a pavement type or thickness level is important in reliability studies. A method used to characterize this distribution is the failure rate or rate of occurrence for a specific level of distress. The failure rate is discussed and mathematically defined within the remainder of this section.

If  $f(t)$  is the probability density of the time to failure of a given pavement type and thickness, that is, the probability that the pavement will fail between times  $t$  and  $t+\Delta t$  is given by  $f(t) * \Delta t$ , then the probability that the pavement will fail on the interval from 0 to  $t$  is give by:

$$F(t) = \int_0^t f(t) dx \quad (1)$$

The probability of survival,  $R(t)$ , is simply 1 minus the probability of failure. The reliability function, expressing the probability that it survives to time  $t$ , is given by:

$$R(t) = 1 - F(t) \quad (2)$$

Thus, the probability that the pavement will fail in the interval from  $t$  to  $t+\Delta t$  is  $F(t+\Delta t)-F(t)$ , and the conditional probability of failure in this interval, given that the pavement survived to time  $t$ , is expressed by:

$$\frac{F(t+\Delta t)-F(t)}{R(t)} \quad (3)$$

Dividing by  $\Delta t$ , one can obtain the average rate of failure in the interval from  $t$  to  $t+\Delta t$ , given that the pavement survived to time  $t$ :

$$\frac{F(t+\Delta t)-F(t)}{\Delta t} \left[ \frac{1}{R(t)} \right] \quad (4)$$

For small  $\Delta t$ , one can get the failure rate,  $Z(t)$ , which is:

$$Z(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1-F(t)} \quad (5)$$

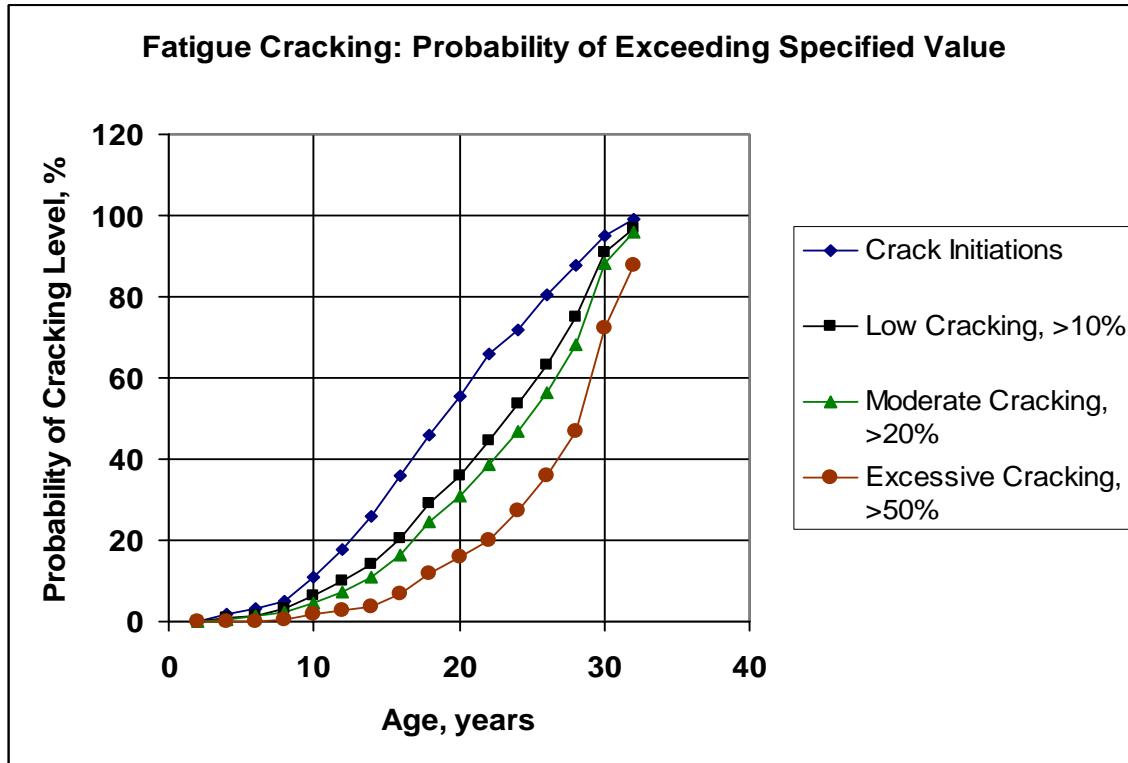
The failure rate can be determined by organizing the performance data in terms of the distribution of pavement age exceeding a critical level (failure) versus the distribution of age for those pavement exhibiting a value lower than the critical value. The critical value for perpetual pavements is nil alligator cracks.

