METHODS FOR DETERMINING THE ENDURANCE LIMIT USING BEAM FATIGUE TESTS

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ABSTRACT

The National Center for Asphalt Technology (NCAT) has lead a research effort for NCHRP project 9-38 to look at the endurance limit for HMA. This study has involved conducting fatigue tests for a number of mixtures over a wide range of strain levels. Tests have been conducted that have required up to 50 million cycles to failure. The Asphalt Institute has also been involved in the portion of the work to test samples having fatigue lives up to 50 million cycles.

The primary objectives of this study were to determine if HMA mixtures do have an endurance limit and to provide guidance on determining this limit for various mixture types. The portion of the study presented in this report includes the data supporting the concept for an endurance limit and examples indicating how the data can be extrapolated from tests conducted at higher strain levels (lower cycles to failure) to estimate the endurance limit.

The results indicate that HMA mixtures do appear to have an endurance limit. This limit has been shown to vary with mix type so there is not just one limit that can be used for all mixes.

Conducting tests to very high numbers of cycles can be very time consuming, taking as much as two months to conduct one test. Methods for extrapolating data are discussed to show how test results with smaller cycles to failure can be extrapolated to estimate fatigue life at higher cycles to failure.

INTRODUCTION

Pavements have been primarily designed to resist rutting of the subgrade and bottom-up fatigue cracking. In classical pavement design, as design load applications increase, pavement thickness must also increase. There is a growing belief that for thick pavements bottom up fatigue cracking does not occur. The concept of an endurance limit has been developed. This concept assumes that there is a strain level below which no fatigue damange occurs. This strain level is referred to as the endurance limit. Therefore, additional pavement thickness, greater than that required to keep strains below the endurance limit, would not provide additional life. This concept has significant design and economic implications.

The concept of the endurance limit was originally developed for metals (*1, 2*). Barret et al (*2*) describe the endurance limit for metals as being a stress below which for uncracked materials, the plot of stress versus cycles to failure becomes essentially horizontal and fatigue does not occur. Monismith and McLean (*3*) first proposed an endurance limit of 70 micro-strain for asphalt pavements. It was observed that the log-log relationship between strain and bending cycles converged at approximatley 70 micro-strain at approximately 5 million cycles. Maupin and Freeman (*4*) noted a similar convergence.

In the field, Nunn (*5*) in the United Kingdom (UK) and Nishizawa et al (*6*) in Japan proposed concepts for long-life pavements for which classical bottom-up fatigue cracking would not occur. Nunn (*5*) defines long-life pavements as those that last at least

40 years without structural strengthening. The UK's pavement design system was based on experimental roads which had carried up to 20 million standard axles. When this study was conducted, these relationships were being extrapolated to more than 200 million standard axles. Nunn (*5*) evaluated the most heavily traveled pavements in the UK, most of which had carried in excess of 100 million standard axles to evaluate the then current design system. Nunn (*5*) concluded:

- For pavements in excess of 180 mm thick, rutting tended to occur in the HMA layers, not in the underlying structure.
- Surface initiated cracking was common in high traffic pavements, but there was little evidence of bottom-up fatigue. Surface initiated cracks tended to stop at a depth of 100 mm.
- It was observed that the stiffness of thick pavements increased with time, most likely due to binder aging. This would not tend to occur if the pavement was weakening due to accumulated damage.
- A minimum thickness for a long-life pavement was recommended as 7.9 inches with a maximum thickness of 15.4 inches. The range is based on a variety of factors such as binder stiffness.

Nishizawa (*6*) reported an endurance limit of 200 micro-strain based on the analysis of in-service pavements in Japan. Similarly, strain levels at the bottom of the asphalt layer of between 96 and 158 micro-strain were calculated based on back-calculated stiffness data from the falling-weight deflectometer for a long-life pavement in Kansas (*7*). Others (*8*, *9*) report similar findings, particularly the absence of bottom-up fatigue cracking in thick pavements and the common occurrence of top-down cracking.

PURPOSE AND SCOPE

The purpose of this study was to confirm the existence of the endurance limit for hot mix asphalt (HMA) and to develop a methodology for determining the strain level corresponding to the endurance limit. In 2003, a pavement structural study consisting of eight test sections was constructed at the NCAT Pavement Test Track representing three pavement thicknesses (*10*). Two binder grades, PG 64-22 and PG 76-22 were used with the same target gradation for the HMA base layers. The base layers from the structural study were replicated in the laboratory using both the PG 64-22 and PG 76-22 binders. In addition, mixes were prepared at optimum plus 0.7 percent binder content. Beam fatigue samples were prepared and tested to determine the endurance limit of each of the four combinations. This paper discusses methods to determine the endurance limit using the data from the PG 64-22 mix at optimum asphalt content.

METHOD OF IDENTIFYING ENDURANCE LIMIT

The base and leveling course of the structural sections (N1 through N8) of the 2003 NCAT Test Track were constructed with a 19.0 mm nominal maximum aggregate size Superpave mixture using a blend of granite, limestone and natural sand aggregates.

The average of the as-constructed gradation and asphalt content are shown in Table 1. The mixture was designed in accordance with Alabama Department of Transportation's specifications with an N_{design} = 80 gyrations. The average in-place gradation was replicated in the laboratory. Beam fatigue samples were produced using two binder grades, PG 64-22 and PG 76-22 and two asphalt contents: optimum (4.6 percent) and optimum plus 0.7 percent (5.3 percent) binder for a total of four mixes. The PG 76-22 was modified with SBS. The loose mix was aged for four hours at compaction temperature. Oversize beams were compacted using a linear kneading compactor. The compactor was originally designed to produce Georgia Loaded-Wheel Rut Test samples and later modified to produce a longer sample for beam fatigue testing. The beams were sawed to size, 380 mm long, by 50 mm thick, by 63 mm wide, using a wet diamond saw.

