Fatigue Life Prediction of Porous Asphalt Overlay

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Abstract

With a large percentage of AC pavements either approaching or at the end of their design lives, PAC overlay of AC pavements has become one of the common methods of rehabilitation. A performance model that can be used to predict the life expectancy of composite PAC/AC pavements reasonably has enormous potential uses. Evaluated the remaining service life of Huai-Xu highway and its fatigue life after overlay construction by the modified fatigue model. The maximum tensile strain of the pavement layers is a significant parameter in this model. Based on linear elasticity theory, the three-dimension model was established, and the maximum tensile strain of three layers was computed. The Results obtained indicate that the fatigue life of the pavement can be increased by around 5.8 years (Xu-Huai direction) and 9.1 years (Huai-Xu direction). It is noticeable that paving PAC overlay can have a significant maintenance effect. The results were compared with an estimation of the real occasion to check its reliability. And it is proved to be a rational approach.

Keywords

Porous asphalt overlay; fatigue life prediction; fatigue model; finite element method.

1. Introduction

Pavement performance gradually declines with the increase of the number of load cycles, diseases such as rutting, cracking and upheaval making pavement in bad condition. When the pavement is deeply deteriorated, normally choosing paving overlay as the best way to improve the service ability of the pavement. As a pavement with satisfactory performances, porous asphalt pavement has unique merits including skid resistance, noise reduction and draining the water quickly. It has been widely applied in the USA, Japan and Europe for its unique advantages of water drainage and noise reduction that result in safety, economic and environment benefits for drivers and neighbouring residents [1].

Fatigue life prediction of the pavement before and after paving overlay is a key point in the process of making rehabilitation plan. An accurate prediction can help people judge when is the best occasion for overlay construction and save maintenance cost. It can also provide a theoretical foundation for pavement structure design. Therefore, fatigue life prediction is significantly worth studying. However, because there are numerous factors influencing the pavement fatigue life, the research of fatigue life prediction is complicated and still requires in-depth study.

This paper takes reconstruction of Nanjing-Suqian-Xuzhou highway in the 13th Five-Year Plan period as the background, analysing the fatigue life of one of its section—Huai-Xu highway before and after porous asphalt overlay construction. The objective of this paper was to first find a proper fatigue equation and then apply it in pavement fatigue life prediction. The results show that the method can make the prediction method for asphalt pavement fatigue life more practical and reasonable. Moreover, it can provide a theoretical and practical reference for the related design task in the future.

2. Research Background

Huai-Xu highway, with a length of 95.754 km, lies in a heavy traffic corridor. It is in Jiangsu Province which was opened to traffic in November 2003. Now the transverse track is the main road disease of Huai-Xu highway. Longitudinal crack, rutting and ravelling follow it, especially rutting and crack are expanding. Some sections were observed to have severe rutting particularly at a high temperature of hot summer. The original pavement structure which is planned to pave overlay is presented in Figure 1. Huai-Xu highway has heavy traffic ever since opening to traffic in the year 2003, the annual average daily traffic is shown in Figure 2. The Huai-Xu highway lies in a rainy area with the high temperature in summer. Since porous asphalt pavement is applicative in this circumstance, reinforcement measures came up to improve the pavement condition and ensure its service ability by paving a 4cm PAC-13 overlay.

Surface layer	4 cm	AK-13
Middle layer	6 cm	AC-20
Bottom layer	8 cm	AC-25
Base	40 cm	cement stabilized macadam
Subbase	20 cm	lime & fly-ash stabilized soil
Subgrade		

Fig. 1 Original Pavement Structure

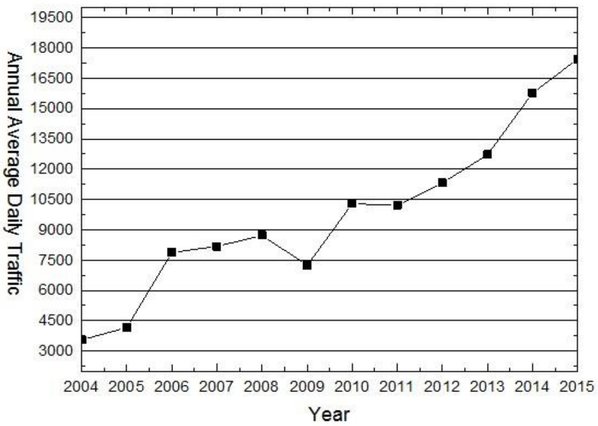

Fig. 2 Traffic Volume on Huai-Xu highway

3. Prediction Model

3.1 Prediction Model of Road Performance

Prediction model of road performance is defined by evaluating the performance and fatigue life of the road. To achieve an accurate and reliable result, different factors such as material type, traffic load, service time and maintenance condition that have an impact on the road condition should be taken into consideration in the process of establishing the model. Generally, there are three kinds of methods for predicting pavement conditions by different formats of mathematical representations: deterministic models, probabilistic models and neural network models.

