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Article

Calibration and Validation of the Shell Fatigue Model Using AC10 and AC14 Dense Graded Hot Mix Asphalt Fatigue Laboratory Data

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Abstract. The Mechanistic Empirical pavement design has been adopted by New Zealand and Australia for more than a decade ago. The details of the design method are documented in the Austroads guidelines. The success of the mechanistic empirical analysis relies on the validity of the empirical performance models which are very dependent on material types and environmental conditions. In the Austroads Mechanistic Empirical pavement design, fatigue and rutting are the two performance indicators used in the design. Austroads guidelines adopt the Shell fatigue model to predict the fatigue life of asphalt pavements. However, it was observed by many practitioners and confirmed by this study that the Shell fatigue model significantly underestimates the fatigue life of the asphalt mixes. In this paper, calibration and validation of the Shell fatigue model were carried out using laboratory fatigue data for AC10 and AC14 hot mix asphalts. Twelve beams of AC10 and thirteen beams of AC14 made with 60/70 binder were used in the calibration of the model. The calibration factor based on the four points bending fatigue test results was found to be in the order of 4.8 shift factor. Eleven beams of AC10 mix made with softer binder 80/100 penetration grade and four beams of AC14 made with 60/70 binder were used in the validation of the model. The calibrated model provides better match for the measured fatigue values.

Keywords: Fatigue, shell, calibration, validation.

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1. Introduction

In the Mechanistic Empirical pavement design method, certain pavement response is correlated with specific mode of failure. For example, tensile strain at the bottom of asphalt is correlated with top down cracks in the asphalt pavement while compressive strain at the top of the subgrade is correlated with the permanent deformation in the asphalt surface. Different modes of failures are adopted by different mechanistic empirical (ME) procedures. In Australia and New Zealand Guidelines [1], two modes of failure are considered, namely fatigue of bound materials and permanent deformation based on the subgrade compressive strain criterion [1]. The Austroads design guidelines adopted the Shell fatigue performance function to predict the fatigue damage of the structural asphalt. The Shell fatigue model was developed by Shell researchers for some common hot mix asphalts at that time in 1978. It was observed by many practitioners that the Shell fatigue function underestimates fatigue life [2]. It was also noted in 2006 and 2007 version of the New Zealand supplement that asphalt pavements designed based on the earlier National Roads Board State Highway Pavement and Rehabilitation design manual which was used in New Zealand between 1989 to 1996 are 30% thinner than that required by the current 2008 Austroads guidelines and yet all pavements designed by this method are all performing well past their design life [2]. This clearly supports the argument that the currently adopted Shell performance function overestimates the design thickness and therefore requires some necessary adjustment to resolve this over-conservatism.

It is clearly obvious from the above discussion that the Shell fatigue function was developed for different types of binders and using different mixes than those are currently used on the New Zealand highway system [3]. Consequently, it is expected to have such differences between the predicted and observed fatigue life. Thus, the Shell model needs to be adjusted to account for these differences. Calibration of a pavement fatigue model is the process of adjusting the predicted values of pavement fatigue so that the predicted and measured values match as closely as possible for different strain levels and different asphalt mixes.

2. Determination of Calibration Factors

Calibration is performed so that the difference between observed results, the measured fatigue of a pavement section, and the Shell model predicted results is reduced to a minimum value [4]. Statistical methods are used to determine calibration factors, which are used to minimize the differences between the measured laboratory data and the model's predicted values. This fitting of the predicted and the observed results is most often accomplished by minimizing an error function of the residuals. After the calibration process of the model, it needs to be validated with an independent set of data to insure its applicability to other pavements.