TABLE 1 Average In-Place Gradation and Asphalt Content

Sieve Size, mm	**Average Percent Passing**
25.0	100
19.0	92
12.5	80
9.5	70
4.75	55
2.36	44
1.18	37
0.600	27
0.300	15
0.150	9
0.075	6
Asphalt Content	4.6

The beams were tested according to AASHTO T321 at 20 °C using an IPC Global pneumatic beam fatigue apparatus. Testing was conducted until a 50 percent reduction in initial stiffness occurred (failure) or 50 million cycles, whichever came first. Samples were tested in constant strain mode using sinusoidal loading at 10 Hz. Two replicate beams were tested at each of the following strain levels: 800, 400, 200, 100, 70, and 50 microstrain. Once a pair of beams both survived to 50 million cycles, the strain level from a log-log plot of strain versus fatigue life equal to a 50 million cycle fatigue life was calculated. Two additional beams were tested at this strain level. Testing was not conducted at additional strain levels below that which initially produced a fatigue life in excess of 50 million cycles. In some cases, three replicates were tested to provide additional information on variability.

If the HMA samples truly exhibited behavior indicating a strain level below the endurance limit, theoretically the samples could be tested for an infinite number of cycles. Testing to an infinite number of cycles in the laboratory is impractical, so a practical definition of the endurance limit was needed. The Highway Capacity Manual states that the maximum number of passenger cars per hour per lane for a freeway at a free flow speed of 65 mph is 2350 (*11*). In rolling terrain, a single truck or bus would replace 2.5 passenger cars (*11*). Thus, one would expect a maximum of 940 trucks per hour or a maximum of 329,376,000 trucks in a 40 year period. Such a case might represent a dedicated truck lane running at capacity 24 hours a day, 7 days a week, 365 days a year, an unlikely occurrence. Similarly, by calculating the appropriate heavy-vehicle adjustment factor and determining its impact on traffic flows (*11*), mixed traffic streams with 25 and 50 percent trucks would produce a maximum of 148,219,200 and 235,118,400 trucks in a 40 year period.

Consider, for example, an FHWA Class 9 vehicle or five-axle single trailer, which typically consists of four tandem axles and a single steer axle. Assuming that one is designing a perpetual pavement for the tandem axle load, the steer axles would have a lower loading so theoretically in a perpetual pavement design would do no damage to the pavement. Thus, each Class 9 vehicle would provide 4 load repetitions to the pavement for a maximum total of 1,317,504,000 axle load repetitions in a 40 year period. This then represents a theoretical maximum loading where every truck is fully loaded and the design lane is at maximum capacity for 24 hours a day, seven days a week, for a 40 year period. This loading condition would be expected to be more severe even than a dedicated truck lane. A similar methodology was used by Mahoney to calculate the maximum number of ESALs expected in a 40 year period (unpublished data).

In actual mixed traffic streams, the highest percentage of trucks tends to be about 50 percent, which would reduce the maximum number of load repetitions to 940,473,600 or a maximum number of load repetitions of 592,876,800 for 25 percent trucks. Even the most heavily traveled highways do not maintain traffic streams at the minimum safe following distance 24 hours a day and not all trucks are loaded. The fact that all trucks are not fully loaded is illustrated by a Washington DOT study of 10 weigh-in-motion sites over a one year period which indicated that the typical number of ESALs for a Class 9 vehicle was 1.2 (*12*). If 1.2 “maximum design load” axles were applied per truck for the maximum number of trucks per lane in a 40 year period (329,376,000), 395,251,200 load repetitions would be applied. Also, in winter months in many parts of the country the pavement stiffness is very high resulting in significantly lower strains. Therefore, it is a reasonable assumption that the maximum possible number of load repetitions expected in a 40 year period is approximately 500 million.

Research conducted during the Strategic Highway Research Program recommended a shift factor of 10 between laboratory beam fatigue results and field performance equating to 10 percent cracking in the wheel-path (*13*). Considering this shift factor, laboratory testing to 50 million cycles would equate to approximately 500 million loading cycles in the field or approximately the maximum possible loading in a 40 year period. Based on these analyses, a mix which provided 50 million cycles or more was considered to be below the endurance limit. Hence, the endurance limit was set at a strain level that would provide 50 million cycles. It takes approximately two months to complete a single test to 50 million cycles.

RESULTS AND DISCUSSION

The test results for the granite 19.0 mm nominal maximum aggregate size mixture with PG 64-22 at optimum asphalt content are shown in Table 2.

