AN ENERGY APPROACH FOR AIRPORT PAVEMENT LOW DAMAGE FATIGUE BEHAVIOR

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ABSTRACT

A correct prediction of the fatigue life is an important issue for the airport pavement structural design, especially with the emergence of new types of aircrafts such as B777 and A380. Design usually requires large amount of laboratory fatigue tests data which is very time consuming. For a thick airport pavement, it is typical to have long fatigue life which can never be reached in the field nor predicted in the laboratory if the traditional fatigue analysis approach is used. In this study, a new energy based approach, ratio of dissipated energy change (RDEC) is applied to develop a simple procedure to predict the fatigue life of hot mix asphalt (HMA) airport pavements under low damage condition, which can greatly shorten the time required for laboratory fatigue testing. It can also provide a fast determination for a thick airport pavement structure to show whether it can have an extraordinarily long fatigue life without structural failure when the “fatigue endurance limit” concept is incorporated. It is expected that the results will provide a methodology for a more rapid laboratory fatigue endurance limit study.

INTRODUCTION

The design of a structurally sound pavement without the necessity of major reconstruction and/or rehabilitation within design period is always a big concern for flexible airport pavement engineers, especially with the emerging new types of aircrafts such as B777 and A380. For a thick airport pavement with heavy loads, it is typical to design the pavement structure to result in low load response and a long fatigue life. In other words, the low damage condition is typical for airport pavement fatigue performance. The “fatigue endurance limit (FEL)” concept can be used to design an airport pavement with “unlimited” fatigue life by limiting the tensile strain at the bottom of asphalt layer below the endurance limit.

Because of the nature of the traditional fatigue analysis and other existing fatigue analysis approaches, it is very difficult to study the hot mix asphalt (HMA) fatigue behavior at low damage levels. When using the traditional strain-fatigue life analysis approach, the design must rely on a large amount of laboratory fatigue testing, which is extremely time consuming. At the low damage level, the fatigue life of tested samples will never reach failure (defined as the 50% initial flexural stiffness modulus reduction cycle) within a reasonable time frame, and the fatigue life has to be extrapolated based on long term fatigue tests with at least 8-million load repetitions [1]. This is not convenient for either practical usage or research purposes.

The objective of this paper is to introduce a new energy based approach for low damage fatigue behavior study and fatigue life estimation which can reduce the testing length required for low strain/damage fatigue testing. It is expected that the results will provide a methodology for laboratory fatigue endurance limit study.

RATIO OF DISSIPATED ENERGY CHANGE APPROACH

The concept of ratio of dissipated energy change (RDEC) approach was first introduced by Carpenter and Jansen [2], and then was well applied and verified by Carpenter et al. [1, 3, 4] for hot mix asphalt (HMA) material fatigue, fatigue endurance limit (FEL), and healing. As a fundamental energy based approach, the RDEC was also demonstrated valid for Portland Cement Concrete materials by Daniel and Bissirri [5]. This approach considers not all dissipated energy is responsible for material damage. Damage only comes from the relative amount of energy dissipation due to each additional load cycle, while the energy dissipated through passive behaviors such as plastic dissipated energy and thermal energy is not considered..

This incremental value, RDEC, which can be calculated based on equation (1), has a direct relation to damage accumulation. The typical cycle count between a and b for RDEC calculation is 100, i.e., b-a=100. Larger number such as 1000 or 10000 can be used when the DE change between every 100 cycle is too small to recognize. Such definition of RDEC provides a true indication of the damage being done to the mixture from one cycle to another by comparing the previous cycle's energy level and determining how much of it contributed to damage.

$$RDEC_a = \frac{DE_a - DE_b}{DE_a \times (b-a)} \tag{1}$$

where:

a, b = loading cycle a and b, respectively;

$RDEC_a$ = the average ratio of dissipated energy change at cycle a, comparing to cycle b;

DE_a, DE_b = dissipated energy at cycle a and b, respectively, which were calculated directly by fatigue testing program, kPa.

The typical RDEC vs. loading cycles curve can be divided into three stages. As shown in Figure 1, it develops a plateau (stage II) after the initial period (stage I). This plateau period, an indication of a period where there is a constant percentage of input energy being turned into damage, will extend throughout the main service life until a dramatic increase in RDEC occurs, which gives a sign of true fatigue failure (stage III). Here, the true fatigue failure represents final fracture with unstable crack propagation. It is a state where the material can no longer sustain further external loading due to internal fracture damage, and shows signs of macroscopically visible structural failure.

The RDEC value at the 50% stiffness reduction point is defined as the plateau value, PV, which is also shown in Figure 1. The detailed procedure to obtain PV from laboratory fatigue test data has been given by Carpenter and Shen [6]. This definition of PV is useful because the Nf_{50} value has been shown to relate precisely to the true fatigue failure (stage III) by Ghuzlan and Carpenter [7]. According to the findings by Shen and Carpenter [4], there is a unique relationship between PV and Nf_{50} (fatigue life at 50% stiffness reduction point) for different mixtures, loading modes, loading levels, and testing conditions (frequency, rest periods, etc.). The established PV-Nf_{50} relationship is presented in Equation (2).

$$PV = 0.4428 Nf_{50}^{-1.1102} \tag{2}$$

The PV is a comprehensive damage index that contains the effect of both material property and loading effect, hence can be a fundamental energy parameter to represent HMA fatigue behavior. A low PV value can be found either in high fatigue resistant materials, low external loading amplitude, or both.