#### **Establish Baseline Survival Curve**

A survivability analysis was completed by Von Quintus, et al. for the Asphalt Institute to determine the expected age to an amount of fatigue cracking that would result in rehabilitation of the roadway (Von Quintus, et al., 2004). The test sections used in the survival analysis were from the General Pavement Study (GPS) 1 and 2 experiments. Figure 4 shows the baseline probability of failure relationship from that data for different levels of alligator or fatigue cracking measured on flexible pavements in the GPS-1 and 2 and Special Pavement Study (SPS) 1 experiments. The average life to crack initiation and a low cracking amount (less than 10 percent of wheel path area) is 19 and 23 years, respectively.

#### **Establish Endurance Limit Concept and Value**

A similar survivability analysis was previously completed by Von Quintus in 1995 for a subset of the test sections included in the GPS-1 and 2 experiments. The test sections were randomly selected from the LTPP program with the thicker HMA layers. This survivability analysis was completed to try and estimate a value for the endurance limit based on alligator cracking observations, rather than just use values estimated from limited laboratory test programs. That survival analysis has not been formally documented in the literature. The following summarizes the hypotheses and points that were considered in that survivability analysis and in developing the survival curve.



**Figure 4** Graphical illustration of the probability of failure or exceeding a specified area of alligator cracking (Von Quintus, et al., 2004).

1. First, it is hypothesized that the slope of the survival curve for conventional-neat HMA mixtures is relatively flat in the range of tensile strains that cause fracture damage. This assumes that the HMA thickness has been designed to prevent alligator cracking within the design period. In other words, the chance of failure for a HMA layer designed for a lower traffic volume or higher tensile strain (thinner HMA layer) should be the same as the HMA layer designed for a higher traffic volume or lower tensile strain (thicker HMA layer).
2. As the tensile strain approaches the endurance limit, it is hypothesized that the slope of the survival curve will start to significantly increase. This range of tensile strains is where the probability of projects exhibiting higher levels of alligator cracking significantly decrease.
3. At and below the endurance limit for conventional-neat HMA mixtures, it is hypothesized that the slope of the survival curve is relatively flat. In other words, the chance of exhibiting alligator cracking at small tensile strains (within the range of no fracture damage) is the same and dependent on other factors not related to wheel loads.

The LTPP data was used to determine the probability of occurrence of alligator cracking for different HMA thicknesses and tensile strains. The EVERSTRESS program was used to calculate the maximum tensile strain at the bottom of the HMA layer for each test section using the equivalent temperature and equivalent single axle load concepts. The equivalent annual modulus for the HMA layer was determined in accordance with the

procedure recommended for use by Von Quintus and Killingsworth, mathematically shown in equation 6 (Von Quintus and Killingsworth, 1997).

$$E_{equivalent} = \frac{\sum [E(T_i)](DF_i)}{\sum (DF_i)} \quad (6)$$

Where:

$$DF_i = 7.4754 \times 10^{10} (E(T_i))^{-1.908} \quad (7)$$

$DF$  = Damage factor for a specific HMA modulus.

$E(T)$  = Elastic modulus at pavement temperature  $T$ .

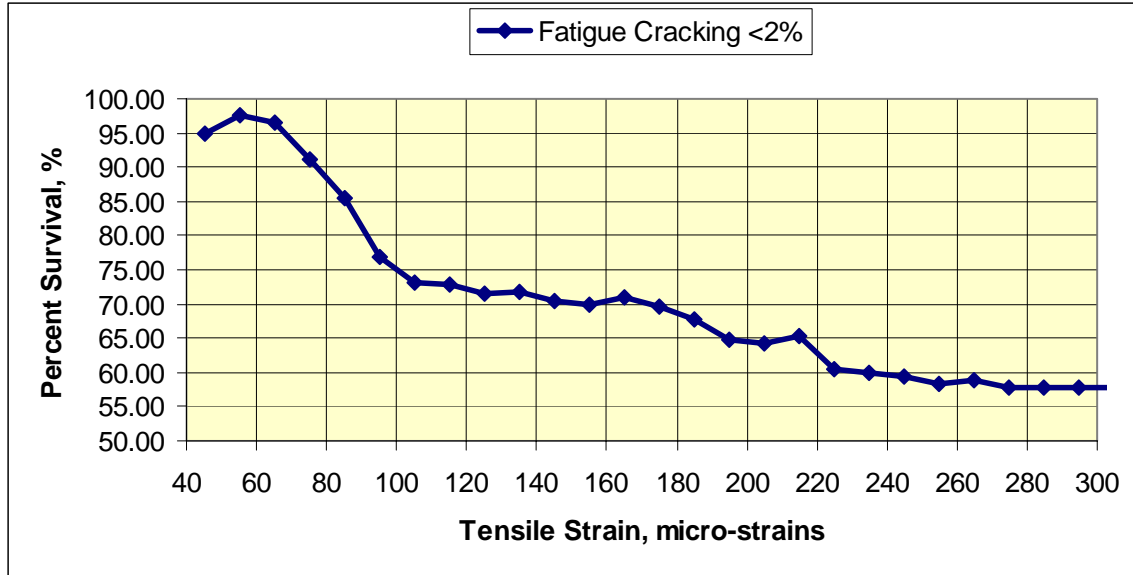
$i$  = Season or time interval for defining the average pavement temperature,  $T$ .