Some models need to be shifted or shifted and rotated in the calibration process to be adjusted. In this paper, only adjustment for the position of the Shell fatigue model will be carried out without any change to the shape of the function. The calibration procedure is based on finding a calibration factor that when multiplied by the Shell predicted fatigue life minimizes the total prediction error. The total prediction error is defined as the sum of the squares of the differences between the predicted and the measured fatigue life values. Calculations of the calibration factor can be formulated as shown in Eq. (1):

$$PFV_i = k * f(X_i) \tag{1}$$

where

PFV_i = Calibrated predicted fatigue value at strain level i,

k = Calibration factor,

$f(X_i)$ is the predicted pavement fatigue value obtained from the Shell fatigue Eq. (2) before any calibration, and X is a set of explanatory variables used in the development of the Shell model (the percentage of bitumen by volume (V_b), asphalt mix stiffness (S_{mix}), and strain level ($\mu\epsilon$)). Thus:

$$f(X_i) = N_i = \left[\frac{6918 * (0.856 * V_b + 1.08)}{{S_{\text{mix}}}^{0.36} * \mu\epsilon_i}\right] \tag{2}$$

N_i = allowable number of load repetitions at strain level i,

V_b = percentage by volume of bitumen in the asphalt mix,
S_{mix} = asphalt mix modulus in MPa (see Table 2 for stiffness modulus values measured at 20 °C), and
$\mu\epsilon_i$ = Tensile strain level *i* produced by the load.
The total prediction error (TPE) can then be calculated from Eq. (3):

$$TPE = \sum_{i=1}^{n} [K * f(X_i) - MFV_i]^2 \tag{3}$$

where
MFV_i = Measured fatigue value at strain level i, and
n = Total number of strain levels or the number of measured fatigue values used in the calibration.

In terms of the calibration factor k, the total prediction error (TPE) function is a quadratic second order equation. The value of the calibration factor that corresponds to the minimum sum of the squares of the errors is the optimum calibration factor value.

To determine the optimum calibration factor, Eq. (3) can be differentiated with respect to the calibration factor k and set to zero [5, 6], then the calibration factor can be determined from Eq. (4).

$$k = \frac{\sum_{i=1}^{n} [f(X_i) * MFV_i]}{\sum_{i=1}^{n} f(X_i)^2} \tag{4}$$

3. Sample Preparations and Laboratory Testing

Two hot mix asphalt concrete designs were used in the laboratory fatigue tests, namely AC10 and AC14. The two mixes are dense graded mixes that are commonly used in New Zealand. The AC10 has a maximum nominal aggregate size of 10 mm and the AC14 has a maximum nominal aggregate size of 14 mm. The mix design of the two mixes was carried out by two local contractors. The two mixes were made with asphalt binder 60/70 penetration grade. The AC10 slabs were mixed and compacted using the University of Canterbury roller compactor. The AC14 beams was compacted and prepared by local contractor. Each asphalt concrete slab was sawn into four beams with width, depth and length of 65 x 60 x 400 mm, respectively. The volumetric properties of the compacted beams of the two mixes AC10 and AC14 are shown in Table 1 and Table 2, respectively. The percentage of air voids in the total mix (VTM) for the AC10 mix ranges from 5.0% to 6.4% with an average value of 5.6%. For AC14 mixes, the percentage of air voids in the total mix ranges from 4.0% to 6.4% with an average of 5.6%. A total of 25 beams were prepared for the calibration of the Shell model with 12 beams of the AC10 mixes and 13 beams of the AC14 mixes. For the validation of the model, additional 15 beams were prepared with 11 beams made of the AC10 mix and 80/100 penetration grade bitumen and 4 beams were made of AC14 mix and 60/70 penetration grade binder.

Table 1. Volumetric properties of the compacted hot mix asphalt AC10 made with bitumen 60/70 penetration grade bitumen.

Beams No	Gmb	Vb	Vbe	VTM	VMA
AC-10-B1	2.27	13.8	13.2	5.6	18.8
AC-10-B2	2.27	13.8	13.2	5.7	18.9
AC-10-B3	2.26	13.8	13.1	5.9	19.0
AC-10-B4	2.25	13.7	13.1	6.4	19.4
AC-10-B5	2.27	13.8	13.2	5.8	18.9
AC-10-B6	2.28	13.9	13.3	5.1	18.4
AC-10-B7	2.28	13.9	13.3	5.1	18.3
AC-10-B8	2.29	13.9	13.3	5.0	18.3
AC-10-B9	2.26	13.7	13.1	6.2	19.3
AC-10-B10	2.28	13.8	13.2	5.4	18.6
AC-10-B11	2.28	13.8	13.2	5.4	18.6
AC-10-B12	2.27	13.8	13.2	5.5	18.7

Table 2. Volumetric properties of the compacted hot mix asphalt AC14 made with bitumen 60/70 penetration grade bitumen.