The RDEC approach defines a unique energy level for the energy based fatigue endurance limit PV_L, which is the onset of the fundamental change in HMA fatigue behavior. If the energy level of a HMA mixture is below the PV_L due to the combination effect of material resistance and external load, the mixture is expected to have extended long fatigue life. According to the study by Shen and Carpenter [4], this critical PV_L value is 6.74E-9.

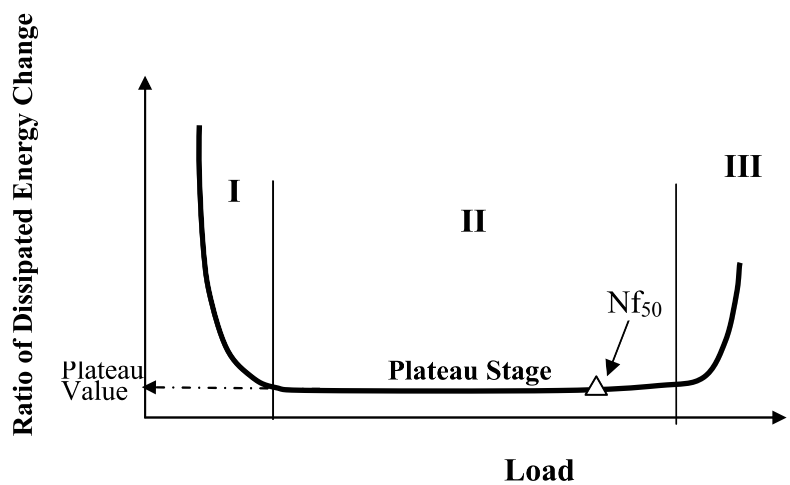

Figure 1. Typical RDEC vs. Loading Cycles Plot and the Indication of PV [1].

FATIGUE LIFE PREDICTION FOR LOW DAMAGE FATIGUE TESTING

Traditional Approach

It is typical to design a flexible airport pavement with thick asphalt layer and low load response (tensile strain) at the bottom of asphalt layer. The "Fatigue Endurance Limit" (FEL) concept can also be used to limit the tensile strain or load damage at the bottom of asphalt layer below the endurance limit to reach extended fatigue life. At such low strain/damage level, the damage accumulation in HMA mixtures is very slow and the load repetitions required to reach fatigue failure are extremely long. The traditional way to obtain the fatigue life at 50% initial stiffness reduction in the laboratory for such low damage testing is to extrapolate the stiffness-Loading Cycle (LC) curve based on limited but long term testing. Different models such as power model, linear model, exponential model, logarithmical model, and Weibull model can be used for the extrapolation [8]. In this paper the power law model is consistently used because it has been found to represent the long term trend of the stiffness-LC curve well when certain curve fitting rules are followed.

To ensure a reasonable extrapolation, tests usually have to be extended to 8 to 48 million repetitions. An example of comparing the predicted fatigue lives by extrapolating different length of stiffness curves varying from 500,000 to 48 million load repetitions are shown in Figure 2 and Table 1. As shown, fatigue lives predicted from less than 5 million load repetitions based on stiffness reduction curves can create very large error. Using this traditional stiffness approach, an 8–million load repetition is a minimum testing length which takes almost 10 days for 10Hz continuous cyclic loading in the laboratory. Greater load repetitions are recommended if higher prediction accuracy is needed.

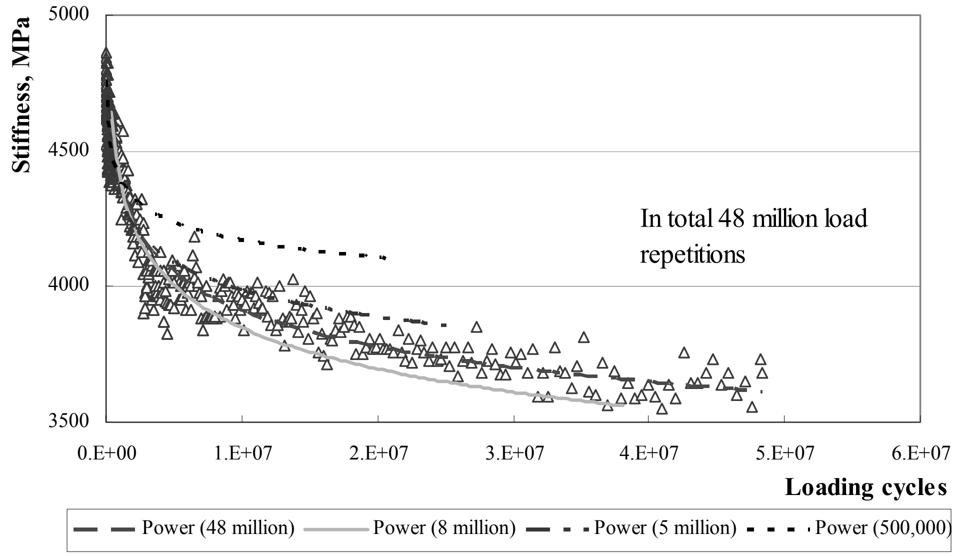

Figure 2. Comparing Stiffness Regression Curves from Different Load Repetitions for Mixture Post-16A from Illinois Department of Transportation (IDOT).