The HMA modulus value,  $E$ , used in the calculation of tensile strain was based on volumetric data and physical properties of the HMA for the equivalent annual temperature. The modulus values for the other pavement and soil layers were based on resilient modulus testing performed in the laboratory for the LTPP test sections.

Figure 5 shows the survival curve from the limited study. A magnitude of 2 percent was used in this initial survival analysis because of the measurement error in alligator cracking with time. A small measurement error could result in significant changes to this definition of the endurance limit. The following discusses the survival curves relative to the three hypotheses listed above.

1. Figure 5 exhibits two ranges of tensile strains that are relatively flat; tensile strains greater than 220 micro-strains and 100 to 170 micro-strains. The reason for this step function between the two ranges is unknown and was unexpected. However, the tensile strains greater than 100 micro-strains would correspond to the first hypothesis – the chance of failure is the same, suggesting that the HMA layers have been designed such that the thickness of the HMA layer was increased for increasing traffic levels and weaker support layers.
2. The increase in survival rate starts around 100 micro-strains. This area or region corresponds to the second hypothesis.
3. The slope of the survival curve becomes flat again at tensile strains less than 70 micro-strains. This area or region corresponds to the third hypothesis.

In summary, the endurance limit is believed to be 65 micro-inches at a 95 percent confidence level for an 18-kip single axle load applied to the pavement at the equivalent annual temperature for the specific site.



**Figure 5** Survival curve for flexible pavements developed from data included in the LTPP GPS-1 and 2 experiments (undocumented study, 1995).

#### **Preliminary Definition of the Endurance Limit as a HMA Mixture Property**

The AAMAS project sponsored by NCHRP recommended use of the indirect tensile strength and modulus tests to estimate the fatigue strength of specific HMA mixtures (Von Quintus, et al., 1991). Figure 6 illustrates that relationship between HMA modulus and tensile strain at failure. Points below the line in Figure 6 are assumed to have inferior fatigue properties, and those above the line exceed the fatigue strength of the “standard” mixture. Laboratory tests and field observations of alligator cracking have been used to check the validity of this relationship over time. Accelerate alligator cracking has been observed where the tensile strain at failure is less than that value from Figure 6 for a specific HMA modulus value based on the equivalent temperature concept. In other words, the concept has not been fully validated but field observations of fatigue cracking and mixture test results do support the hypothesis.

Figure 6 was developed long before the endurance limit concept was introduced and is independent of Figure 5. However, a micro-strain of 65 (one percent of the tensile strain at failure) corresponds to an equivalent annual modulus value of 450 ksi – a typical value used for many neat or conventional (unmodified) HMA mixtures. Von Quintus used this relationship to estimate or define the endurance limit for different HMA mixtures as 1 percent of the tensile strain at failure measured in accordance with the test protocol from the AAMAS study (Von Quintus, 2001). This definition and Figures 5 and 6 would suggest that the endurance limit is a mixture property. Insufficient test data exists within the LTPP database to estimate the endurance limit for the HMA mixtures included in Figure 5. As such, that definition has yet to be confirmed and validated.



**Figure 6 Relationship between modulus and tensile strain at failure to estimate the fatigue strength of HMA mixtures (Von Quintus, et al., 2001).**