Beam No	Gmb	Vb (%)	Vbe	VTM (%)	VMA (%)
1	2.51	12.4	10.3	5.2	15.6
2	2.53	12.5	10.4	4.5	14.9
3	2.53	12.5	10.4	4.6	15.0
4	2.55	12.5	10.5	4.0	14.4
5	2.49	12.3	10.3	6.0	16.2
6	2.49	12.2	10.2	6.2	16.4
7	2.50	12.3	10.3	5.9	16.2
8	2.49	12.3	10.2	6.1	16.3
9	2.48	12.2	10.2	6.6	16.8
10	2.48	12.2	10.2	6.6	16.8
11	2.48	12.2	10.2	6.5	16.7
12	2.48	12.2	10.2	6.3	16.5
13	2.49	12.3	10.3	6.0	16.2

4. Laboratory Fatigue Testing

A total of 40 fatigue tests were carried out on beams using constant strain mode in the four point bending test. Each specimen was subjected to a haversine loading pulse of frequency 10 Hz at 20 °C until failure. A total of 25 beams were used for calibration and 15 beams were used in the validation process. Tables 3 and 4 show the fatigue results for the 25 beams that were used in the calibration process measured at different strain levels ranging from 300 $\mu\varepsilon$ to 600 $\mu\varepsilon$. Tables 3 and 4 show also the Shell predicted fatigue life using the total percentage of binder by volume. By comparing the laboratory measured fatigue values for AC10 and AC14 and the Shell predicted fatigue values, one can clearly see that the Shell fatigue function underestimates the fatigue life by an average factor of 5 and 5.5 respectively.

Figure 1 shows the relationship between the predicted and the measured fatigue lives for the different strain levels. The Shell predictions are consistently under the equality line indicating that the Shell model is biased toward underestimating the fatigue lives of the two asphalt mixes. From Fig. 1, it is obvious that a calibration factor is necessary to adjust the shell model to provide a better match with the actual measured fatigue lives.

Table 3. Measured and the Shell predicted fatigue lives of the AC10 tested beams.

Beam Number	Strain Level ($\mu\varepsilon$)	Initial Flexural Strain	Measured Number of Cycles	Shell Prediction	Ratio of Measured and Predicted Fatigue
AC-10-B1	350	3664	1997070	415507	4.8
AC-10-B2	350	2937	2335240	614812	3.8
AC-10-B3	400	3636	1031050	212547	4.9
AC-10-B4	400	3180	1078130	264523	4.1
AC-10-B5	450	3652	386250	117732	3.3
AC-10-B6	450	3628	629720	123059	5.1
AC-10-B7	500	3716	382490	69708	5.5
AC-10-B8	500	3180	424060	92472	4.6
AC-10-B9	550	3244	315850	52239	6.0
AC-10-B10	550	3401	356670	50023	7.1
AC-10-B11	600	3329	208360	33605	6.2
AC-10-B12	600	3546	136310	29804	4.6

Table 4. Measured and the Shell predicted fatigue lives of the AC14 tested beams.

Beam Number	Strain Level ($\mu\varepsilon$)	Flexural Stiffness (MPa)	Measured Number of Cycles	Shell Equation	Ratio of Measured and Predicted Fatigue
1	400	4530	649490	87782	7.4
2	400	4576	466150	89519	5.2
3	500	4047	182820	36397	5.0
4	300	4491	1230550	399354	3.1
5	600	3752	97300	15679	6.2
6	500	4203	145420	31516	4.6
7	450	4297	217710	51852	4.2
8	300	4223	2248110	402579	5.6
9	600	3548	62260	16840	3.7
10	300	4409	3235560	363792	8.9
11	450	4150	342000	53814	6.4
12	450	4318	299600	50380	5.9
13	600	4381	68230	11840	5.8