Table 1.

Fatigue Life Prediction from Different Extrapolation Length of Stiffness Curve (IDOT Mixture Post-16A)

Extrapolation Length	Nf	Error (%)
48 million	1.71E+11	
30 million	1.56E+11	-9.02
8 million	3.23E+10	-81.10
5 million	1.32E+13	> 1000
1 million	2.87E+18	> 1000
500,000	4.15E+16	> 1000

It is important to follow a consistent rule for the stiffness-LC curve fitting process considering its subjective nature. Different curve fitting methods are discussed here and an error analysis is performed to compare the errors created due to curve fitting an 8-million load repetition test. In this study, three samples (6-7-6SB, 5N9020A, Post16A) tested at the Advanced Transportation Research and Engineering Laboratory (ATREL) at the University of Illinois at Urbana Champaign (UIUC) are used as examples. Standard four-point bending beam fatigue test [9] with controlled strain mode at low strain levels were performed to extended load repetitions (30-48 millions) where the 50% initial stiffness reduction failure is not reached. The fatigue lives were predicted based on the extended testing (30-48 millions) and regarded as reference for the error comparison with the 8-million testing. Although the data is limited because such long term testing is extremely time consuming, the results obtained here can provide guidance for general low strain fatigue data analysis. The detailed Nf_{50} prediction and error analysis for each individual sample follows 3 steps:

1. Plot the stiffness-LC curve for the whole testing length (30-48 millions), and fit the curve with the highest R^2 fit using power law relationship. Check the trend of the fitted curve. If the trend does not follow the extension trend of the original curve, adjust the results by increasing the starting cycle of the fitting segment until the trend of the fitted curve follows the original data trend. Use the power law equation to predict Nf_{50} as the reference fatigue life.

2. Plot the stiffness-LC curve up to 8 million load repetitions on the same chart and fit the curve using the power law relationship. Three curve fitting methods are used here to compare the error and set up a consistent curve fitting rule. They are: (1) fit the curve to the highest R^2 value; (2) fit the curve using fixed test length of 2–8 million load repetitions; and (3) fit the curve using fixed test length of 3–8 million load repetitions.

3. Predict the Nf_{50} based on the three curve fitting methods individually, and calculate the errors relative to the reference fatigue life obtained in step 1.

Table 2 gives the predicted Nf_{50} for the three samples and the relative errors using different curve fitting methods for 8-million cycle testing. It appears that the highest exponential slope of the stiffness-LC curve (highlighted in Table 2) from the three curve fitting methods generally gives a good result, i.e., closer to the reference exponential slope. In fact, examining the stiffness-LC plots for the three samples as shown in Figures 3-5, the actual long term trend of the stiffness-LC curve for 8-million cycle testing is between power law relation and linear relation (exponential relation) but relatively closer to the power law relation. Power law regression from short tests (comparing 8million with 30million) tends to underestimate the curve exponential slope and overestimate the fatigue life, whereas linear regression tends to greatly underestimate the fatigue life. Therefore, for low strain/damage fatigue testing when fatigue life (Nf_{50}) is unknown, this study uses a power law regression. The three regression rules suggested in step 2 are compared for each sample and only the one gives the highest exponential slope of the stiffness-LC curve is adopted and used for fatigue life prediction.

Table 2.

Nf_{50} Predictions and Errors for 3 Extended Testing Samples Based on Stiffness Curves.

Mix ID	long term testing as reference				test to 8 million load repetitions									
	testing length	high R^2, good trend fit			highest R^2 fit				2-8 million fit			3-8million fit		
		abs(slope) of stiff-LC	Nf	R^2	abs(slope) of stiff-LC	Nf	R^2	error (%)	abs(slope) of stiff-LC	Nf	error (%)	abs(slope) of stiff-LC	Nf	error (%)
6-7-6SB	37 million	0.0364	8.47E+12	0.85	**0.0372**	**5.91E+12**	**0.89**	**30**	0.0323	4.74E+13	460	0.024	1.18E+16	>1000
5N9020A	30 million	0.0286	3.32E+15	0.35	0.009	4.60E+35	0.63	>1000	**0.0283**	**7.35E+15**	**121**	0.0226	1.50E+18	>1000
Post 16A	48 million	0.0501	1.71E+11	0.93	**0.0584**	**3.23E+10**	**0.88**	**81**	0.0507	1.18E+11	31	0.0274	5.85E+14	>1000