## Updated Survivability Analysis Using LTPP Data

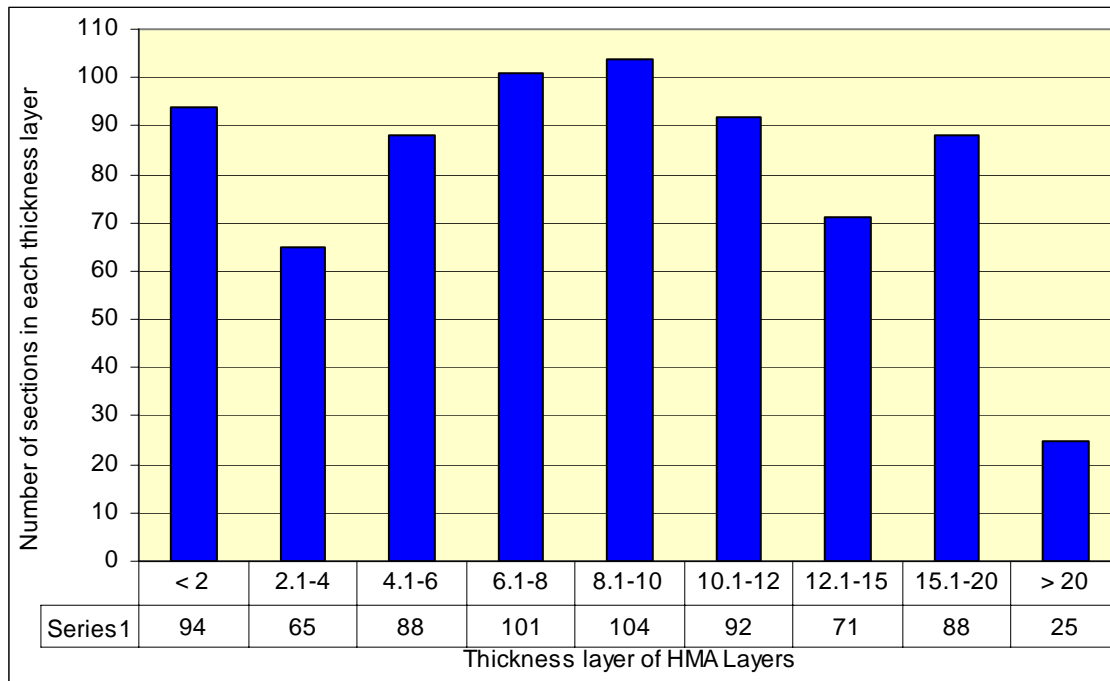
### Expanded Data Set

The survivability analysis completed for this project included the same test sections from the 1995 study, plus additional test sections within the GPS 1 and 2 and SPS-1 experiments. An expanded subset of the LTPP test sections was used, which were randomly selected to cover all environmental regions, soil types, and HMA thicknesses. The additional test sections used in the updated survivability analysis were from the GPS-1 and 2 and SPS-1 experiments – LTPP database version VR 2004.06, release 18.0 (2004). Figure 7 shows the distribution of HMA thickness for all test sections included in the updated survivability analysis.

Figure 8 shows the distribution of pavement age for the test sections with more than 10 inches of HMA that were used to update the 1995 survival curve (Figure 5). As shown, the age of about half of the thicker test sections included in the updated study are greater than 15 years but less than 20. Many of these additional test sections were from the SPS-1 experiment that was excluded from the initial study to estimate the endurance limit. The reason that the SPS-1 test sections were excluded from the study in 1995 is that most of the projects within the SPS-1 experiment were new at that time.

The other important parameter in the survivability analysis is the truck traffic applied to each of these test sections. Without significant truck traffic, defining the endurance limit from field observations has limited meaning. Figure 9 shows the distribution of the cumulative number of 18-kip ESALs for the test sections included in the updated survivability study that have HMA thickness in excess of 10 inches. The cumulative

truck traffic for these thicker test sections is considered moderate traffic with most test sections having less than 15 million cumulative 18-kip ESALs.



**Figure 7 Distribution of HMA thickness for the test sections used in the updated survivability analysis.**

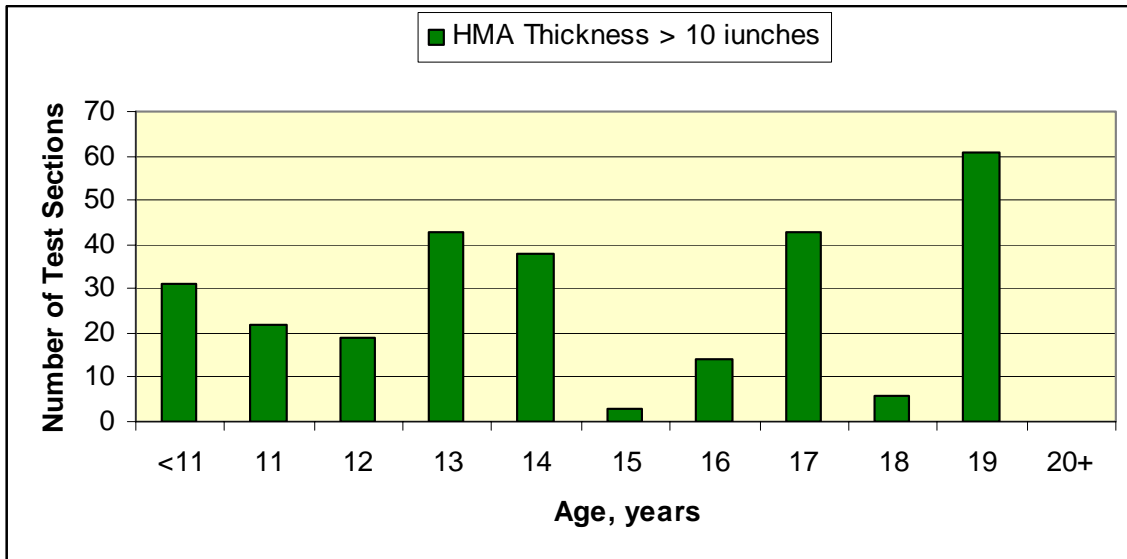
In summary, the test sections with the thicker HMA layers are not new pavements (Figure 8), but do have truck traffic levels that are lower than what would be considered heavy truck traffic (Figure 9). This level of truck traffic is a concern to the definition established for the endurance limit. Much higher levels of truck traffic are needed to validate the endurance limit design premise with field observations and data.

