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Dynamic Analysis of Composite Pavement using Finite Element Method and Prediction of Fatigue Life

Benyamin Zarei, Gholam Ali Shafabakhsh*

Faculty of Civil Engineering, Semnan University, Semnan, Iran

Keywords

Composite pavement,
Fatigue life,
Finite element method,
Dynamic analysis,
Mechanistic-empirical method.

Abstract

The combination of flexible and rigid pavements can be achieved by a new structure called composite pavement. This type of pavements benefit from both high-quality asphalt and concrete materials. These pavements are capable of carrying heavy traffic and, if properly designed, meet a higher fatigue life than traditional pavements. This will increase the service life and reduce the maintenance cost of the pavement. In this paper, firstly, the dynamic analysis of composite pavement and its comparison with flexible pavement is conducted. Then, the effect of various parameters on the fatigue life of the pavement is studied. A three-dimensional finite element model of composite pavement under moving load is used and the fatigue life of the pavement is predicted as well. The results indicate that, due to the high stiffness of the concrete layer, it has a structural role in the pavement, and as a result, the thickness of this layer has a greater effect on the fatigue life of the pavement comparing with other parameters. Therefore, the performance of the pavement under traffic loads can be improved by choosing the correct thickness of the concrete layer.

1. Introduction

The composite pavement structure is a combination of rigid and flexible materials. A typical type of these pavements consists of a layer of hot mix asphalt (HMA) on portland cement concrete (PCC) layer [1]. Due to the use of two layers of high-quality materials, each of which having unique properties, these pavements have a high potential and are suitable for carrying heavy traffic [2]. In this structure, the PCC layer is considered to be the main layer in terms of structure due to its great stiffness. This layer is responsible for tolerance and transfer of applied loads and is designed to increase service life, durability and resistance to fatigue failure. The HMA layer is supposed to provide a smooth surface for easy and safe driving. This layer also decrease the reconstruction time of the pavement due to its fast and easy implementation. Although flexible and rigid pavements have been studied in recent years, composite pavements are less studied in the literature [3]. Some institutes, including AASHTO and the Asphalt Institute, have proposed regulations for designing the composite pavements which often examine the design of asphalt overlays on existing concrete pavement [4].

One of the pavement design approaches, the mechanistic-empirical, which has replaced empirical methods and is widely used by researchers in recent decades, use pavement responses (stress, strain and deformation) under traffic and environmental loads to predict failures, especially fatigue cracks [5, 6]. There are several methods to determine the pavement responses including laboratory and numerical method [7]. In laboratory methods, it is possible to obtain the pavement responses by locating sensors at certain points in the pavement (e.g. under the asphalt or concrete layers). Nowadays, numerical method cover a wide range of studies. One of numerical methods widely considered by the investigators is the finite element method (FEM). In this method, it is possible to determine the pavement responses in different locations by accurate modeling of the pavement, and finally, predict the pavement failures [8].

Fatigue cracks are one of most common failures in composite pavements. These cracks usually start under the PCC layer and extend to the pavement. Although many studies have been carried out on the prediction of fatigue cracks in flexible and rigid pavements, the study of these cracks in composite pavements has been less considered by researchers [9,10].

In this study, the finite element method has been used for dynamic analysis of composite pavement. The pavement responses are determined at the critical points under the moving load, and then the pavement fatigue life is predicted by the model provided by the mechanistic-empirical pavement design guide (MEPDG). Finally, the effect of

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* Corresponding Author:
E-mail address: ghshafabakhsh@semnan.ac.ir – Tel, (+98) 9123207154

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various parameters such as model geometry and material properties of the layers on fatigue life is studied. Also, it is worth mentioning that in this study the properties of materials for pavement layers is considered to be in the form of linear elastic. This assumption is logical because the loading is dynamical and the level of the strains is low.

2. 3D Finite Element Model

In order to predict the failures of composite pavement in mechanistic-empirical analysis, it is necessary to obtain pavement responses under proper condition. The finite element method is a powerful technique for this purpose. The model should be defined in such a way that the pavement behavior is acceptably similar to the actual condition, so that the obtained results can be used to predict the performance of the pavement. Among the factors affecting the analysis results of finite element model, are the model geometry, the properties of materials, the boundary conditions, loading and meshing [11].

In this study, ABAQUS software is used to create a three-dimensional finite element model of composite pavement. Dimensions of this model are 10*3.5 meters. These dimensions are chosen in such a way that the stress concentration on the edges and corners is negligible.

In this model, to define the boundary conditions, roller supports for edges of the model are used in a longitudinal direction and a fully fixed support is used for the sub-model. The meshing of the model is chosen to get the most accurate results. For this purpose, after analyzing the model with different types of meshing, 8-nodes linear brick reduced integration C3D8R elements with dimensions of 0.05*0.05 meters were selected for asphalt and concrete layers. For the pavement subgrade, larger meshes were considered to shorten the analysis time. The materials characteristics of the composite pavement layers are taken from previous researches [12,13]. The composite pavement section and the three-dimensional finite element model are shown in Figures 1 and 2, and the properties of the materials are given in Table 1.