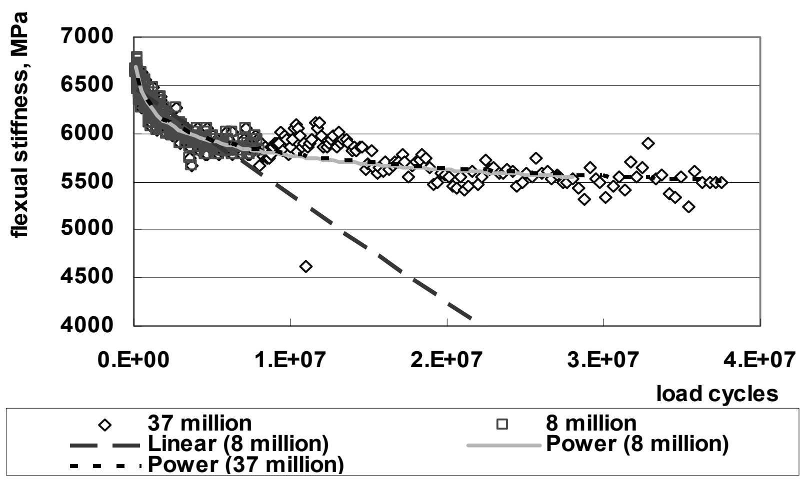

Figure 3. Stiffness vs. Loading Cycles Curve for Sample 6-7-6SB.

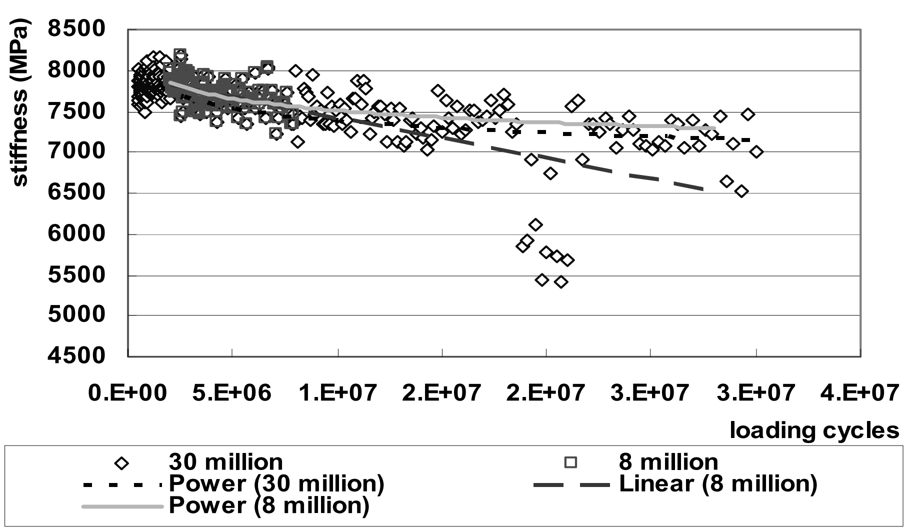

Figure 4. Stiffness vs. Loading Cycles Curve for Sample 5N9020A.

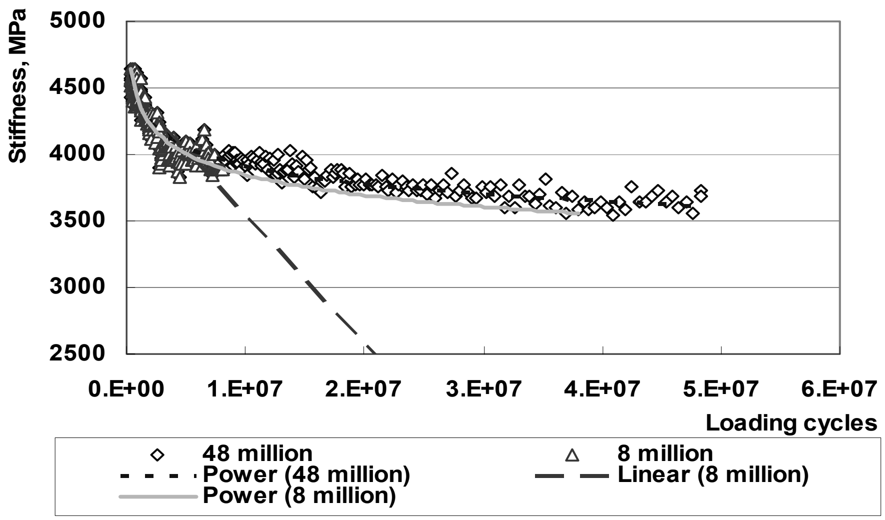

Figure 5. Stiffness vs. Loading Cycles Curve for Sample Post-16A.

Simplified RDEC Approach

The energy based RDEC approach provides a simplified way to use shortened testing to predict Nf at low damage level. In addition, the energy parameter, PV, can be obtained at the same time, which is useful for further fatigue endurance limit and healing studies [4, 6]. This approach is especially useful for flexible airport pavement with thick asphalt structures when the estimated fatigue behavior under low damage condition is needed. This approach is based on the research hypothesis that the plateau stage can be reached much earlier than the stiffness failure, and the findings that the PV-Nf follows a unique relationship for the whole damage level including low strain/damage level, which has been validated by Shen and Carpenter [4]. It is worth noting that in process of validating the PV-Nf relationship at low damage level, long term testing was used to ensure a reasonable prediction of Nf and PV.

The detailed procedure to predict the PV and Nf using the simplified approach is explained as follows:

1. For a sample tested at low strain level, plot the DE (Dissipated Energy) -LC data, and fit the DE-LC curve using a power law relationship. Obtain the slope of the curve, k. For curve fitting, it is recommended to eliminate the initial segment (initial load repetitions) of the DE-LC curve and use the latter part of the segment to ensure the fitted curve correctly represents the data's real trend. The fitting segment used should be no less than 1/4 of the total testing length in order to avoid misleading extrapolations. The detailed curve fitting rules will be discussed and explained later in this paper.