**HMA Thickness-Based Definition**

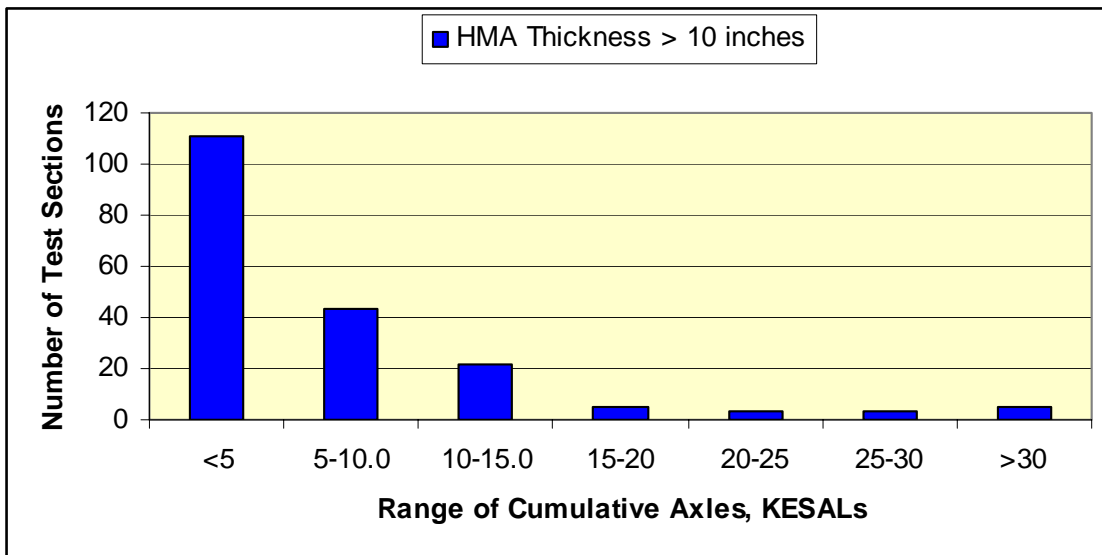
The asphalt industry has proposed some maximum HMA thicknesses that are believed to be resistant to alligator cracking. The LTPP database was used to determine the level of HMA thickness at which none to little alligator cracking has been observed on HMA pavement surfaces.

Figure 10 compares the amount of fatigue cracking (percent of wheel path area) from the most recent distress survey and HMA thickness. The test sections with thinner HMA layers generally have more fatigue cracking, as expected. However, there are an appreciable number of test sections with thicker HMA layers (15 inches or more) that have levels of fatigue cracking exceeding 5 percent. The minimum thickness to prevent alligator cracking is difficult to accurately define, because the strength of the foundation of the HMA layer is also important. In other words, flexible pavements with HMA thicknesses exceeding 15 inches but with weak foundations can exhibit alligator cracking.

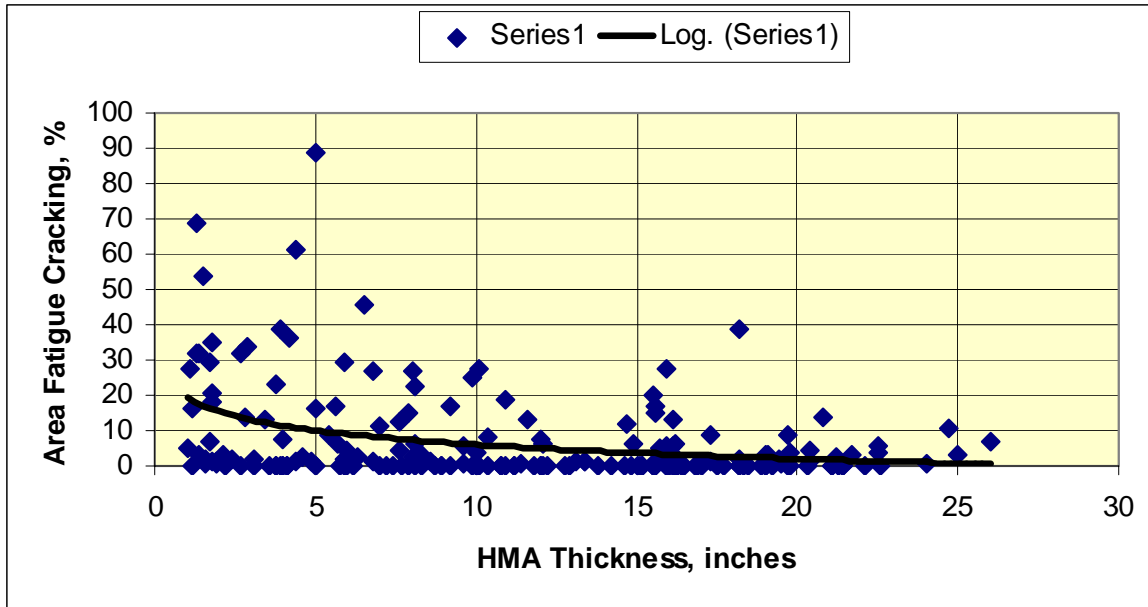
Figure 10 suggests that there is no HMA thickness for which the occurrence of alligator cracks is minimized.