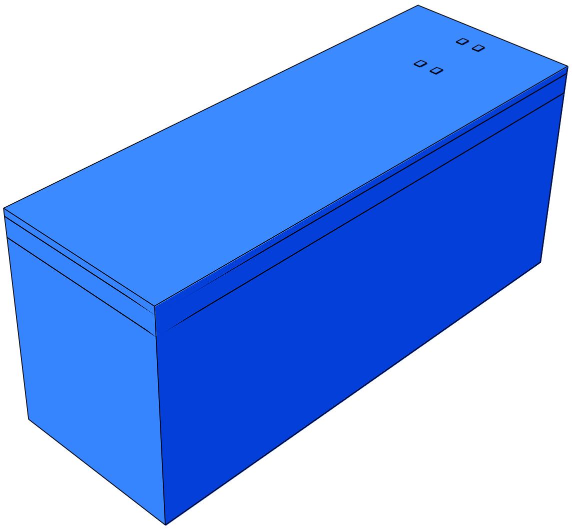

Figure 1. Three-dimensional finite element model

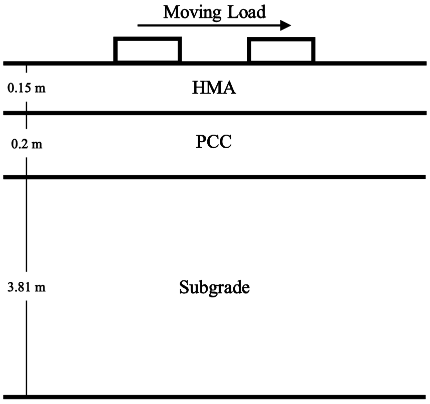

Figure 2. The Composite Pavement Section

Table 1. Pavement layer parameters used for the 3D FEM

Layer	Density (kg/m^3)	Module of elasticity (MPa)	Poison ratio
HMA	2280	2550	0.3
PCC	2400	27430	0.18
Subgrade	1730	152	0.4

2.1. Validation

In this study, Pennsylvania University field testing results have been used to validate the finite element model. In 1993, Sebaaly et al. [13] conducted a full-scale field experiment supported by the federal highway administration (FHWA). This experiment was conducted to investigate the effect of velocity and load magnitude on the tensile strains under the asphalt layer. For this purpose, the sensors were placed under the asphalt layer and in the vehicle motion path. Three speeds of 32, 56 and 80 km/h were selected. A semi-trailer vehicle with a single axle on the front and the tandem axle on the back was used. The pavement structure used in the Pennsylvania test includes a layer of asphalt which is based on the aggregate base and the subgrade.

The properties of the materials and the thickness of the asphalt layers and subgrade are similar to Table 1. The base layer has an elastic modulus of 207 MPa and a Poisson coefficient of 0.35 [13]. Figure 3 shows the comparison of the results from the analysis of the finite element model and field results.

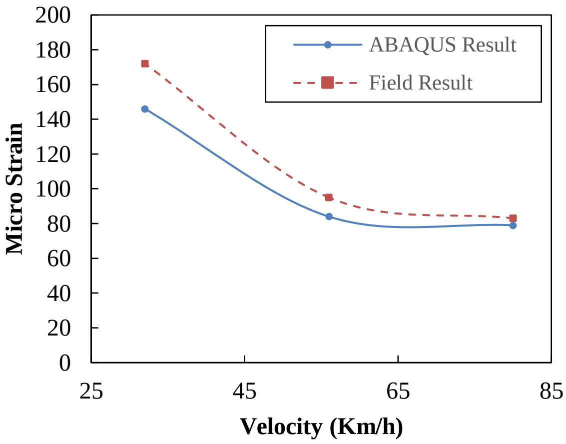

Figure 3. Comparison of ABAQUS and field results

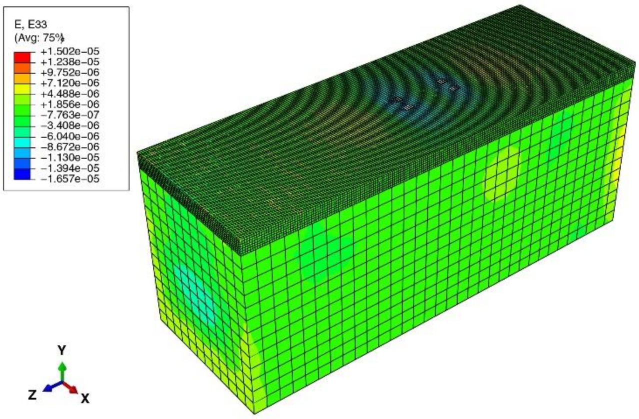

Figure 4. Longitudinal strain distribution

As shown in Figure 3, the difference between experimental and ABAQUS results at speeds of 32, 56 and 80 km/h are 15, 11 and 4 percentage respectively, and so there exists a good correlation between these results. It also indicates that by increasing the speed of the vehicle, the tensile strain under the asphalt layer as well as the difference between experimental and ABAQUS results have decreased.