2. Calculate the RDEC at each loading cycle using Equation 3, as described in Carpenter and Shen [6], where the slope k is given by the fitted DE-LC curve, and a represents any cycle a. Plot the RDEC-LC curve (log-log) of the low strain/damage fatigue testing for this sample.

$$RDEC_a = \frac{1-(1+\frac{100}{a})^k}{100} \tag{3}$$

3. Plot the unique PV-Nf curve according to Equation (2) on the same chart.

$$PV = 0.4428 Nf_{50}^{-1.1102} \tag{2}$$

4. Extend the RDEC-LC curve until it crosses the unique PV-Nf curve.
5. The intersection point of these two curves produces: y=PV, x=Nf_{50}.
6. For low strain/damage fatigue testing, the PV calculation, Equation (4), can be simplified as Equation (5).

$$PV = \frac{1-(1+\frac{100}{Nf_{50}})^k}{100} \tag{4}$$

$$PV = \frac{1-(1+\frac{100}{Nf_{50}})^k}{100} \approx -\frac{k}{Nf_{50}} \tag{5}$$

7. Combine Equations (2) and (5), and solve for Nf_{50}.

$$Nf_{50} = (\frac{-k}{0.4428})^{-9.0744} \tag{6}$$

8. Using the calculated Nf_{50} in Equation (2), the PV for the tested sample is obtained.

Figure 6 shows examples of how the fatigue life is predicted using the simplified RDEC approach. The dashed lines represent the extended RDEC-LC curves for two samples tested at low strain/damage level, 5N90P2A and 3N904A. As the dashed lines cross the PV-Nf unique curve, the corresponding x-values indicate their predicted fatigue lives, and the y-values are the PV values for the two tested samples.

In addition to showing the predicted fatigue life, it is also important to check if the RDEC-LC curve passes below the fatigue endurance limit line, PV_L. An RDEC-LC curve below the PV_L will indicate the loading level is below the FEL and the sample will have an extremely long (nominally "unlimited") fatigue life under this loading level.

Also indicated in Figure 6 are the examples of the RDEC-LC curves for mix 5N90P at normal strain levels. They present the data trend developed during normal strain level fatigue tests and the corresponding failure point at each strain level.

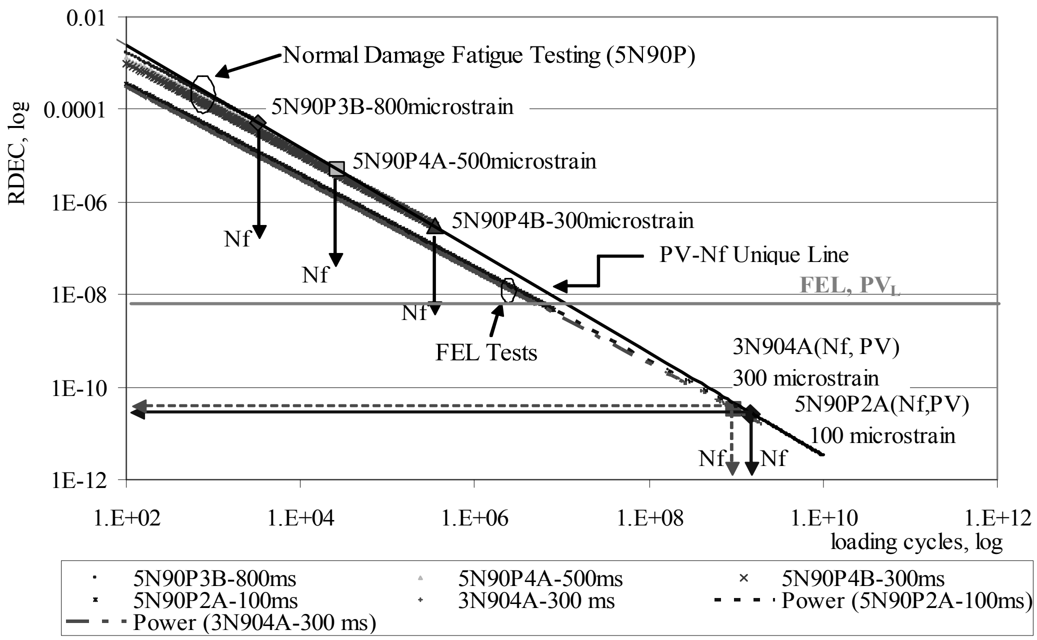

Figure 6. Fatigue Life Prediction Using RDEC Approach.

The simplified RDEC approach was applied to normal strain fatigue tests to give an indication how the predicted Nf and PV compare with the measured results. One thing that needs to be pointed out is that at normal strain/damage level, the damage level is relatively high and the dissipated energy change rate is fast. To use the RDEC approach to predict fatigue life, Equation (4) cannot be simplified into Equation (5) and the intersection point of the RDEC curve and the unique PV-Nf curve may need to be obtained mathematically or by "trial and error". Table 3 records the measured and predicted Nf and PV for four Illinois DOT mixtures tested at different controlled strain levels. The relative errors in Nf and PV due to prediction are also given in the table. These results are compared and presented in Figure 7 and 8. The data points are well distributed along the line of equality, indicating reasonable predictions.

