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Research Article

Flexible Pavement Performance in relation to In Situ Mechanistic and Volumetric Properties Using LTPP Data

Mohammad Jamal Khattak and Nagaraju Peddapati

Department of Civil Engineering, University of Louisiana at Lafayette, 254J Madison Hall, Lafayette, LA 70504, USA

Correspondence should be addressed to Mohammad Jamal Khattak; khattak@louisiana.edu

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This research study focuses on the actual performance of the flexible pavements and its relationship with the in-situ mechanistic and volumetric properties. The data required for the study were obtained using the Long Term Pavement Performance database. Approximately, 116 flexible pavement sections throughout United States were analyzed and discussed. The results indicated that the temperature has a significant affect on the backcalculated modulus of the hot mix asphalt layer. However, no strong relationship was observed between the hot mix asphalt backcalculated modulus and in situ air voids. It was found that fatigue life was a function of tensile strain at the bottom of hot mix asphalt layer, peak surface deflection, hot mix asphalt air voids and maximum specific gravity, and ambient air temperature. Similar relationships between the rut life, mechanistic and volumetric properties were established for wet-freeze and wet-no-freeze climatic zones. The sensitivity analysis revealed that the rut performance in wet-no-freeze sections is mainly affected by higher base and roadbed compressive stresses and strains. On the other hand, the performances in wet-freeze sections are highly depended on roadbed compressive strain and modulus ratio of subbase to roadbed.

1. Introduction

This study focuses on the actual performance of the flexible pavements and its relationship with the in situ, mechanistic and volumetric properties. In general, pavements are subjected to various kinds of loading and different environmental conditions, over time that manifest various distresses and affects the pavement performance. These distresses include rutting, fatigue cracking, temperature cracking, transverse cracking, and age-related block cracking [1]. Under a set of loading and environmental conditions the performance of the flexible pavements is function of properties of asphalt concrete mixture, volumetric properties (air voids, volume in mineral aggregate (VMA), specific gravity, and asphalt content) and mechanistic properties of HMA mixture, and underlying base and subbase and roadbed materials [2]. The temperature also has detrimental effects on the performance of the pavement; if the temperature is too high it causes rutting and low temperature will cause thermal cracking. By providing appropriate VMA, it is believed that rutting may be minimized, and mixture durability can be enhanced [3]. It is found that tender mixtures compacted to lower air void content (AV) will undergo less permanent deformation than if they are compacted to higher AV content. Lateral distortion can also follow traffic consolidation if the mix density reaches a critical AV content (normally less than 3%), and in fact becomes overlubricated with asphalt cement [3]. Environmental factors that allow the compaction equipment to obtain the density with less compaction effort also affect permanent deformation [4, 5]. The shape angularity of the sand particles, the percentages of sand content in the HMA mixtures, and the type of mineral filler also influence the rut and fatigue life of the asphalt pavements [6]. The effect of AV on the pavement performance does not change significantly with the different target levels of asphalt content. Not surprisingly, the effect of deviations in AV becomes greater as the target AV becomes smaller. It was observed that 1 percent increase in AV produces an approximate

20 percent reduction in fatigue life. Likewise, if the target range of AV was 5 to 6 percent, 1 percent increase in AV produces an approximate 10 percent reduction in rutting life [7, 8]. Higher AV can also increase the livelihood of rutting and other pavement failures like fatigue cracking, temperature cracking, and transverse and longitudinal cracking [5]. Low AV (less than 3 percent), on the other hand, increases the likelihood of bleeding, shear flow, and rutting in the wheel paths. If the modulus of the asphalt layer is high (indicates that the stronger the material), it is less susceptible to rut and fatigue conditions. In other words, it has more rut and fatigue life. On the other hand, if the peak surface deflection is higher, the pavement is more susceptible to various distresses such as fatigue and low temperature cracking. The more the tensile strain in the asphalt layers the less the fatigue life is [1, 9].