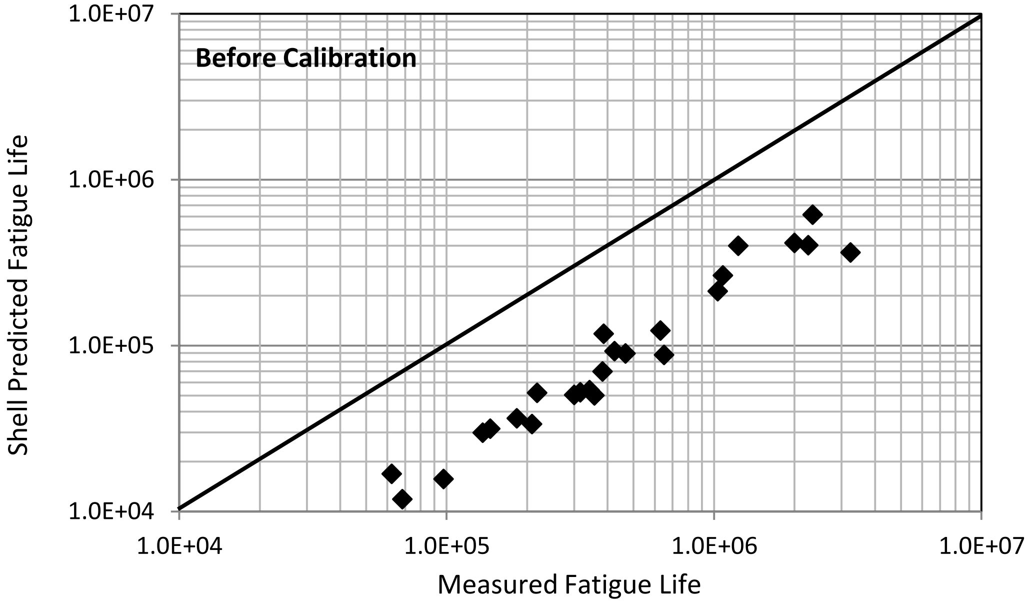

Fig. 1. Shell predicted fatigue life versus actually measured fatigue life.

5. Determination of Calibration Factor

By analyzing the data in Tables 3 and 4 for the laboratory measured fatigue lives and the Shell predicted fatigue lives and Eq. (4) a calibration factor can be computed.

A calibration factor of 4.8 when multiplied by the Shell model will provide a minimum total prediction error as previously explained in the mathematical derivations. Therefore, the calibrated Shell fatigue model can be rewritten and simplified as shown in Eq. (5):

$$N_{f(calibrated)} = \left[\frac{9467 * (0.856 * V_b + 1.08)}{E^{0.36} * \mu\epsilon}\right]^5 \tag{5}$$

Figure 2 shows that applying an optimum calibration factor to the Shell model signifcantly adjusts the prediction of the model and minimizes the prediction error of the model and that the calibrated Shell fatigue model provides unbiased predictions with no consistent overestimation or underestimation as most of the data points clustered around the line of equality.