Table 3.

Measured and Predicted Nf and PV for Four IDOT Mixtures.

Mix ID	strain	Test Data		Simplified Prediction			Error (%)	
		Nf	PV	abs(slope) of DE-LC	Nf	PV	Nf	PV
3N704A	1000	810	3.03E-04	0.2622	415	5.49E-04	-48.77%	81.22%
3N704B	800	3840	4.39E-05	0.1711	5500	3.12E-05	43.23%	-29.01%
3N705A	500	12820	1.80E-05	0.1734	5428	3.16E-05	-57.66%	75.69%
3N706A	300	261070	5.28E-07	0.1196	144075	8.30E-07	-44.81%	57.22%
3N90T2B	1000	1380	1.53E-04	0.2183	1040	1.98E-04	-24.64%	29.42%
3N90T2A	800	1830	1.02E-04	0.1926	2200	8.62E-05	20.22%	-15.50%
3N90T1B	500	24190	3.63E-06	0.1431	28289	5.06E-06	16.94%	39.35%
3N90T1A	300	397370	2.62E-07	0.1043	498923	2.09E-07	25.56%	-20.21%
6N501A	1000	2130	8.37E-05	0.1908	2555	7.30E-05	19.95%	-12.78%
6N501B	800	2110	8.86E-05	0.1921	2430	7.72E-05	15.17%	-12.89%
6N502A	500	31650	5.25E-06	0.1497	18790	7.97E-06	-40.63%	51.76%
6N502B	300	462960	3.36E-07	0.1109	285908	3.88E-07	-38.24%	15.44%
5N90P3B	800	3300	5.25E-05	0.1764	4700	3.71E-05	42.42%	-29.32%
5N90P4A	500	26900	5.05E-06	0.1361	44593	3.05E-06	65.77%	-39.56%
5N90P4B	300	357210	2.99E-07	0.1068	402426	2.65E-07	12.66%	-11.24%

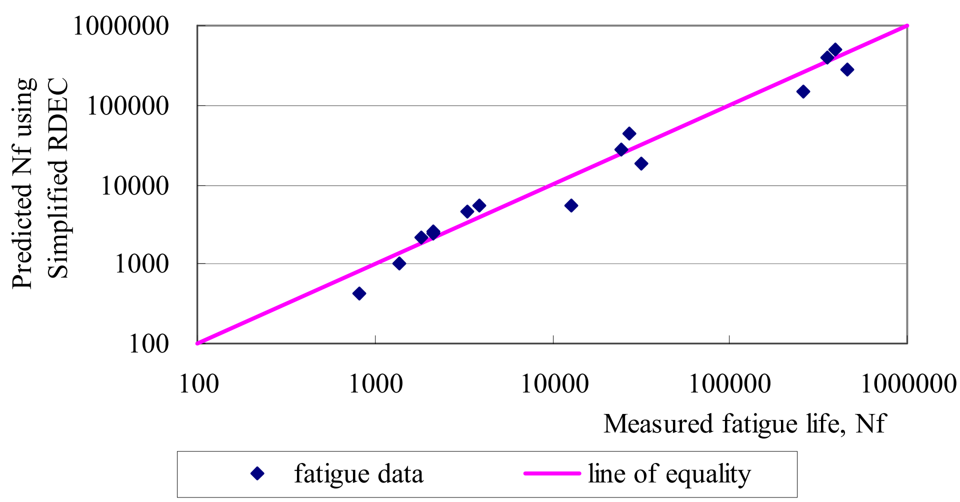

Figure 7. Comparison of the Measured and Predicted Fatigue Life.

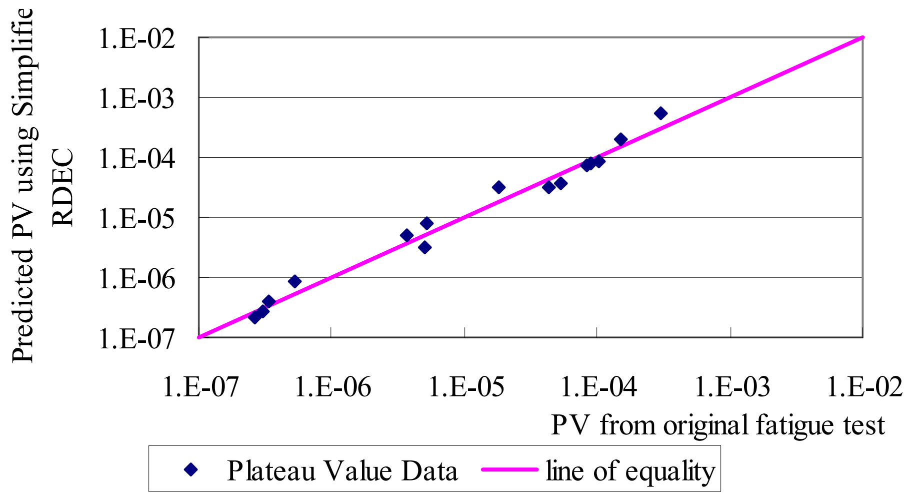

Figure 8. Comparison of the PV from Tests and from Prediction.