Various studies have been conducted to develop cracking models to predict the cracking performance. Prediction models for cracks in pavements have tried to predict crack initiation and progression along with percentage of area cracking using ESAL, structural number, and California bearing ration (CBR) values [10]. World Bank model was developed from a comprehensive database of in-service pavements for initiation of cracking using mechanistic characteristics of pavements [11]. Rauhut et al. [12, 13] suggested sigmoid form of cracking and proposed a model to convert damage index (DI, a damage function) to percentage of area cracking. Similar models have been utilized in Texas Pavement Design System to capture the long-term behavior of pavements for fatigue, longitudinal and transverse cracking [14]. Cracking models based on statistical analysis have been developed by long-term pavement performance (LTPP) program, Mississippi and Washington Departments of Transportations, and other state agencies [15–17] Variables used in these models are pavement distress characteristics, subgrade characteristics, traffic characteristics, and mechanistic properties and climatic factors. However, the resulting models are applicable only within the range of the data used for the development of the model. These models need calibration when used out of their boundary conditions and often the form of the model has to be modified.

This paper mainly deals with the study of the rut and fatigue performances of the flexible pavements in relationship to in situ volumetric and mechanistic properties. Relationships were developed between the number of equivalent single axle load (ESAL) to accumulate 4 mm rut depth (rut life) and 10 percent of pavement area cracked (fatigue life) with in situ volumetric characteristics of hot mix asphalt (HMA) layer and mechanistic properties of the pavement layers.

2. Data Source and Analysis

The long-term pavement performance (LTPP) DataPave release 11.5 version NT 3.0 was used in this study. Initially, all those sections that had fatigue and longitudinal cracks, and rutting data were downloaded from the LTPP DataPave. Approximately, 116 sections were selected that provided good record of pavement performance, volumetric and mechanistic properties over the past fifteen years. It seemed that most of the pavement sections did not reached rut depth of 12 mm or 15 percent of pavement area cracked or were repaired and rehabilitated. Therefore to keep the data set to a reasonable number the 4 mm rut depth and 10 percent of pavement area cracked for rut and fatigue life, respectively, were selected for data analyses. In addition, the data was also sorted and analyzed based on the following:

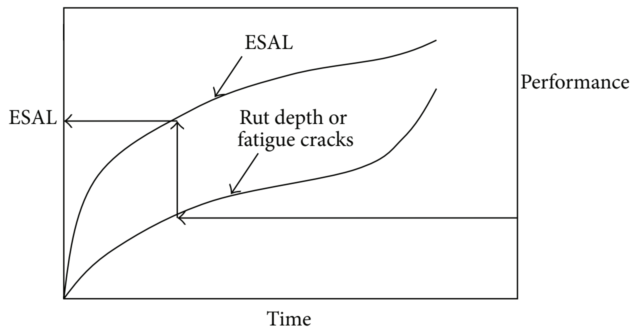

Figure 1: Pavement performance (rut and fatigue) as a function of time and ESALs.

(1) climatic zones (wet-no-freeze, wet-freeze, dry-no-freeze, and dry-freeze),

(2) HMA layer thickness (less than 10 cm, 10 to 20 cm, and greater than 20 cm),

(3) type of subgrade material (granular base, GB; granular subbase, GS; treated base, TB; and silty soil, SS).

The longitudinal and fatigue cracks data were obtained from MON_DIS_AC_REV module of the LTPP database. The extent of pavement fatigue for each pavement section was determined from a combination of fatigue and longitudinal crack data. The longitudinal cracks in the wheel path were converted into fatigue area by multiplying the width of wheel path (0.15 m) with the section length of about 152 m. It should be noted that fatigue and longitudinal cracks of all extents (low, medium, and high) for both left and right wheel paths were added for fatigue area calculations. For rut depths the data from straightedge rut depth method was acquired from MON_T_PROF_INDEX_POINT module of LTPP database. The computations of the rut depths were based on the average of both the wheel paths and all the data points within the sections were obtained. The ESALs data obtained from the traffic module included both the data from historical and monitoring modules (TRF_MON_EST_ESAL, and TRF_HIST_EST_ESAL). Figure 1 illustrates a typical plot for the determination of ESALs corresponding to a 4 mm rut depth and 10 percent of pavement area cracked for rut and fatigue life, respectively. The volumetric properties were obtained from the inventory module INV_PMA_ORIG_MIX.