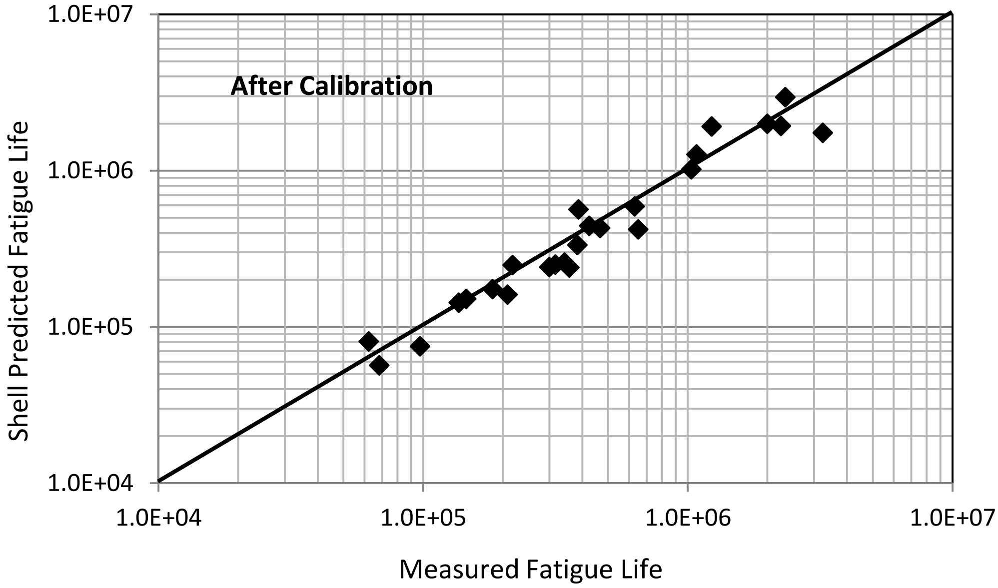

Fig. 2. Calibrated Shell predicted fatigue lives versus measured fatigue values.

6. Validation of the Calibrated Model

Tables 5 and 6 contain the fatigue data measured for the validation process. Eleven beams of AC10 hot mix asphalt prepared with 80/100 penetration grade binder were prepared at the University of Canterbury Transportation laboratory. Four point bending beam fatigue with constant strain mode was applied. Strain levels, flexural stiffness and fatigue lives of the AC10 beams are shown in Table 5. Additional four beams of AC14 made with binder 60/70 penetration grade were prepared at Downer NZ laboratory; the strain levels, flexural stiffness and fatigue lives of these mixes are shown in Table 6. All beams were tested using haversine constant strain mode with frequency 10 Hz at 20 ^{o}C. Figure 3 shows the measured fatigue data in tables 5 and 6 versus the Shell predicted fatigue values before calibration. It is again clear that the Shell fatigue model consistently underestimated the fatigue life of both the AC10 with 80/100 binder and AC14 with 60/70 binder. Figure 4 shows the measured fatigue data versus the Shell predicted fatigue after calibration using Eq. (5). From Fig. 4, it can be seen that the calibrated Shell model provides a better match compared to the non calibrated model. It should be noted that the AC10 mixes used in the validation process were made with softer binder 80/100 compared to the AC10 used in the calibration of the model yet the calibrated model still provide a better match compared to the none calibrated Shell model. The author acknowledges that fifteen fatigue tests are still small sample to provide robust validation; however, the methodology is quite valid. With the collaboration with the Transportation industry, more data can be generated to provide a more rigorous calibration and validation.

Table 5. Fatigue data measured at for AC10 hot mix made with 80/100 penetration grade binder for validation.

Beam Number	Strain Level ($\mu\varepsilon$)	Flexural Stiffness (MPa)	Measured Fatigue Life
1.1	500	2796	836040
1.2	600	2846	227310
1.3	450	3071	1451880
3.1	450	2773	2044350
3.2	600	3059	523250
3.3	450	3363	2232350
3.4	500	2862	1408550
4.1	550	2721	483630
4.2	400	3071	1692350
4.3	350	3266	5695740
4.4	450	3053	905990

Table 6. Fatigue data measured at independent laboratory for AC14 hot mix made with 60/70 penetration grade binder for validation.

Beam Number	Strain Level ($\mu\varepsilon$)	Flexural Stiffness (MPa)	Measured Fatigue Life
1	350	4479	986420
2	350	5162	1179760
3	550	4035	58480
4	650	4102	52240