Linear and non-linear regression analysis are often used in developing deterministic prediction models [2]. Power curve [3]and sigmoidal curve [4]are the most popular non-linear regression formats in predicting pavement conditions. Mechanistic−Empirical Model usually requires the maximum stress, strain or deflection calculated by mechanics, and evaluates the damage by failure criteria of materials. It combines advantages of other models, the data which is required for establishing the model is obtained by precise experiments to guarantee the accuracy, and the analysing process is based on theoretical condition. Thus, it has some advantages over other deterministic models, especially for pavement overlay construction.

Probabilistic model predicts the pavement condition with the certain probability, which is different from the deterministic model. It is believed that future deterioration of the pavement is related to the deterioration that the pavement has experienced in the past [5]. Probabilistic models include Survival curves, Markov model and Semi -Markov model. A probabilistic model can predict the pavement condition based on the previous condition. However, because it is based on statistics, a huge sample capacity is needed to assure the prediction accurate. However, sometimes the process of collecting pavement condition data is challenging. When there was not enough data for analysing, the result would be far away from reality.

Artificial Neural Network, which has the basic characteristics of biological nervous system, is a computing system that could find optimal solution by machine learning. It has been applied into highway field for the pavement condition prediction in the last decade because of its prominent self-learning ability. However, it has the similar defect to the probabilistic model. The learning sample for pavement condition prediction must be typical and carefully chosen to assure the precision of prediction.

3.2 Factors That Could Affect Pavement Condition

The performance of the pavement declines constantly during its service time. In order to develop accurate models, factors that affect the pavement condition should be identified. There are numerous variables that could affect the deterioration of pavements. These factors include materials, pavement structure, maintenance condition, traffic load and climates [6]. Reliable data is the core of developing prediction models. These data of Huai-Xu highway can be obtained from asphalt pavement maintenance management and decision-making support system [7].

3.3 Fatigue Model

Paris predicted the fatigue life of structure base on fracture mechanics. He considered that fatigue life is determined by stress intensity factor of crack tip and material property. Paris equation is shown as follows:

$$\frac{d_a}{dN} = A(\Delta K)^n \qquad (1)$$

Where N and a represent for load cycles and crack length separately; A and n are material parameters; is the difference of stress intensity factor of crack tip for each cycle of load [8].

Paris equation is only suitable for some specific crack types, so it leads an enormous deviation from the real condition. The prediction of fatigue life does not fit the actual fatigue life.

Fatigue damage is unavoidable because of the impact of traffic load. Miner presented the concept of calculating accumulative damage to predict fatigue crack in 1945. Damage can be represented by the ratio of predictive traffic load cycles dividing allowable traffic load cycles, namely damage rate. When damage rate reaches to 1, it is considered that the pavement is destroyed [9]. Allowable traffic load cycles are considered to be related to the tension strain in the bottom of asphalt layer. Differences among pavement design methods mainly exist in the transfer function of this process. AASHTO Pavement Design Guide proposed the remaining-life factor in its overlay design equations as follows:

$$N_{\mathrm{f}} = \mathrm{f}_1(\varepsilon_1)^{-f_2}(E_1)^{-f_2} \qquad (2)$$

Where represents the allowable traffic load cycles, is the tension strain in the bottom of the asphalt layer and is the elastic modulus of asphalt mixture.

Shell model and Asphalt Institute(MS-1) use the model above, the main difference is the parameter value adopted in the model. The fatigue equation from Shell is:

$$N_f = A_f F^n K_{1a} (\frac{1}{\varepsilon_t})^5 (\frac{1}{E})^{-1.4}$$
$$F^n = 1 + \frac{13909E^{-0.4} - 1}{1 + \exp^{(1.354h_{ac} - 5.408)}} \tag{3}$$
$$A_f = experimental\ data - adjustment\ coefficient$$

Asphalt Institute(MS-1) fatigue equation is obtained by controlling stress model in fatigue test:

$$N_f = 0.00432C(\frac{1}{\varepsilon_t})^{3.291}(\frac{1}{E})^{0.854} \tag{4}$$

Where $C = 10^M$; $M = 4.84(\frac{V_b}{V_a - V_b} - 0.69)$; V_a is air void of asphalt mixture; V_b is effective porosity.

In China, according to the specifications for design of highway asphalt pavement, the theory for paving overlay is based on elastic multi-layer theory, and predicting the fatigue life of pavement after paving overlay by the fatigue equation as follows:

$$N_f = 280\sigma^{-4.5} \tag{5}$$

Where N_f is fatigue life, σ is the tensile stress of asphalt mixture.