**Figure 8** Distribution of age for those test sections with HMA layer thicknesses in excess of 10 inches.



**Figure 9** Distribution of cumulative equivalent single axle loads for the test sections used in the survivability analysis with HMA layer thicknesses in excess of 10 inches.



**Figure 10** Comparison of area fatigue cracking (area alligator cracking based on a percent of wheel path area) and HMA layer thickness.

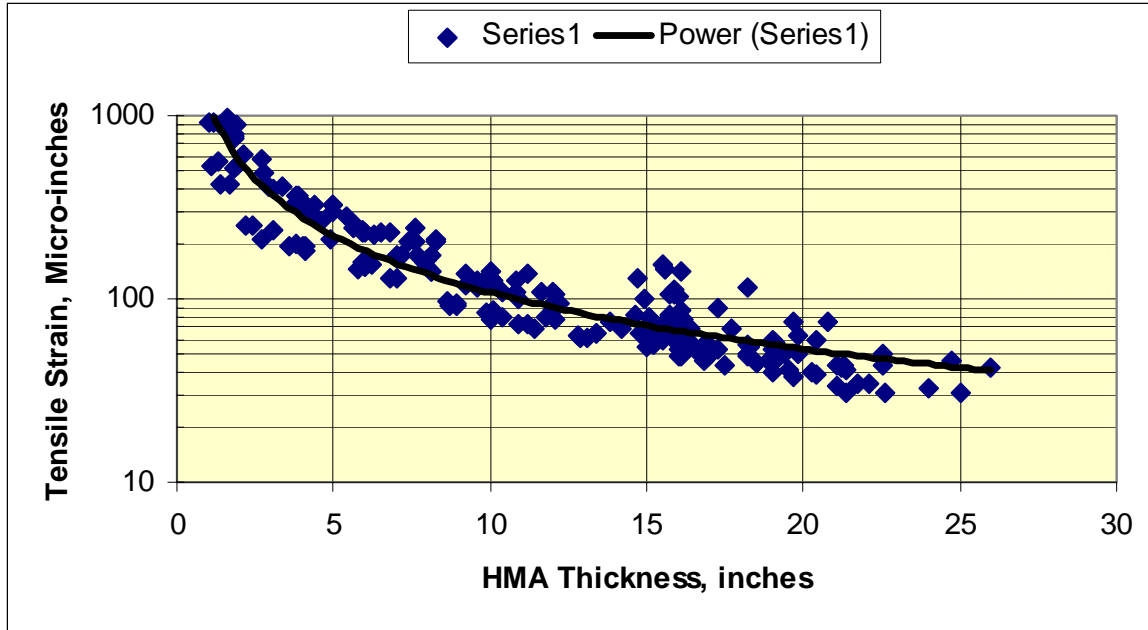
**Maximum Tensile Strain-Based Definition**

Figure 11 compares the maximum tensile strain calculated for each section and HMA thickness. The modulus of the HMA layer was determined using the equivalent temperature concept for an 18-kip ESAL, as used in the original survivability analysis. The tensile strains decrease with increasing HMA layer thickness, as expected.

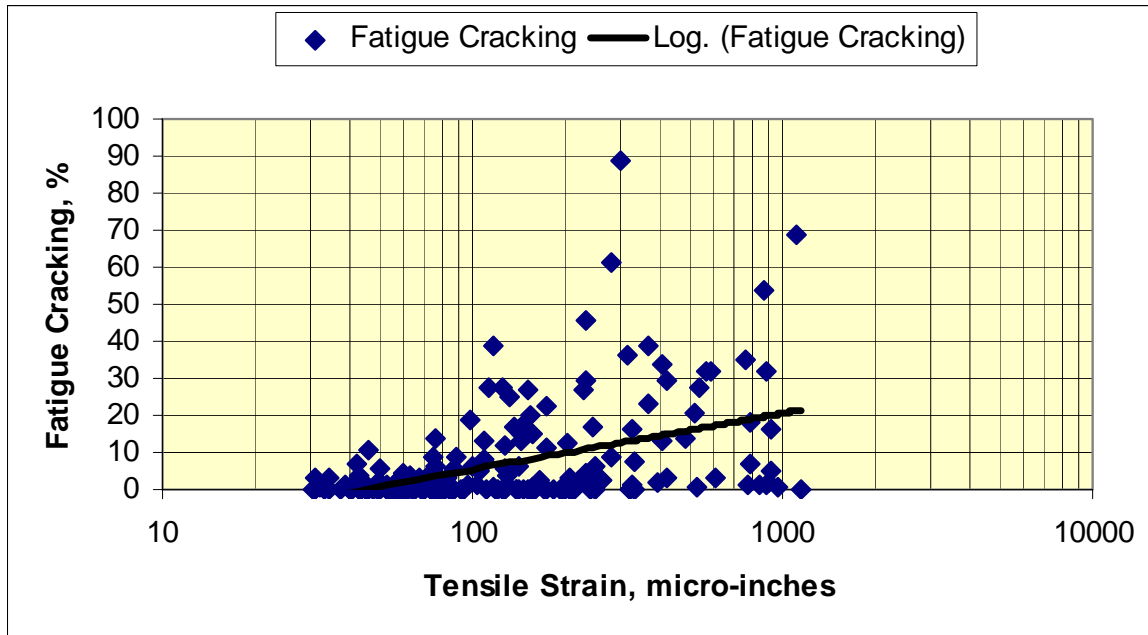
Figure 12 compares the maximum tensile strain at the bottom of the HMA layer and the amount of fatigue cracking observed on the LTPP test sections from the most recent distress survey included in the LTPP database. The test sections with the lower tensile strains have less fatigue or alligator cracking, just like the original survivability study.