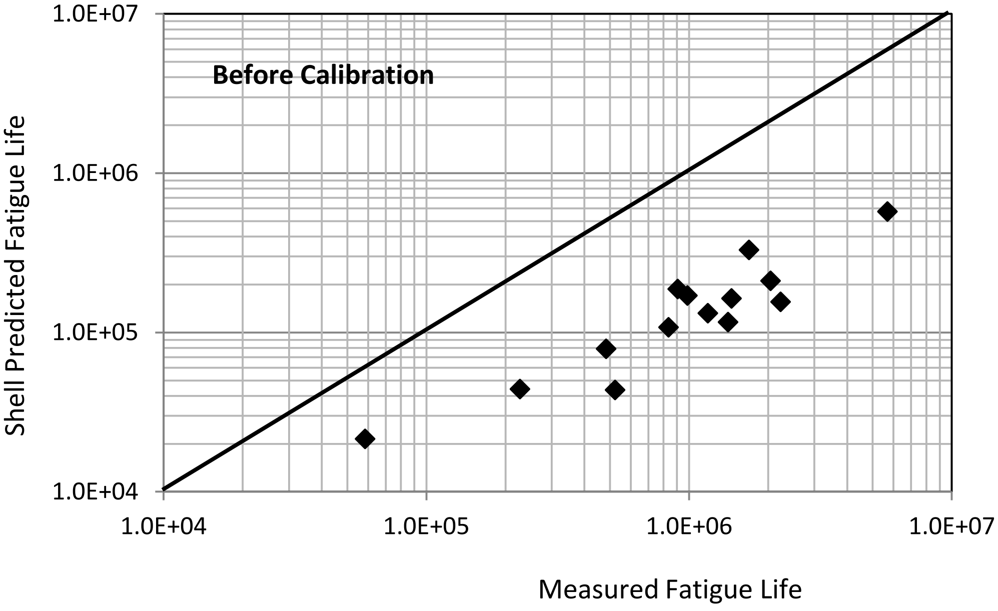

Fig. 3. Measured versus predicted fatigue life using the Shell fatigue model before calibration.

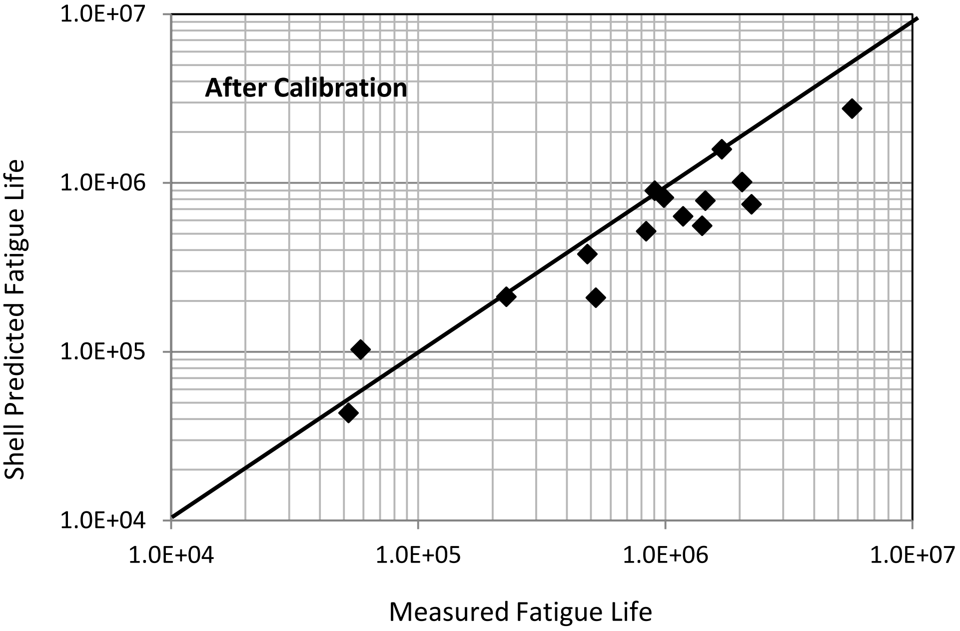

Fig. 4. Validation of the calibrated Shell fatigue model.

7. Conclusions

In this study, a total of forty asphalt concrete beams were made with AC10 and AC14 dense graded asphalt mix and using 60/70 and 80/100 penetration grade bitumen. The forty beams were tested using constant strain mode for different strain levels ranging from 300 $\mu\varepsilon$ to 650 $\mu\varepsilon$. A total of 36 beams were tested in the University of Canterbury, Transportation laboratory and the other four beams were tested in the Downer NZ laboratory. A calibration factor was driven from the measured and predicted fatigue lives for a total of 25 beams (a total of 13 beams of AC14 and 12 beams of AC10) tested at different strain levels. A calibration factor of 4.8 was computed from the measured and predicted fatigue values. The calibrated model provided unbiased prediction with no consistent overestimation or underestimation. The calibrated model was validated with fifteen beam fatigue tests that were carried out at both the University of Canterbury laboratory and Downer contractor laboratory. The calibrated model provided a reasonably better match compared to the non-calibrated model.

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