Table 1: Summary of the selected test sections showing transformation functions for HMA modulus values versus pavement temperature.

Section ID	State ID	No. of data points	Transformation functions	R^2 value
9–1803	CT	21	$Y = 14976e^{-.0353x}$	0.91
48–1068	TX	25	$Y = 12177e^{-.05130x}$	0.97
13–1005	GA	16	$Y = 24829e^{-.050x}$	0.96
28–1016	MS	26	$Y = 31190e^{-.0554x}$	0.80
48–1077	TX	26	$Y = 18770e^{-.0498x}$	0.93
48–1122	TX	29	$Y = 16415e^{-0.0475x}$	0.87
25–1002	MA	25	$Y = 10513e^{-.0512x}$	0.95
23–1026	ME	17	$Y = 19669e^{-.0674x}$	0.92
27–6251	MN	11	$Y = 14011e^{-.0422x}$	0.92
28–1016	MS	14	$Y = 31190e^{-.0554x}$	0.80

Y = Backcalculated HMA Modulus, MPa, X = HMA Pavement Temperature, °C.

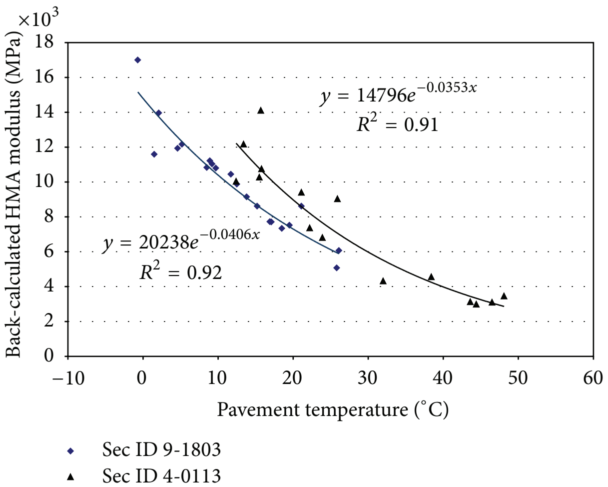

Figure 2: Typical plot of back-calculated HMA modulus as a function of pavement temperature.

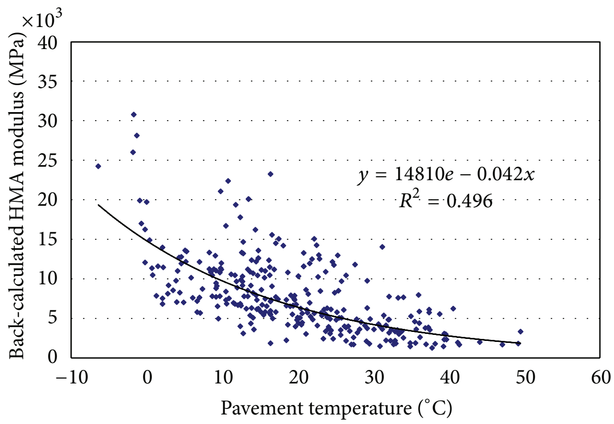

Figure 3: Back-calculated HMA modulus as a function of pavement temperature for all the states and test sections studied.