With the further research of tensile stress in the pavement, fatigue life of asphalt mixture is related to the maximum tensile strain of the pavement, based on the analysis of pavement structure in China. The fatigue equation is described as follows:

$$N_f = 6.32 \times 10^{(15.6 - 0.37\beta)} k_T^{-1} \left(\frac{1}{\varepsilon_a}\right)^{3.97} \left(\frac{1}{E^a}\right)^{1.58} (VFA)^{2.72} \left(\frac{1 + 0.3E_a^{0.43}(VFA)^{-0.85} e^{(0.024h_a - 5.41)}}{1 + e^{(0.024h_a - 5.41)}}\right)^{3.33} \tag{6}$$

Where N_f is fatigue life of asphalt mixture, which is represented as equivalent single axle loads; h_a is the thickness of asphalt mixture layer(mm); β is target reliability; K_T is temperature adjustment coefficient; E_a is dynamic modulus of asphalt mixture at 20 °C; VFA is the aggregate voids filled with asphalt; ε_a is the tensile strain of the pavement, it is described as follows:

$$\varepsilon_a = p\overline{\varepsilon_a}$$
$$\overline{\varepsilon_a} = f(\frac{h_1}{\delta}, \frac{h_2}{\delta} \ldots\ldots \frac{h_{n-1}}{\delta}; \frac{E_2}{E_1}, \frac{E_3}{E_2} \ldots\ldots \frac{E_0}{E_{n-1}}) \tag{7}$$

Where $\overline{\varepsilon_a}$ is theoretical tensile strain coefficient; P, δ are the ground pressure of standard axle load (MPa) and equivalent circle radius (cm); E_0 is resilient modulus of top subgrade in equilibrium Humidity condition; $h_1, h_2 \ldots h_{n-1}$ are the thickness of each structure layer; $E_0, E_1 \ldots E_{n-1}$ are the elastic modulus of each structure layer.

After survey and analysis, the recommended parameters value of fatigue model is shown in table1 and table2 below.

Table 1 Parameters of Old Pavement

Parameter of Fatigue Model	β	k_T^{-1}	ε_a (10^{-6})	E_a (MPa)	VFA (%)	h_a (mm)
Recommended Value	1.65	1.27	Calculated by FEM Model	9600	70	180

Table 2 Parameters of PAC Overlay

Parameter of Fatigue Model	β	k_T^{-1}	ε_a (10^{-6})	E_a (MPa)	VFA (%)	h_a (mm)
Recommended Value	1.65	1.27	Calculated by FEM Model	8000	65	40

Take parameters of the fatigue model in table1 into equation 6, (the allowable load cycles of the old pavement) can be represented as follows:

$$N_{f1} = 1.5301 \times 10^{14} \times (\frac{1}{\varepsilon_a})^{3.97} \tag{8}$$

Take the basic parameters of the fatigue model in table2 into equation 6, N_{f2} (the allowable load cycles of the pavement after paving PAC-13 overlay) can be represented as follows:

$$N_{f2} = 2.7593 \times 10^{14} \times (\frac{1}{\varepsilon_a})^{3.97} \tag{1}$$

For the old pavement, pavement condition or remaining service life should be evaluated by equation 10 first to obtain the practical load cycles threshold.

$$\frac{n_r}{N_b} = 1 - \frac{n_e}{N_a} \tag{2}$$

Where n_r is the practical equivalent single axle loads of the pavement after paving overlay; N_b is the allowable equivalent single axle loads of the pavement after paving overlay. N_a is the allowable equivalent single axle loads of the old pavement; n_e is the practical equivalent single axle loads of the old pavement.

The process of old pavement remaining life prediction is: first take the tensile strain of the pavement into consideration to obtain N_a and N_b. In consideration of remaining service life of the pavement, damage rate needs to be calculated.

The damage rate of Xu-Huai direction $\frac{n_r}{N_b} = 1 - \frac{n_e}{N_a} = 1 - \frac{2834}{2834 + 550} = 0.84$;

The damage rate of Huai-Xu direction $\frac{n_r}{N_b} = 1 - \frac{n_e}{N_a} = 1 - \frac{1132}{1132 + 550} = 0.673$.

3.4 Finite Element Method Model of Pavement

Based on equation 8 and 9, tensile strain is the significant parameter for calculating the allowable equivalent single axle loads of pavement. To obtain, a finite element method model of pavement is established.

Tested the samples drilled from Huai-Xu highway to get the compressive modulus and took confidence coefficient into consideration, the result of each layer is shown in table3.