Test Length for Simplified RDEC Approach

To use the simplified RDEC approach to predict PV and Nf, the most critical step is to determine the exponential slope of the DE-LC curve. Conceptually, the longer the test length used for the prediction, the more accurate the exponential slope obtained, but the more testing time it consumes. Therefore, it is important to look for a balanced test length that can provide a good prediction as well as a reasonable testing time. In addition, a general curve fitting rule should be followed to minimize the error created due to different personnel since picking data segment for curve fitting is an empirical process.

A data analysis for various lengths of shortened testing was applied to five samples: three tested at University of Illinois at Urbana-Champaign (6-7-6SB, 5N9020A, Post 16A) at controlled 70 microstrain, and two tested at National Center for Asphalt Technology (NCAT #2, #21) at controlled 200 microstrain [8]. All five samples were tested beyond 20-million load repetitions. Two NCAT samples (#2, #21) actually reached the 50% initial stiffness reduction failure, while the other three did not reach the defined failure and the extrapolated fatigue life from long term testing is used as a reference to be compared with the shortened testing. The simplified procedure based on the RDEC approach, was applied for Nf and PV prediction for both shortened testing (1million, 5million and 8million load repetitions) and extended testing where extended testing was needed.

For the curve fitting process, several methods for picking the starting point of the data segment were compared including fitting the DE-LC curve to the highest R^2, and fitting the curve with a fixed cycle length (such as 2-8million, 3-8million, 2-5million, etc.). By comparing different methods, it was found that the pure “highest R^2” fitting is not sufficient to represent the correct curve trend and can create high error. In other words, R^2 values alone are not adequate to evaluate extrapolation model. Therefore, at this time, the “fixed curve fitting length and good trend” rule is followed. That is, fit the DE-LC using several testing lengths, for example, 2-8million cycles, 4-8million cycles, 2-5million cycles, and compare the fitted curve with the original curve trend. The exponential slope that best represents the original trend of the DE-LC curve is used for the PV and Nf prediction. Also, it should be cautioned that no matter which rule is used to fit the DE-LC curve, the fitting length should not be less than 1/4 of the testing length to avoid error.

Table 4 gives the comparison of the Nf and PV values predicted from shortened testing with the ones from extended testing. The results are also plotted in Figure 9. For each sample, the variability due to fitting the DE-LC curve from different testing lengths is indicated. As shown in Figure 9, both the long term testing and the shortened testing provide the same information, namely, that the specific PV values are all below the endurance limit line. In particular, the PV values of sample #2 and #21 are very close to the endurance limit line, indicating 200 microstrain could approximately be the strain endurance limit for the NCAT mixture. If the general fatigue behavior, whether the sample is below or above the fatigue endurance limit, is the major concern, the shortened test (but no less than 1million load repetitions) can give reasonable results. That is, the shortened test can provide a quick determination whether the sample tested under a certain loading level is exhibiting fatigue behavior that will be below the fatigue endurance limit without an accurate prediction of the precise number of load repetitions. However, large variations are found when comparing the PV and Nf values from shortened testing with the extended testing. Increasing the testing length from 1million to 8million load repetitions, in most cases, decreases the errors. Therefore, depending on the research requirements and error tolerance, different testing length can be used. Even a test as short as 1-million load repetition can provide reasonable fatigue life and PV information when the simplified RDEC approach is used, which is a good laboratory time saving for fatigue endurance limit (FEL) study.

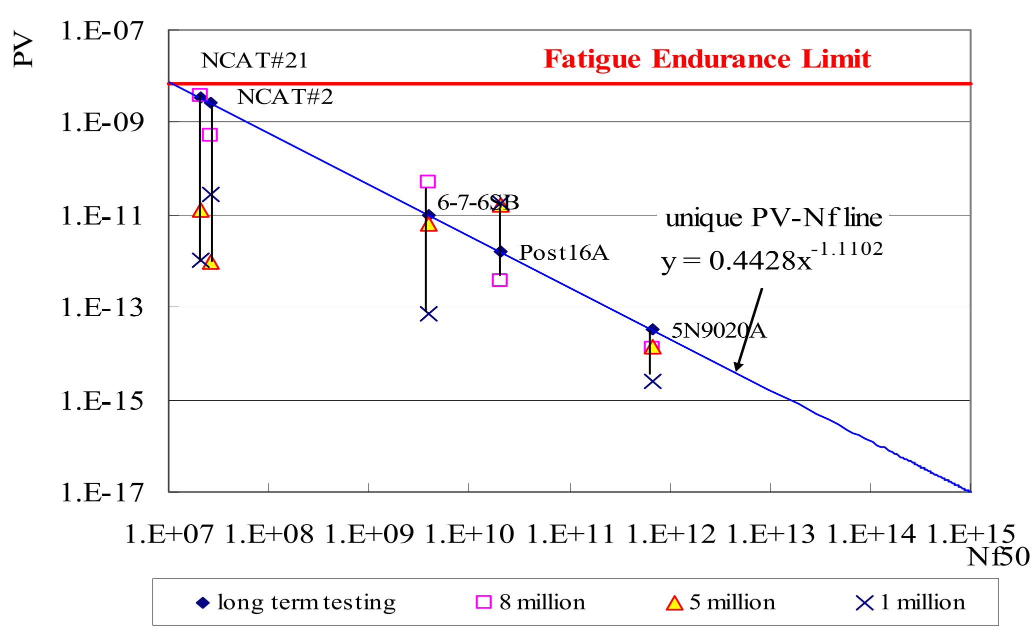

Figure 9. PV Predictions Based on Extended and Shortened Testing.