3. Results and Discussion

3.1. Back-Calculated HMA Layer Moduli. Due to variations in temperature the modulus of the HMA layer of the flexible pavement is very much affected, which will in turn affect the performance of the pavement, thus, leading to the conditions that facilitate rutting at high temperatures, fatigue cracking at medium to low temperatures, and thermal cracking at very low temperatures. Figure 2 shows the typical plot of back-calculated HMA modulus as a function of middepth pavement temperature, of two sections from two different states. It is evident that the HMA modulus and pavement temperature have very good relationship with R^2 of about 0.92. Similar relationships were obtained for other test sites and are listed in Table 1. It is clear from the data in Table 1 that the HMA modulus and pavement temperature follow the exponential function. Figure 3 illustrates the relationship between HMA modulus and temperature for all the geographical regions of the United States that were investigated in this study. Although, there is no good relationship mainly due to varying material properties, pavement structure, seasonal variations, and climatic zone, the trend is reasonable, that is, the modulus of hot mix asphalt decreases with the increase in temperature.

In order to investigate the role of climatic zone for modulus-temperature relationship the data was sorted according to climatic zones and analyzed. The summary of the results is shown in Table 2. It can be seen that except for the dry-freeze zone the modulus-temperature relationship has improved when compared to the relationship for all the data points.

Finally, the HMA moduli were corrected to the reference temperature of 25°C using the relationships developed for each individual site. The correction factor was of the following form:

$$\mathrm{CF} = e^{\beta(T-\mathrm{Tr})}, \quad (1)$$

where CF is correction factor for HMA moduli, T is test temperature, Tr is reference temperature, and β is a constant and its value changes based on each pavement site (0.03 to 0.07).

Numerous studies have shown that there is a significant effect of percentage of air voids on the HMA stiffness. Most of these research studies were based on laboratory data. In general, increase in air voids will decrease the modulus.

Table 2: Summary of the modulus-temperature relationship sorted according to climatic regions.

Climatic regions	State ID	No. of points	Transformation function	R^2 value
Wet-no-freeze	GA, TX, MS, NM, ID, MN, MA, AR, and DC	318	$Y = 14810e^{-0.042x}$	0.50
Wet-freeze	CT, AL, WA, TN, and AK	43	$Y = 26320e^{-0.0545x}$	0.54
Dry-no-freeze	CA, RI, SD, and UT	813	$Y = 19542e^{-0.042x}$	0.70
Dry-freeze	AZ, NC, and OK	40	$Y = 16101e^{-0.0354x}$	0.38

Table 3: Rut life as a function of air voids sorted by base type.

Base type	State ID	No. of points	Transformation function	R^2 value
GB	NC, TX, SC, GA, CA, PE, MO, MA, CT, MT, ID, NV, AK, CO, and NM	32	Exponential	0.07
GS	SC, MS, GA, AR, MD, NJ, HI, TN, and PQ	19	Exponential	0.54
TB	CO, WA, PQ, NM, OK, TX, MS, GA, CA, DE, AR, and MD, NJ, TN, WY, CA, ME, and MN	39	Exponential	0.02

In order to investigate the effect of air voids on back-calculated HMA modulus the temperature-corrected moduli values were plotted as a function of air void and are shown in Figure 4. The data in the figure reveals that there is no apparent relationship between the back-calculated moduli and in situ air voids.

3.2. Relationship between Rut Life and Volumetric and Mechanistic Properties. In order to investigate the relationship between the rut life and volumetric and mechanistic properties, the rut life was plotted against each parameter. The rut life was defined as the number of ESAL to accumulate 4 mm rut depth. Figure 5 shows the rut life as a function of percentage of air voids for all the test sections selected for this study. It can be seen that there is no good relationship between rut life and percentage of air voids. However, the trend seems reasonable, that is, with the increase in air voids the rut life decreases. The data was also sorted first by base type (see Table 3) and then by thickness and base type (see Table 4). In general, with an exception of few test sites there is no relationship based on base type.

Similarly the rut life data was plotted against other volumetric and mechanistic properties and various exponential functions were obtained as shown in Figures 6 and 7. It should be noted that stresses, strains, and deflections in various layers were obtained using MICHPAVE, a finite element-based software. Finally, two relationships were developed according to the climatic zones and are shown below.