Methods for Extrapolating Fatigue Life

There are a number of methods for determining the fatigue life including: exponential models, power models, dissipated energy methods and Weibull functions. In addition, some tests at low strain levels can be extrapolated using the linear portion of the stiffness versus loading cycles curve. Each of these will be discussed and examples given of the predicted fatigue lives. AASHTO T321 specifies an exponential model

TABLE 2 Granite 19.0 mm NMAS mix with PG 64-22 at Optimum AC%

Beam ID	Air Voids, %	Initial Flexural Stiffness, MPa	Micro-Strain	Cycles Tested	Cycles to 50% Initial Stiffness	Avg. Cycles to Failure
18	6.6	5,175	800	6,000	6,000	6,377
3	6.8	4,686	800	7,130	7,130	
7	7.4	4,522	800	6,000	6,000	
10	6.8	5,153	400	246,220	246,220	252,136
46	7.0	5,239	400	57,000	267,808[1]	
1	7.0	5,868	400	242,380	242,380	
2	6.6	5,175	200	26,029,000	26,029,000	20,445,922
6	7.2	6,435	200	12,930,000	14,537,186[2]	
21	7.4	6,240	200	20,771,580	20,771,580	
5	6.7	4,519	170	34,724,500	34,724,500	66,942,707
23	6.8	5,645	170	60,000,000	9.92E+07[3]	
4	6.7	6,602	100	50,000,000	3.64 E+12[3]	1.14 E+13
13	7.4	5,059	100	50,000,000	1.92 E+13[3]	

[1] Failure extrapolated. Testing suspended at 58 percent of initial stiffness at 57,000 due to computer problem.

[2] Software froze, apparently due to error writing to network drive. Sample stiffness 3,439 MPa, at 53.4 percent of initial stiffness. Result extrapolated using linear regression of latter cycles.

[3] Results extrapolated using natural logarithmic model.

(Equation 1) for the calculation of cycles to 50 percent initial stiffness:

$$S = Ae^{bn} \tag{1}$$

where,

S = sample stiffness (MPa),
A = constant,
b = constant, and
n = number of load cycles.

The constants are determined by regression analysis of loading cycles versus the natural logarithm of the flexural stiffness. The number of cycles to failure is determined by solving Equation 1 for 50 percent of initial stiffness. In this study, for samples tested to less than 50 million cycles, the number of cycles reported to reach 50 percent of the initial stiffness is the actual number of cycles recorded by the test equipment, not the number of cycles determined using Equation 1. No discussion is provided in AASHTO T321 regarding whether or not all of the data (particularly the initial data) should be used when solving for the constants in Equation 1.

Sample 6 of the PG 64-22 mix at optimum asphalt content, which was tested at 200 micro-strain, is used as an example. Figure 1 shows various methods of fitting the relationship between sample stiffness and cycles to failure. Generally speaking, Equation 1 does not provide a good fit to the test data for Sample No. 6 or for the other samples tested.

Initially, the extrapolations conducted in this study used a logarithmic model (Equation 2):

$$S = \alpha + \beta \times \ln(n) \qquad (2)$$

where,

α and β are regression constants.

When all of the fatigue data is used to fit a logarithmic model, the slope of the fitted line at higher numbers of loading cycles may be flatter than the actual data. This leads to an overestimation of the fatigue life. However, by eliminating a portion of the early loading cycles, a good match to the data can generally be obtained, particularly at low strain levels. In Figure 1, a logarithmic model is shown where the first million loading cycles were not included in the regression analysis. This provides a better fit to data, but it still (in this case) would tend to overestimate the fatigue life. Further, the number of early loading cycles which are not included needs to be determined by trial and error. Note that both logarithmic models shown in Figure 1 provide high R^2 values. The logarithmic model which includes all of the data actually provides a slightly higher R^2 value even though it provides a poor fit to the data at a high number of loading cycles. This suggests that R^2 values alone are not adequate to evaluate extrapolation models.

The ratio of dissipated energy, developed by Shen and Carpenter (*14*) also requires that the number of cycles to 50 percent of initial stiffness be calculated in order to determine the plateau values. Shen (unpublished data) recommend a power model (Equation 3) for the extrapolation of stiffness versus loading cycles:

$$S = \alpha \times n^{\beta} \qquad (3)$$

where,

α = 10 raised to the power of the intercept from regression of log (S) versus log (n), and

β = the slope from regression of log (S) versus log (n).