An updated survival curve was developed for the additional alligator cracking data recorded in the LTPP database. Figure 13 shows the results from the survival analysis for a range of fatigue cracking levels. The results from the updated survival analysis are significantly different from the initial 1995 study. In fact, the updated survival curve for the 1 and 2 percent alligator cracking levels would indicate that there is no endurance limit for these sections. The relationships shown in Figure 13 for the 1 and 2 percent cracking levels have a peak survival rate significantly less than 100 percent and then begin to decrease (increasing probability of exceeding the allowable value) with lower tensile strain values.

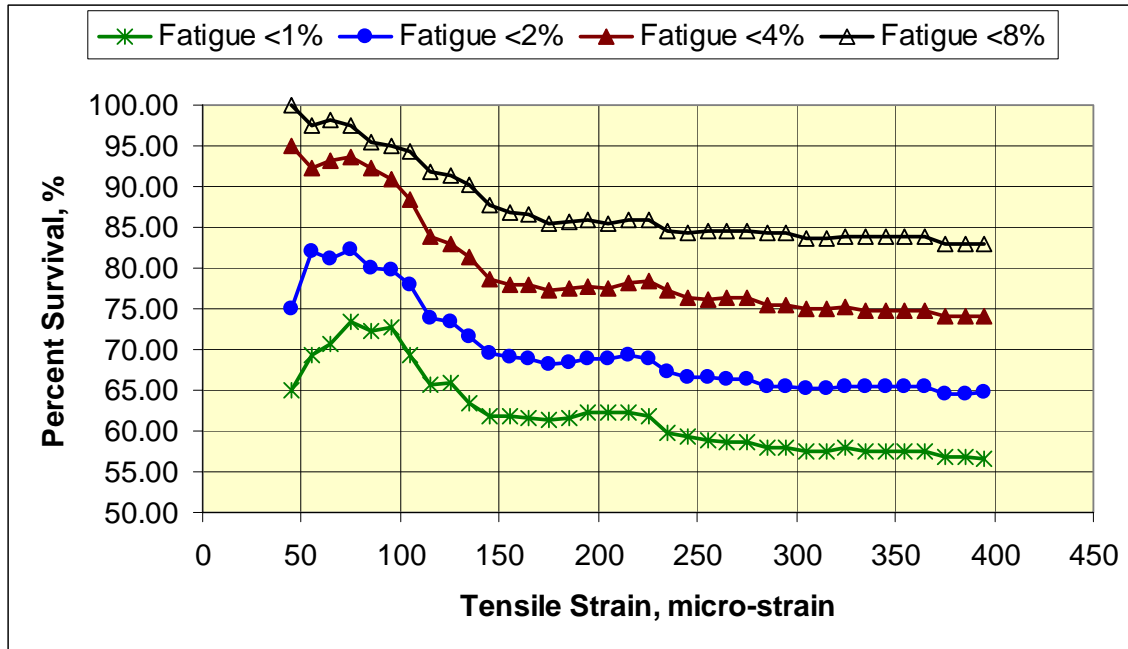
Some of the GPS test sections without alligator cracks in 1995, now have some alligator cracks recorded in the LTPP database for the test sections with the thickest HMA layers. Possible reasons for the significant difference in results from the survival curve developed in 1995 are summarized below.



**Figure 11** Comparison of the maximum tensile strain at the bottom of the HMA layer and HMA thickness.



**Figure 12** Comparison of the area fatigue cracking for and maximum tensile strain computed at the bottom of the HMA layer.



**Figure 13** Survival curves based on the maximum tensile strain at the bottom of the HMA layers of flexible pavements included in the LTPP program.<sup>1</sup>

- Adding the SPS-1 projects to the updated analysis. It is expected that including the SPS-1 projects did not cause this difference in findings, unless the fatigue cracking initiated from some other design-site feature that would have a higher probable occurrence within the SPS-1 test sections, as compared to the GPS sections. In addition, the study completed for the Asphalt Pavement Alliance concluded that there was a possibility that the GPS test sections selected by the individual agencies for the LTPP program are biased towards the better performing pavements. The SPS-1 projects were built during the LTPP program and would not be biased towards better performing pavements. It is expected that this is not the reason for the difference in survival curves.
- Change in the LTPP definition of longitudinal cracking in the wheel path. The change in definition could have affected the updated survival curve. Some of the previously measured longitudinal cracks that are assumed to have initiated at the surface are now recorded as alligator cracking and are assumed to have initiated at the bottom of the HMA layer. The cracking maps and video distress data logs can be reviewed to segregate longitudinal cracks with crack deterioration along the edges from traditional alligator cracks. However, this evaluation process is time consuming.