Wet-freeze:

$$\begin{aligned} \text{Ln}(N_d) &= 6.083 - 0.156\,(\text{AV}) - 1560.09\,(\varepsilon_{\text{RB}}) \\ &\quad - 0.00085\,(\sigma_{\text{BS}} * \sigma_{\text{RB}}) + 0.955\left(\frac{E_{\text{SB}}}{E_{\text{RB}}}\right), \\ R^2 &= 89.6\%, \qquad \text{SEE} = 0.48, \end{aligned} \tag{2}$$

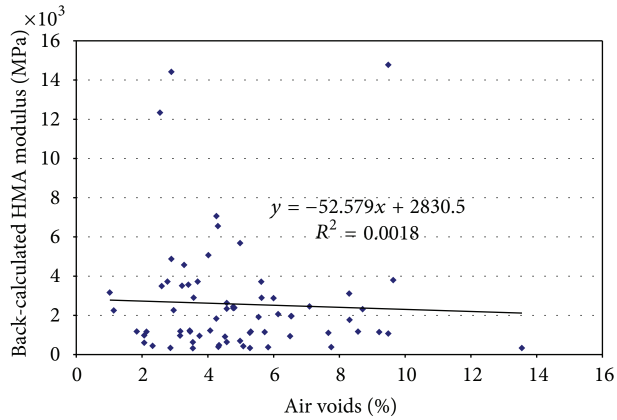

Figure 4: Back-calculated HMA modulus as a function of percentage of in situ air voids.

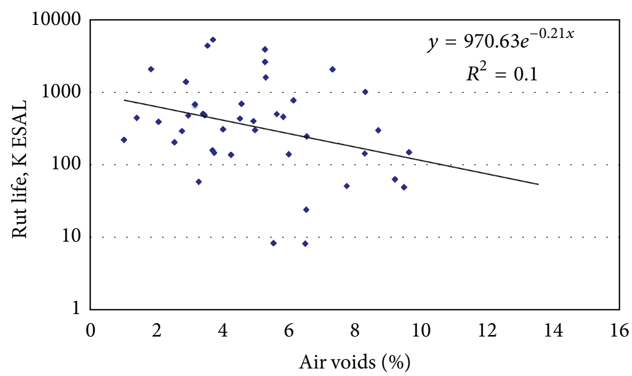

Figure 5: Rut life as a function of percentage of air voids.

where N_d is rut life (KESALs to accumulate 4 mm of rut depth), AV is percent air voids, ε_{RB} is roadbed compressive strain, $\sigma_{\text{BS}}, \sigma_{\text{RB}}$ are subbase and roadbed stresses, respectively,

Table 4: Rut life as a function of air voids sorted by base type and thickness of HMA layer.

HMA thickness	Base type	State ID	No. of points	Transformation function	R^2 value
Total thickness of HMA < 10 cm	GB	SC, CA, TX, ID, AK, and NC	7	Linear	0.99
	GS	MS, GA, PQ, NJ, CO, and NM	7	Exponential	0.78
	TB	OK, MS, GA, DE, AR, MD, NS, and MN	11	Linear	0.05
Total thickness of HMA 10–20 cm	GB	CT, NC, TX, GA, PE, MA, NV, MT, ID, and AK	18	Exponential	0.06
	GS	NM, AR, NJ, HI, TN, WA, and CO	3	Linear	0.98
	TB	NC, TX, OK, GA, CA, MD, CO, and WY	12	Linear	0.04
Total thickness of HMA > 20 cm	GB, GS	TX, GA, AK, WA, MD, CO, and PQ	4	Power	0.33
	TB	OK, TX, NJ, TN, and MD	5	Exponential	0.13