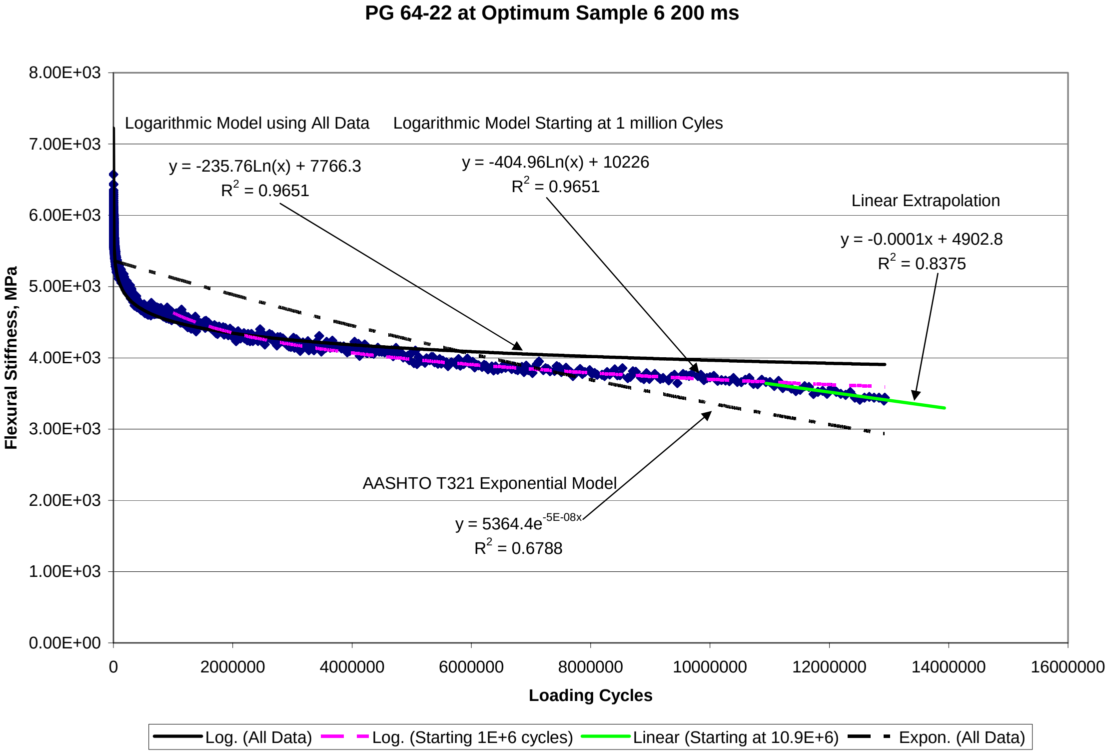

FIGURE 1 Example of Various Methods of Extrapolation

The power model has a similar shape to the logarithmic model. Shen (unpublished data) also report the need to eliminate a number of initial cycles to obtain a good fit to the slope at high numbers of cycles. Failure to eliminate some of the initial cycles results in an overestimation of the fatigue life.

The Weibull survivor function is another alternative for determining fatigue life. Failure data can often be modeled using a Weibull distribution. Tsai et al (*15*) applied the Weibull survivor function (Equation 4) to HMA beam fatigue data.

$$S(t) = \exp\left(-\lambda \times n^{\gamma}\right) \tag{4}$$

where,

S(t) = probability of survival until time t,
λ = scale parameter (intercept),
γ = shape parameter (slope).

The scale and shape parameters for laboratory beam fatigue data are determined by linear regression of the form shown in Equation 5:

$$\ln(-\ln(SR)) = \ln(\lambda) + \gamma \times \ln(n) \tag{5}$$

where,

SR = stiffness ratio or stiffness at cycle n divided by the initial stiffness.

Figure 2 shows an example of the data from the two 100 micro-strain samples from the PG 64-22 at optimum mixture in the form of Equation 5. Tsai et al (*15*) observed that the concave down shape, exhibited by sample 13, “implied that the fatigue damage rate is slowed down and flattens out with increased repetitions and thus causes no further damage after a certain number of repetitions.” Such behavior may be indicative of the endurance limit.

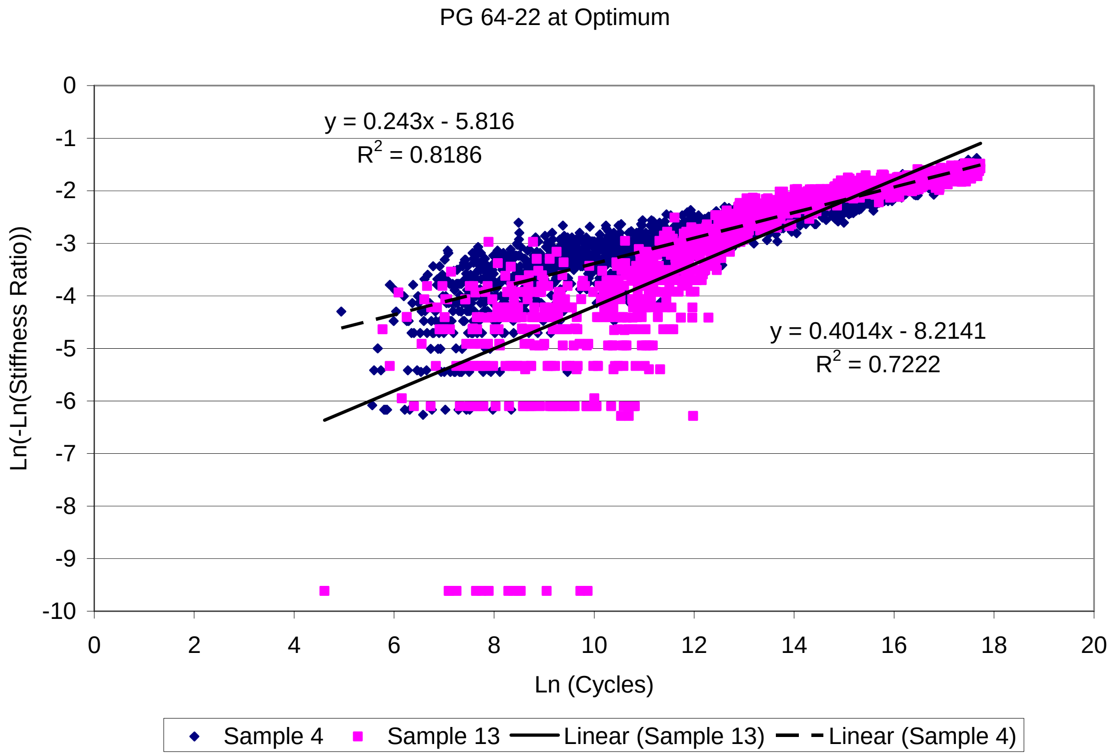

FIGURE 2 Weibull Survivor Function for PG 64-22 at Optimum 100 micro-strain Samples

The discussion on extrapolation techniques is provided as an introduction to future methodologies for identifying the endurance limit. In this study, tests were conducted to a maximum of 50 million cycles in order to confirm the existence of the endurance limit. As noted previously, it takes approximately two months to complete a single test. This extended test time is not practical for routine determination of the endurance limit. One alternative to determine the strain level that corresponds to the endurance limit for a given mixture would be to conduct beam fatigue tests at a low strain level to a more limited number of cycles (say less than 10 million or approximately ten days) and extrapolate the data. Thus a model would be fit to the stiffness versus loading cycle data and the number of cycles required to reach 50 percent of the initial stiffness would be extrapolated. A significant deviation from a log-log plot of strain versus cycles to failure would indicate the strain level corresponding to the endurance limit (this will be shown later). There are two main requirements for this technique that need to be evaluated, 1) the appropriate form of the model, and 2) the minimum number of cycles that need to be tested.