Table 4.

Compare Nf and PV Predicted from Different Test Length.

	long term testing		8 million testing		5 million		1 million	
Mix ID	Nf	PV	Nf	PV	Nf	PV	Nf	PV
6-7-6SB	3.85E+09	1.01E-11	9.09E+08	5.02E-11	5.63E+09	6.63E-12	3.32E+11	7.17E-14
5N9020A	6.78E+11	3.25E-14	1.61E+12	1.24E-14	1.41E+12	1.44E-14	6.67E+12	2.56E-15
Post 16A	2.02E+10	1.60E-12	7.60E+10	3.69E-13	2.55E+09	1.60E-11	2.33E+09	1.76E-11
NCAT#2	26,029,000[a]	2.59E-09	1.11E+08	5.19E-10	3.11E+10	9.95E-13	1.52E+09	2.84E-11
NCAT#21	20,733,210[a]	3.34E-09	1.91E+07	3.66E-09	3.20E+09	1.24E-11	3.02E+10	1.03E-12

[a] Measured actual fatigue life. All other fatigue lives are predicted.

SUMMARY AND RECOMMENDATIONS

The procedure introduced in this paper presents a simple method of fatigue behavior analysis at low strain/damage levels based on an energy approach. It provides a means to quickly estimate the fatigue life (Nf) and energy parameter, plateau value (PV), of laboratory fatigue samples when the actual fatigue life is extremely long and hard to determine under low damage conditions. In addition to the number of cycles to fatigue failure, the energy parameter of HMA mixtures with respect to material and load information can be obtained. These can be very useful for flexible airport pavement design and the incorporation of the fatigue endurance limit (FEL) concept.

By using this procedure, the time required for laboratory low damage fatigue testing can be shortened. Depending on the error tolerance and accuracy requirements, testing from 1-million to 8-million load repetitions can be used for routine design and FEL study purposes which takes from 28 hours to 10 days for 10Hz continuous loading in the laboratory.

The results presented in this paper are still limited to laboratory work. Further field data calibration and validation is required for implementation in the material and structural design process. After appropriate calibration and introducing a shift factor, this procedure, based on the fundamental energy approach, can incorporate the “fatigue endurance limit” concept into pavement design. It can provide a fast determination whether a thick airport pavement structure can have an extraordinarily long fatigue life without structural failure.

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DISCLAIMER

The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the Federal Aviation Administration. This paper does not constitute a standard, specification, or regulation.

REFERENCES

1. Carpenter, S. H., Khalid A. Ghuzlan, and Shihui Shen, "A Fatigue Endurance Limit for Highway and Airport Pavement." Journal of Transportation Research Record (TRR), No. 1832, pp. 131-138, 2003.
2. Carpenter, S. H., and M. Jansen, "Fatigue Behavior Under New Aircraft Loading Conditions." Proceedings of Aircraft Pavement Technology in the Midst of Change, pp. 259-271, 1997.
3. Ghuzlan, K., Fatigue Damage Analysis in Asphalt Concrete Mixtures Based Upon Dissipated Energy Concepts, Ph.D. Thesis, University of Illinois at Urbana-Champaign, Urbana, IL, 2001.
4. Shen, S., and Carpenter, S. H., "Application of Dissipated Energy Concept in Fatigue Endurance Limit Testing." Journal of Transportation Research Record: Transportation Research Board, No. 1929, pp. 165-173, 2005.
5. Daniel, J. S. and W. M. Bisirri, "Characterizing Fatigue in Pavement Materials Using a Dissipated Energy Parameter", Proceedings of the Geo-Frontiers 2005 Congress, Austin, Texas, 2005.
6. Carpenter, S. H., and Shen, S., "A Dissipated Energy Approach to Study HMA Healing in Fatigue." Accepted to Journal of Transportation Research Record (TRR), 2006.
7. Ghuzlan, K., and Carpenter, S. H., "An Energy-Derived/Damage-Based Failure Criteria for Fatigue Testing." Transportation Research Record (TRR), No. 1723, pp. 131-141, 2000.
8. Prowell, B., Brown, E. R., Quintus, H. V., Carpenter, S. H., Shen, S., Anderson, M., Daniel, J., Bhattacharjee, S., and Maghsoodloo, S.,"Endurance Limit of Hot Mix Asphalt Mixtures to Prevent Fatigue Cracking in Flexible Pavements." NCHRP 9-38, Draft Final Report, National Center for Asphalt Technology (NCAT), Auburn, Alabama, 2006.
9. "AASHTO Standard Specifications For Transportation Materials And Methods Of Sampling And Testing." 23rd Edition, Part 2B. T321-03: Determing the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending, AASHTO, Washington, D.C, 2003.