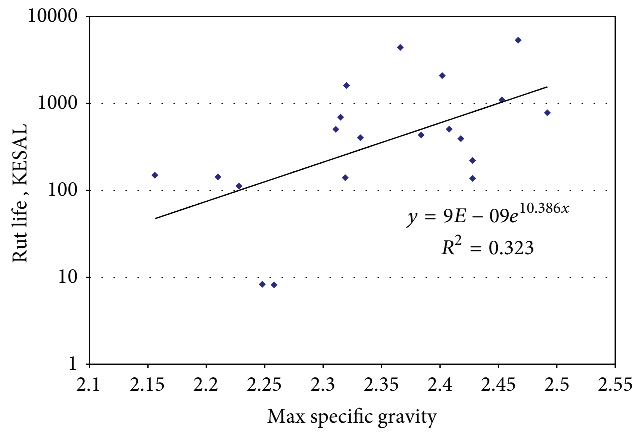

Figure 6: Rut life as a function of maximum specific gravity of HMA layer.

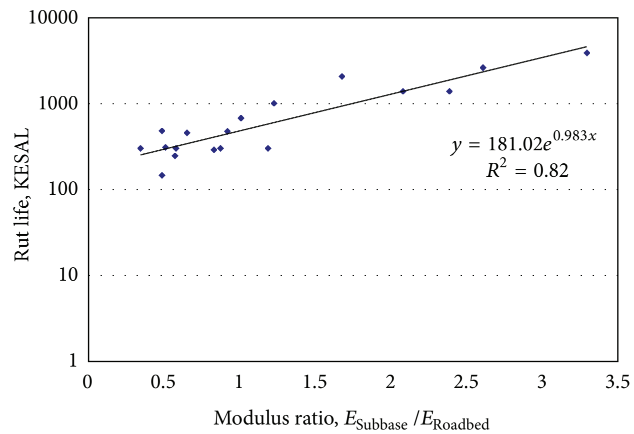

Figure 7: Rut life as a function of modulus ratio of subbase and roadbed.

and E_{SB}/E_{RB} are modulus ratios of the subbase layer and roadbed.

Wet-no-freeze:

$$\begin{aligned}\text{Ln}\left(N_d\right) &= -6.598 + 0.871 * \text{Ln}\left(\frac{\sigma_{BS}}{\sigma_{RB}}\right) - 16.274 * \left(\varepsilon_{BS}\right)^{0.5} \\ &\quad - 0.001\left(\frac{E_{AC}}{E_{RB}}\right) + 5.363\left(M_{sg}\right) - 0.154\,(\text{AV}), \\ R^2 &= 0.63, \qquad \text{SEE} = 1.193,\end{aligned} \tag{3}$$

where, N_d is rut life (KESALs to accumulate 4 mm of rut depth), AV is percent air voids, ε_{BS} is base compressive strain, σ_{BS}, σ_{RB} are subbase and roadbed stresses, respectively, and E_{AC}/E_{RB} are modulus ratios of the subbase layer and roadbed.

The predicted versus actual rut life was plotted as shown in Figure 8. It is obvious that the newly developed model predicts the rut life of pavements fairly well. The sensitivity analysis of the above equations revealed that the rut performance in wet-no-freeze sections is mainly affected by higher-base and roadbed compressive stresses and strains. On the other hand, the performances in wet-freeze sections highly depended on roadbed compressive strain and modulus ratio of subbase to roadbed.

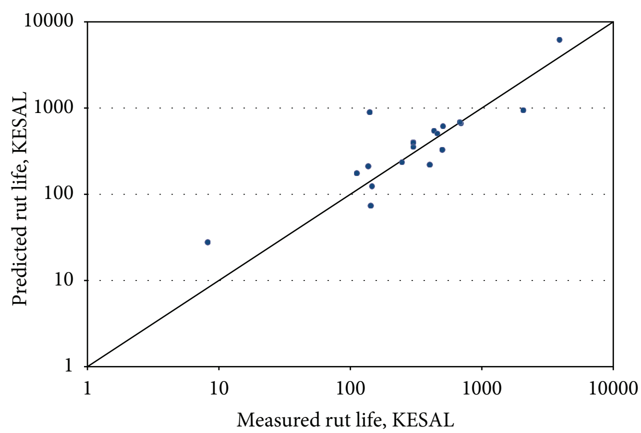

Figure 8: Predicted versus actual rut life.