<sup>1</sup> Preliminary results from NCHRP project 9-38 (*Endurance Limit of Hot Mix Asphalt Mixtures to Prevent Fatigue Cracking in Flexible Pavements*) that is in progress; Prime Contractor – National Center for Asphalt Technology.

- Assumption of where alligator cracks recorded in the LTPP database initiated. As noted above, alligator cracks are assumed to initiate at the bottom of the HMA layer and propagate to the surface. The validity of this assumption would have an effect on the survival curve. In addition, the maximum tensile strain at the bottom of the HMA layer was based on the assumption of full-bond between all HMA lifts. If partial bond exists between two lifts near the surface, load-related cracks can initiate at that location and propagate downward as well as upward. To determine the location of crack initiation and whether full-bond exists between all HMA lifts requires a forensic investigation.
- The initial and updated survivability analysis was performed assuming that stripping or moisture damage is not present within the HMA layer. Stripping and moisture damage were adequately identified during the initial sampling and coring program for the GPS test sections. For the SPS-1 projects, stripping or moisture damage may have occurred on some of the projects and resulted in premature alligator cracking for the thicker sections. This possible cause for the difference in findings can be resolved with forensic investigations.
- An additional reason or explanation for the difference in results is that there is no endurance limit for HMA mixtures.

## Summary and Conclusions

The 1995 survival curve and test results from the Asphalt Aggregate Mixture Analysis System (AAMAS) suggested that the endurance limit design premise has some validity. Conversely, the survival analysis completed with the updated LTPP performance data suggests just the opposite. Reasons for this discrepancy in results between different time periods were provided in the paper and could support or reject the hypothesis.

Based on the results from the updated survival analysis, forensic investigations of the test sections with the thicker HMA layers are needed to confirm the location of crack initiation and other assumptions used noted above in the survivability analysis. No definite conclusion can be reached from the field performance data collected to date in the LTPP database without a forensic investigation to confirm crack propagation direction and determine which reason is correct.

In summary, however, it is still believed by the author that the endurance limit is a valid design premise and is a HMA mixture property. As the modulus decreases, the endurance limit increases in portion to the results presented in Figure 6.

## Acknowledgement

The data used in this paper and study were extracted from the LTPP database, version VR 2004.6 release 18.0 (2004). In addition, the survival analysis using the updated LTPP database was completed as part of NCHRP project 9-38, which is currently in progress.

## References

1. N.G. Gharaibeh and M.I. Darter, *Longevity of Highway Pavements In Illinois—2000 Update*, Final Report FHWA-IL-UI-283, Illinois Department of Transportation, Springfield, Illinois, 2002.
2. N. G. Gharaibeh and M. I. Darter, *Probabilistic Analysis of Highway Pavement Life for Illinois*, Transportation Research Record 1823, Transportation Research Board, Washington, D.C., 2003.
3. NCHRP, *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures: Part 1 – Introduction and Part 2 – Design Inputs*, Final Report for NCHRP 1-37A, Prepared for National Cooperative Highway Research Program, Applied Research Associates, Inc., March 2004.
4. NCHRP, *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures: Part 3 – Design Analysis and Part 4 – Low Volume Roads*, Final Report NCHRP 1-37A, Prepared for National Cooperative Highway Research Program, Applied Research Associates, Inc., March 2004.
5. Von Quintus, H.L. and B. Killingsworth, *Analyses Relating to Pavement Material Characterizations and Their Effects on Pavement Performance*, Publication Number FHWA-RD-97-085, Federal Highway Administration, Washington, DC, August 1997.
6. Von Quintus, Harold L. and Brian Killingsworth, *Design Pamphlet for the Determination of Layered Elastic Moduli for Flexible Pavement Design in Support of the 1993 AASHTO Guide for the Design of Pavement Structures*, Publication No. FHWA-RD-097-077, Federal Highway Administration, Washington, DC, September 1997.
7. Von Quintus, Harold L., Jagannath Mallela, and Jane Jiang, *Expected Service Life and Performance Characteristics of HMA Pavements in LTPP*, Final Report 5672-2/1, Applied Research Associates, Inc., prepared for the Asphalt Pavement Alliance, June 2004.
8. Von Quintus, Harold L., J.A. Scherocman, C.S. Hughes, and T.W. Kennedy, *Asphalt-Aggregate Mixture Analysis System: AAMAS*, NCHRP Report No. 338, National Cooperative Highway Research Program, National Research Council, Washington, DC, March 1991.
9. Von Quintus, Harold L., *Hot-Mix Asphalt Layer Thickness Design for Longer-Life Bituminous Pavements*, Transportation Research Circular No. 503 – Perpetual Bituminous Pavements, Transportation Research Board, National Research Council, Washington, DC., December 2001.