The samples tested at 100 micro-strain for the PG 64-22 at optimum asphalt content were first used to evaluate the ability of the various models to predict the sample stiffness at 50 million cycles. Four models were considered: exponential (AASHTO T 321), logarithmic, power, and Weibull function. All of the initial cycles were included when fitting the models. Figures 3 and 4 show the percentage of the actual measured stiffness at 50 million cycles for each of the models for samples 4 and 13, respectively. The cycles shown in Figures 3 and 4 represent the total number of cycles (starting at the first cycle) used to fit the model. The stiffness at 50 million cycles extrapolated using that model is then shown as a percentage of the measured stiffness on the y-axis. For example, if sample 4 would have been tested to 10 million cycles and a logarithmic model fit to the data, the extrapolated stiffness at 50 million cycles would be 108.2 percent of the measured stiffness at 50 million cycles.

Examination of Figures 3 and 4 shows that the exponential model consistently underestimates the stiffness at 50 million cycles and is slow to converge on the measured stiffness (testing would need to be conducted to a high number of cycles to even approach the measured stiffness. This would suggest that the exponential model recommended by AASHTO T 321 is not a good choice for extrapolating fatigue data. The predicted stiffness' using the logarithmic and power models are basically the same in Figures 3 and 4. Both converge to a reasonable predicted stiffness within 10 million cycles. However when all of the loading cycles are used, both overestimate the stiffness at 50 million cycles and consequently would overestimate the fatigue life. The Weibull function converges quickly and provides the most accurate results for sample 4, but does a relatively poor job for sample 13. Recall that the Weibull function for sample 13 had the convex down shape in Figure 2.