3.3. Relationship between Fatigue Life and Volumetric and Mechanistic Properties. Similar analyses as that of rut life were conducted for fatigue life of the test sections. Due to less number of data sets, the data from all test sections

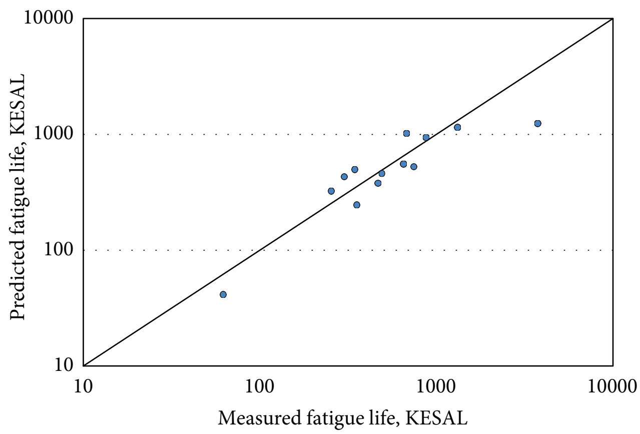

Figure 9: Predicted versus actual fatigue life.

were utilized for establishing the relationship. It was found that fatigue life of the flexible pavement is a function of ratio of maximum specific gravity to air voids, ambient air temperature, tensile strain at the bottom of the HMA layer, peak surface deflection, and ratio of strain-to-peak surface deflection. Using the linear regression analyses the following relationship was developed:

$$\begin{aligned}\operatorname{Ln}\left(N_f\right) &= 3.71 - 0.534\left(\frac{M_{\text{sg}}}{\text{AV}}\right) + 2.989\left(\frac{T_{\text{ab}}}{25}\right) - 0.0774\left(\frac{E_{\text{AC}}}{E_{\text{RB}}}\right) \\ &\quad - 232.83\left(\varepsilon_t\right) - 3.318\left(\delta_p\right) - 143.292\left(\frac{\varepsilon_t}{\delta_p}\right), \\ R^2 &= 82\%, \qquad \text{SEE} = 0.58,\end{aligned} \tag{4}$$

where, N_f is fatigue life (KESAL for 10% pavement area cracked), AV is percent air voids, ε_t is tensile strain at the bottom of HMA layer, δ_p is peak surface deflection, mm, T_{ab} is ambient air temperature, °C, $E_{\text{AC}}/E_{\text{RB}}$ are modulus ratios of the HMA layer and roadbed, and M_{sg}/AV are ratios of maximum specific gravity and percentage air voids.

Similar to the rut life, the fatigue life model exhibited good predicting capabilities as shown in Figure 9.

4. Conclusions

The study investigated the actual performance of the flexible pavements and its relationship with the in situ mechanistic and volumetric properties. The data required for the study were obtained from LTPP database. The results indicated that the back-calculated moduli of HMA layer were significantly affected by the pavement temperature. In general, the temperature correction factor for most of the sites followed an exponential function. It was found that there was no strong relationship between the back-calculated moduli of HMA layer and the air voids. However, the trend was reasonable, that is, the modulus decreased with the increase in air voids. The fatigue and rut life of pavements exhibited good relationships with the volumetric properties of HMA and mechanistic characteristics of the pavement layers. The sensitivity analysis of the rut model revealed that the rut performance in wet-no-freeze sections is mainly affected by higher-base and roadbed compressive stresses and strains. On the other hand, the performances in wet-freeze sections highly depended on roadbed compressive strain and modulus ratio of subbase to roadbed moduli.