Table 3 Properties of Pavement Layers

Layer Type	PAC-13 (overlay)	AK-13 (surface layer)	AC-20 (middle layer)	AC-25 (bottom layer)
Resilient Modulus(MPa)	1400	2000	1900	1500

The pavement structure was established in 3D using ABAQUS, the size is X×Y×Z=6m×3m×6m (X is transverse direction; Y is the depth; Z is the longitudinal direction, driving direction is along Z axle negative direction). All elements input into the model were DC3D8R (8 nodes 6 surfaces linear reduced integral unit), the surface especially the load area is closely divided. Boundary conditions for the FE model exert a significant influence on the predicted response of a pavement structure.

Boundary conditions are X-direction displacement of surfaces along X-direction is restrained, Y-direction displacement of surfaces along Y-direction is restrained and the bottom is fully restrained. The FE mesh employed is shown in Figure 3.

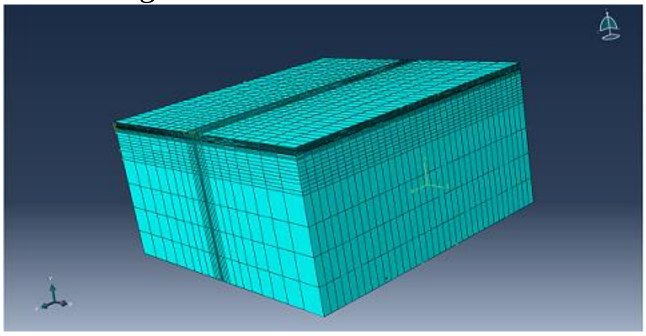

Fig. 3 The 3D FE Model

The load area is divided into 36 rectangles. The width of the rectangle is the same as the width of wheel load. The length of moving in the longitude direction is the actual load moving distance. The movement of load is realized by VDLOAD subroutine. The interfaces between pavement layers were assumed to be perfectly bonded. The maximum tensile strain of the layers in the central of load area is computed as the parameter of the model.

The results are shown in table 4.

Table 4 Tensile Strain (10-6)

Results	Overlay Bottom	Surface Layer Bottom	Middle Layer Bottom	Bottom Layer Bottom
Before paving	/	71	75	69
After paving	65	54	51	33

4. Pavement Fatigue Life Prediction

Allowable equivalent single axle loads of the old pavement is calculated as follows:

$$N_a = 1.5301\times1014\times(\frac{1}{75})^{3.97} = 5.50\times106 \text{ (times)}$$

In Xu-Huai direction, dividing n_a by average equivalent single axle loads (2 million/year), remaining service life is around 2.75 years; In Huai-Xu direction, dividing n_a by average equivalent single axle loads (900 thousand /year), remaining service life is around 6.11 years. Allowable equivalent single axle loads of the pavement after paving overlay is calculated as follows:

$$N_a = 1.5301\times1014\times(\frac{1}{54})^{3.97} = 2.03\times107 \text{(times)}$$

In Xu-Huai direction, n_r = 0.84× N_b = 0.84×2.03×107=1.71×107(times). Dividing n_r by average equivalent single axle loads (2 million/year), service life after reconstruction is around 8.55 years, it increases by 5.8 years; In Huai-Xu direction, n_a = 0.673× N_b = 0.673×2.03×107=1.37×107 (times). Dividing n_r by average equivalent single axle loads (900 thousand/year), the service life after reconstruction is around 15.2 years, it increases by 9.1 years.

According to the specifications for the design of highway asphalt pavement[], cumulative equivalent axle loads are over 4×106 times/lane, the particular value changes from 4.4×106 times to 27×106 times. Basically, 3 to 5 years later, the crack disease will happen after the highway opening to traffic.

Assuming the equivalent single axle loads is 6000 times/day, the estimation of fatigue life can be obtained by 6000×365×(3~5) = 6.57×106~10.95×106(times). Compared with the prediction value above, they are in the same order of magnitude, which can prove the accuracy of the prediction method.

5. Conclusion

This paper took the maximum tensile strain of asphalt mixture layers as indictor, evaluated the fatigue life of porous asphalt overlay.

Took the overlay construction of Huai-Xu highway as an example to predict the fatigue life of pavement. Obtained the maximum tensile strain of the old pavement and the pavement after paving overlay by establishing and calculating with ABAQUS. Put parameters into the fatigue equation. The Results obtained indicate that the fatigue life of the pavement can be increased by around 5.8 years (Xu-Huai direction) and 9.1 years (Huai-Xu direction). It is noticeable that paving PAC overlay can has a significant maintenance effect.

Acknowledgements

The project was sponsored by the 13th Five-Year Plan for Nanjing-Suqian-Xuzhou highway maintenance. The authors also would like to thank Jiangsu Transportation Institute engineers and contractors who helped provide the data for this study.

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