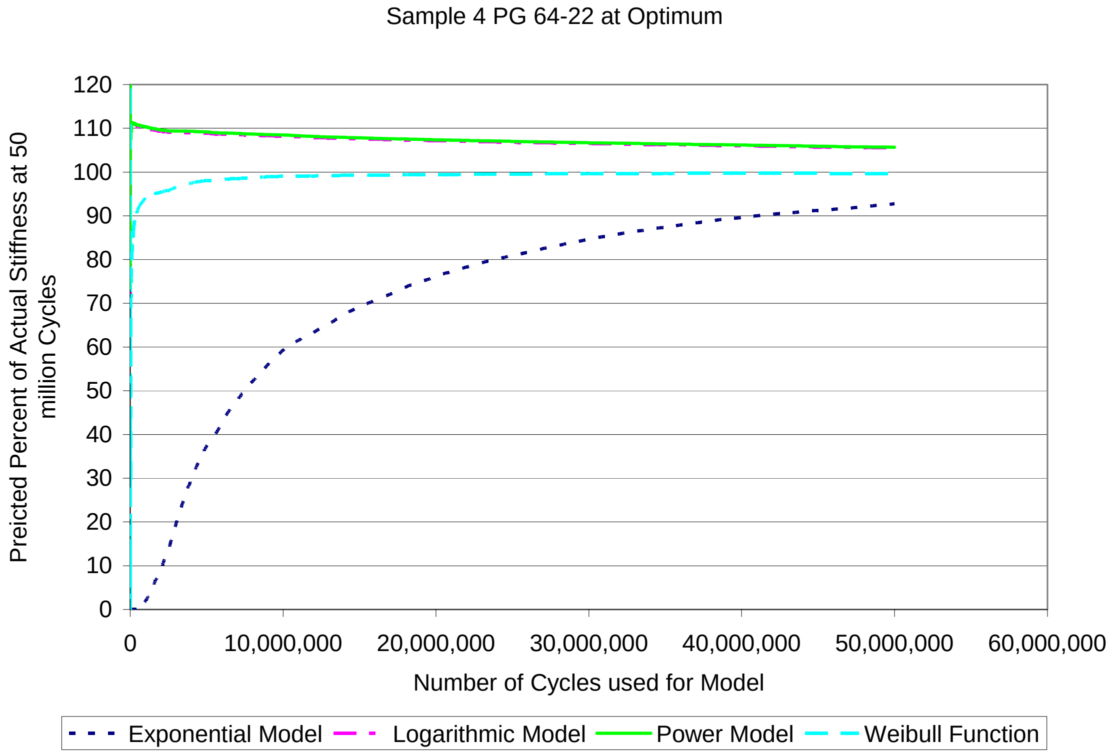

FIGURE 3 Convergence of Extrapolated Stiffness for Sample 4

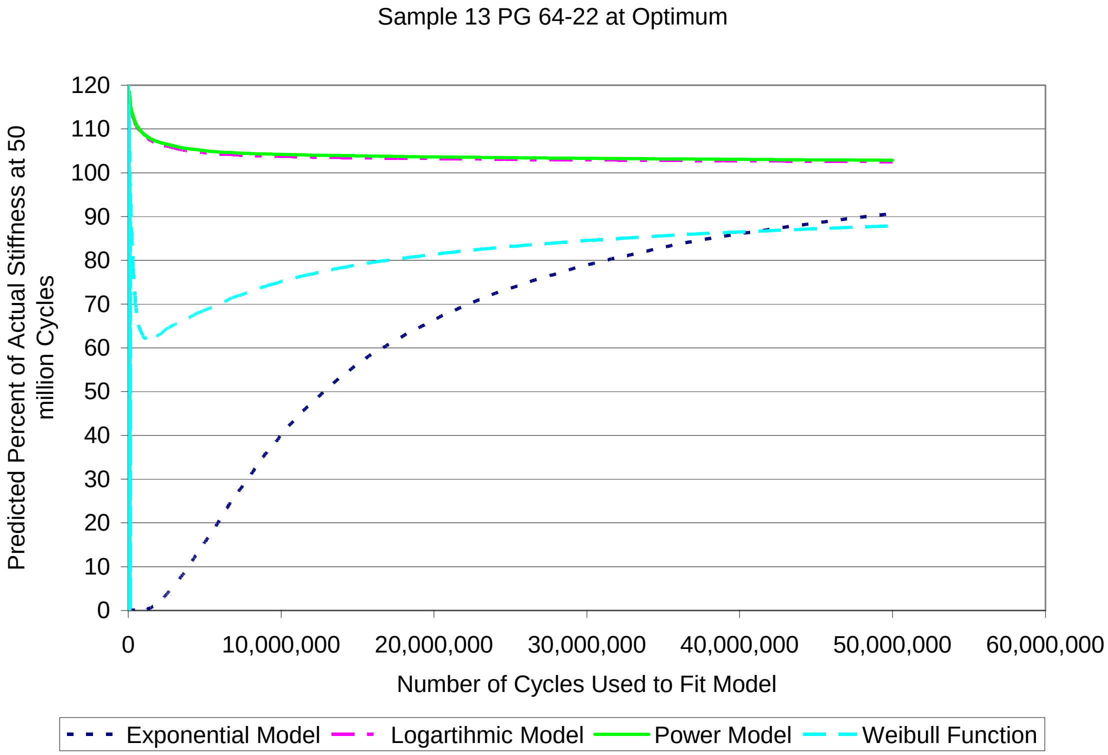

FIGURE 4 Convergence of Extrapolated Stiffness for Sample 13

The accuracy of the stiffness prediction is not the only factor which will affect the accuracy of the fatigue life extrapolation. The shape of the model will also have an effect. Logarithmic and power models can produce very flat slopes at high numbers of loading cycles which result in overestimation of the fatigue life (particularly if some of the initial cycles are not eliminated to better match the slope of stiffness versus loading cycles at a high number of loading cycles). Since the PG 64-22 at optimum asphalt content beams tested at 100 micro-strain did not fail, they could not be used to evaluate the accuracy of the fatigue life extrapolations. Therefore the PG 64-22 at optimum asphalt content samples tested at 200 micro-strain were used, since these samples failed at a high number of cycles. Predictions were based on models developed using the first 4 million loading cycles and the first 10 million loading cycles. A previous study on the endurance limit by Peterson and Turner (*16*) extrapolated the fatigue life based on testing to 4 million cycles. Shen and Carpenter (*14*) extrapolated test results based on tests conducted to greater than 8 million cycles.

Table 3 shows the fatigue life predictions for samples 2 and 21 of the PG 64-22 mix at optimum asphalt content. Both samples were tested at 200 micro-strain. In all cases, the exponential model underestimates the measured fatigue life and the logarithmic and power models overestimate fatigue life. The Weibull function seems to provide the most reasonable estimations, although there is significant error for sample 2 using the first 10 million cycles. When looking at the accuracy of fatigue predictions, it should be considered that one typically looks at strain versus fatigue life data on a log-log plot. The log of 26 million, the measured fatigue life for sample 2, is 7.41, while the log of 56 million, the fatigue life estimated based on the first 10 million cycles is 7.75. This indicates the two predictions are relatively close.

TABLE 3 Comparisons of Fatigue Life Extrapolations Using Four Models

Model	Sample 2		Sample 21	
	4 million cycles	10 million cycles	4 million cycles	10 million cycles
Actual	26,029,000	26,029,000	20,771,580	20,771,580
Exponential	6,012,055	13,657,870	4,935,588	9,876,585
Logarithmic	2,538,114,702	2,826,296,906	483,900,279	317,265,901
Power	38,048,289,325	34,312,439,544	4,192,727,459	1,780,688,228
Weibull	33,078,629	55,924,460	14,414,637	19,080,795

As noted previously, by excluding some of the initial loading cycles to better match the slope of the stiffness versus loading cycles curve at the highest number of cycles tested, the predictions using a logarithmic and power model can be significantly improved. Further, as the strain level being tested approaches the endurance limit, the shape of the curve between stiffness and loading cycles changes such that the logarithmic or power models tend to provide a better fit to the data. This is illustrated by comparing sample 21, tested at 200 micro-strain, and sample 13, tested at 100 micro-strain. Figure 5 shows the logarithmic model and Figure 6 shows the Weibull function.