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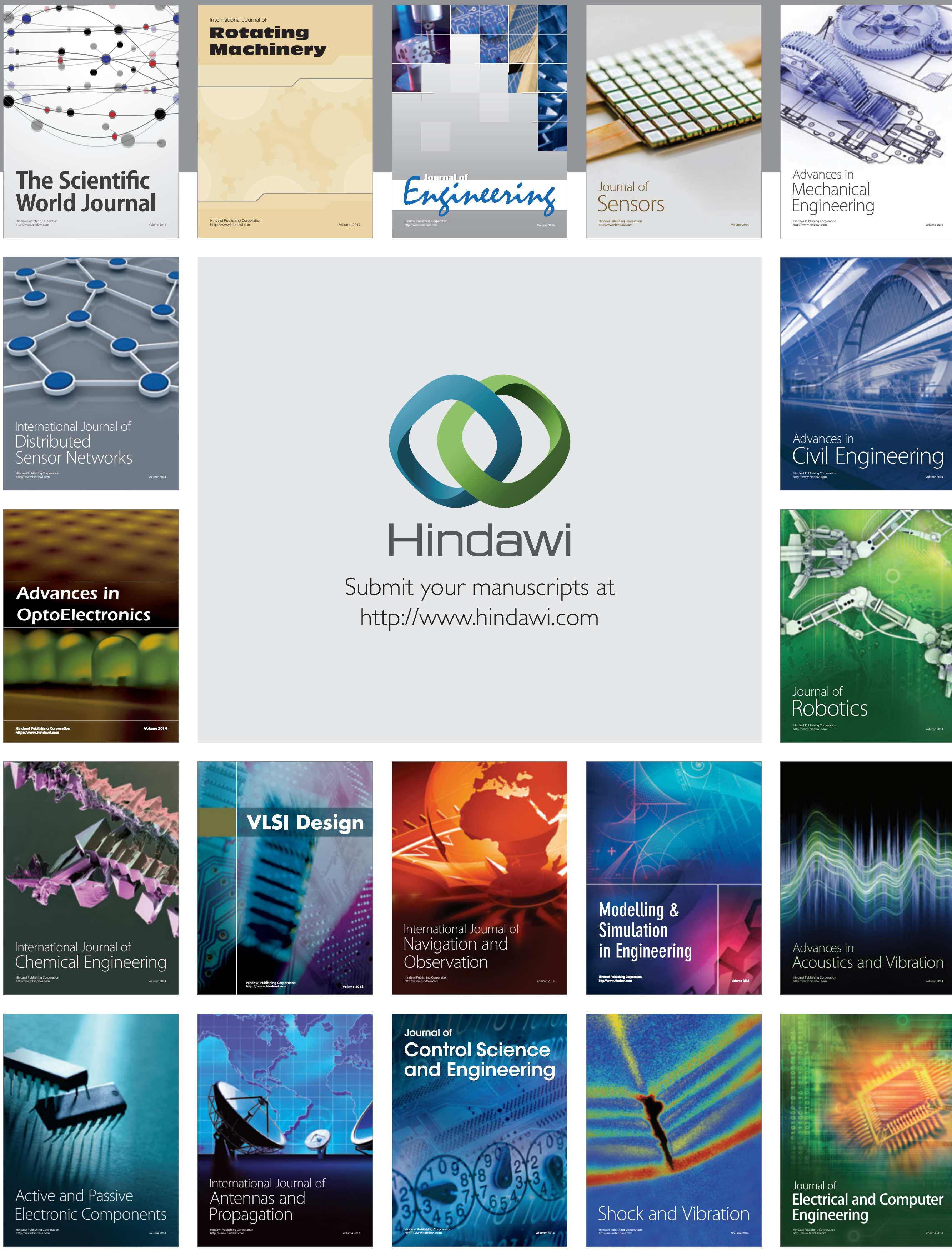
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