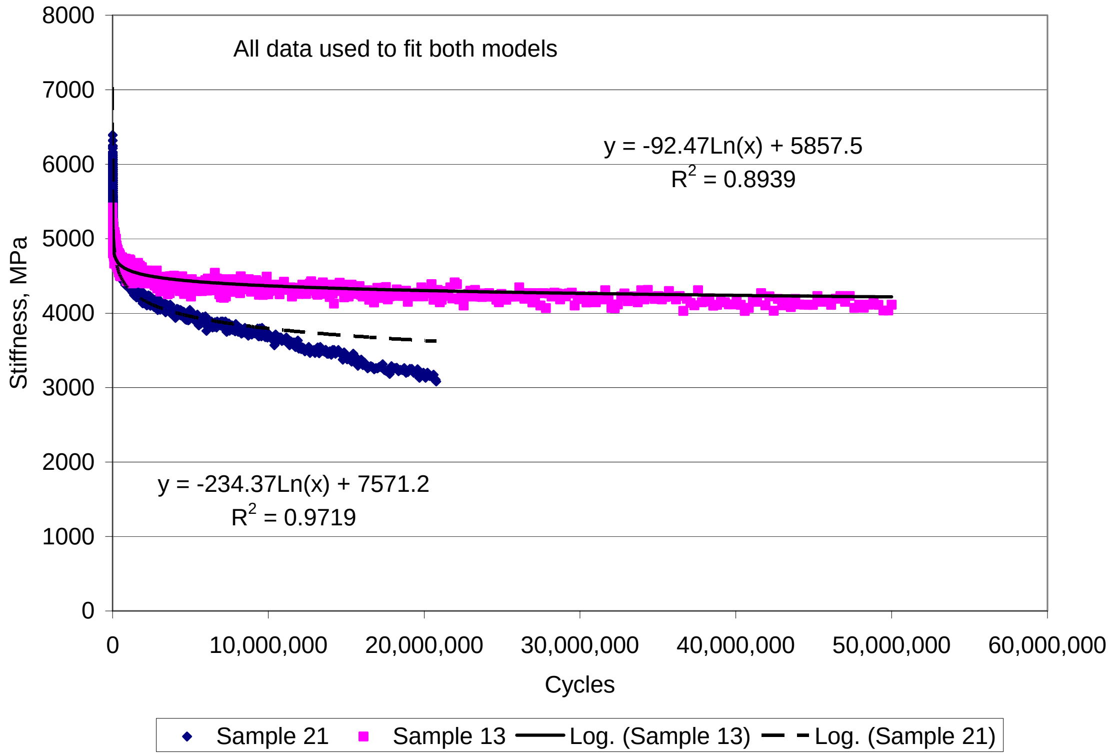

FIGURE 5 Logarithmic Models for Samples 13 and 21

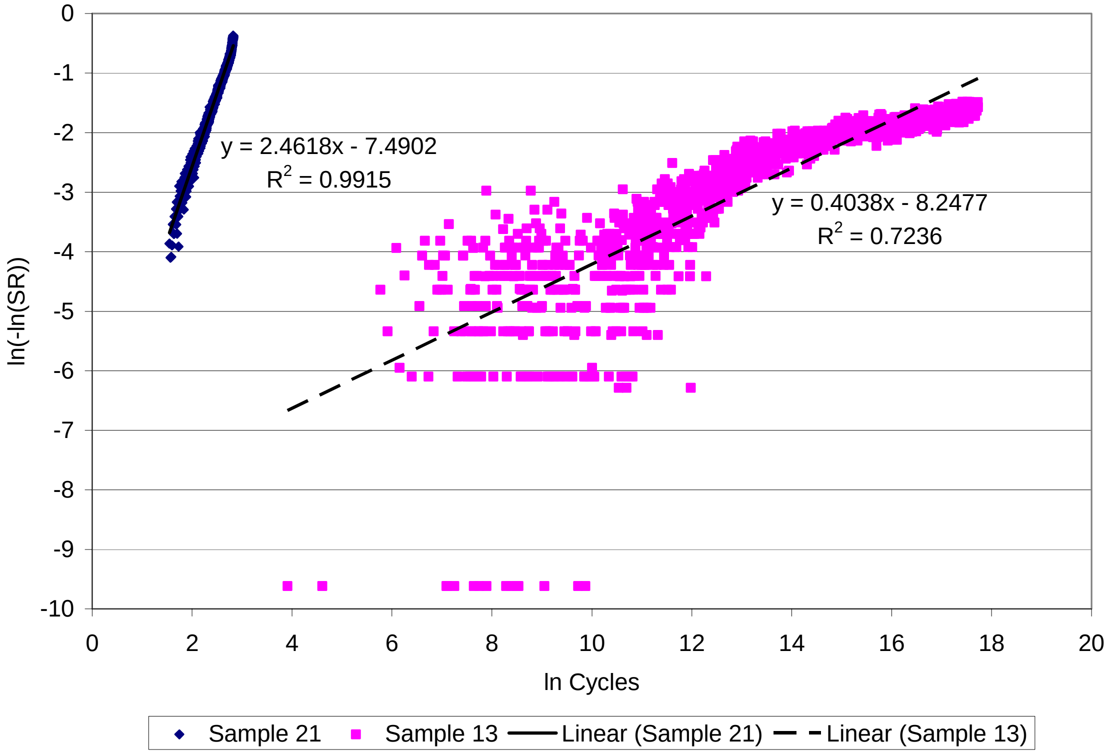

FIGURE 6 Weibull Functions for Sample 13 and 21

Note that the logarithmic model provides a better fit to the data at a high number of cycles for sample 13 and the Weibull function provides a better match to the data for sample 21. At low strain levels, there is not a mathematical solution for some of the initial stiffness versus cycle data when using the Weibull model. Once this data is eliminated, all of the remaining data can be used.

Although the exponential model recommended in AASHTO T 321 does not appear to be a good choice for extrapolating the number of cycles to 50 percent of initial stiffness for samples which are not tested to failure, it does provide a prediction of fatigue life for samples tested to failure. The advantage of using an exponential model to determine the number of cycles to failure for samples tested to failure is unclear.

Existence of an Endurance Limit

Numerous studies have indicated a good relationship between the log of strain and log of cycles to failure. A significant deviation from this relationship could be an indication of the endurance limit. Figure 7 shows a plot of strain versus cycles to failure for the PG 64-22 mix at optimum asphalt content. A regression line was fit to the data which failed in less than 50 million cycles. The logarithmic and Weibull function extrapolations are shown for the samples which did not fail in less than 50 million cycles. The extrapolations using the logarithmic model for the samples tested at 100 micro-strain indicate a clear deviation for the straight line extrapolation based on testing conducted at higher strain levels (3.64 E+12 and 1.92 E+13, respectively for samples 4 and 13). This deviation supports the concept of an endurance limit. However, the extrapolations based on the Weibull function do not show a similar deviation. In fact, sample 4 is indicated as having a longer fatigue life based on the single stage Weibull function. Figure 2, presented previously, shows the fit of the Weibull function for samples 4 and 13 tested at 100 micro-strain.

Note that the slope (γ) for sample 4 is less (0.243 compared to 0.404 for sample 13), which results in a longer fatigue life. However as noted previously, the data for sample 13 indicates a flattening of the slope at a high number of cycles indicating a decrease in damage or endurance limit. Thus a single stage Weibull function predicts a fatigue life of 5.49 E+9 and 3.00 E+8, respectively for Samples 4 and 13 tested at 100 microstrain. Neither of the fatigue life estimates includes a shift factor. A better extrapolation using the Weibull function might be obtained if some of the initial data at a low number of cycles were not included, similar to the logarithmic model or if a two or three stage Weibull function model were used to account for the change in slope. Both the logarithmic model and Weibull function produce similar fatigue lives for sample 23 tested at 170 micro-strain (99 million and 104 million cycles, respectively). Regardless of the exact procedures for fatigue life predictions, the test results indicate that pavements can be designed with a limiting strain value that will produce an exceptionally long, if not infinite fatigue life. Similar results, at even higher strain levels, have been observed for the other mixes tested in the study.

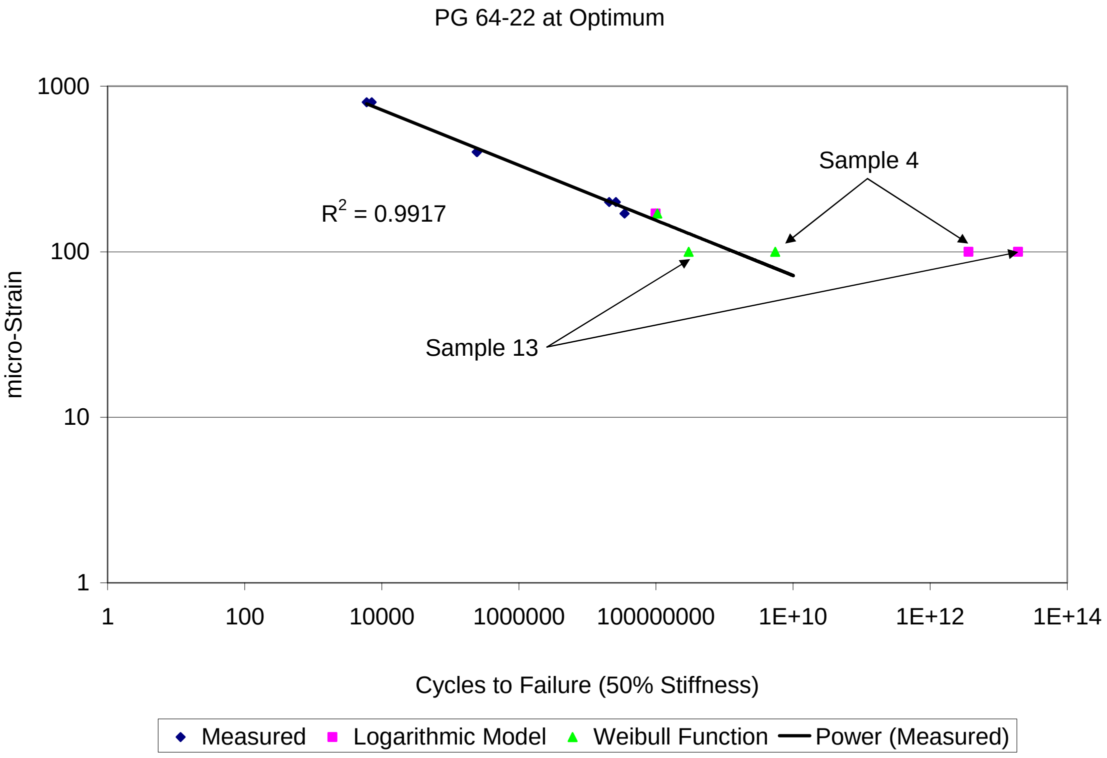

FIGURE 7 Strain versus Cycles to Failure for PG 64-22 at Optimum

CONCLUSIONS

The following are the significant findings to date from this research project:

- The exponential model recommended by AASHTO T 321 does not appear to be appropriate for the extrapolation of beam fatigue data. It can be used to model the failure point if the beam is tested to failure (50 percent of initial stiffness).
- Laboratory beam fatigue testing needs to be conducted to in excess of 10 million cycles to make an accurate prediction of the endurance limit.
- The Weibull function appears to be the best model to extrapolate the number of cycles to failure near the endurance limit and at strain levels higher than the endurance limit. Fatigue lives for beam fatigue tests conducted below the endurance limit are probably best extrapolated using a logarithmic model.
- Behavior indicative of both a practical and theoretical endurance limit was observed for the PG 64-22 mix at optimum binder content at approximately 100 microstrain.

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