3. Dynamic Analysis of Composite Pavement

Composite pavement is a combination of two rigid and flexible materials. Each of these materials has different performance in terms of structure and so, composite pavement behavior under traffic loads will be complicated [14].

In most conducted analyzes, loading of the vehicle has been statically considered, but pavement performance is strongly influenced by dynamic loading [15]. Figure 4 indicates the longitudinal strain distribution at the full model of composite pavement under dynamic loading. In Figure 5, the performance of the flexible pavement used in the Pennsylvania University Test and composite pavement used in this paper was compared under the same loading conditions and at a speed 56 km/h. As can be seen, tensile strains under the asphalt layer in the composite pavement have fallen sharply. The reason for reducing these strains is the high stiffness of the concrete layer, which strongly affects the performance of composite pavement.

In Figure 6, a comparison was made between longitudinal strains in the asphalt and concrete layer in the composite pavement. As can be seen, the compressive strain is greater than the tensile strain under the asphalt layer. Since asphalt has a higher resistance to compressive strains than tensile strains, these strains are not a destructive factor for the asphalt layer. On the other hand, tensile strains under the concrete layer are slightly more than the asphalt layer, so it can be concluded that in composite pavements, unlike flexible pavements, critical strains occur under the concrete layer. These results prove that the concrete layer plays a structure role in composite pavements and as a result, the strength of the pavement is measurable based on the strength of the concrete layer.

The tensile strains under the concrete layer are the main cause for creating fatigue cracks in composite pavement. Increasing these strains reduces fatigue life and thus, reduces the service life of the pavement. In this paper, the effect of different parameters on the tensile strain under the concrete layer is investigated and the best method for reducing these strains is selected. For this purpose, the model presented by the Mechanistic-Empirical Pavement Design Guide (MEPDG) for determining the fatigue life of composite pavements is used. In Tables 2 to 4, the effect of various parameters such as the thickness of the asphalt and concrete layer and the elastic modulus of the concrete layer on the PCC layer tensile strain is shown. From the results obtained, it can be concluded that increasing the thickness and the elastic modulus of the layers reduces the tensile strain under concrete layer. Meanwhile, the thickness of the concrete layer is more effective than other parameters.

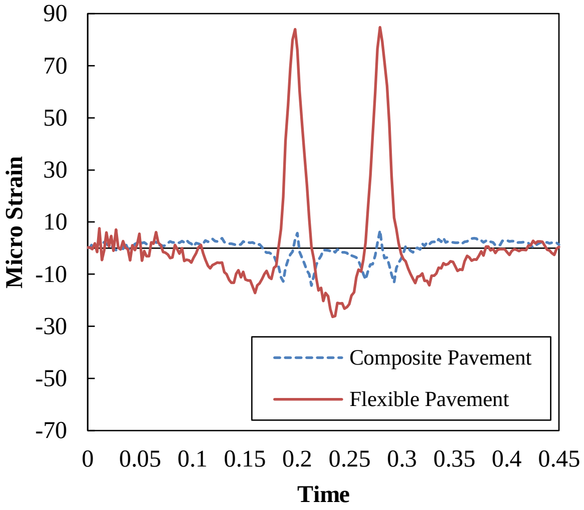

Figure 5. Comparison of the flexible and composite pavement

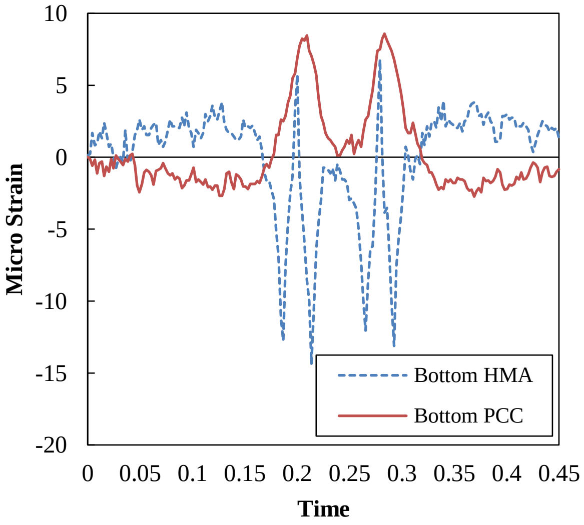

Figure 6. Comparison of the longitudinal strains in the asphalt and concrete layer in composite pavement

Table 2. Tensile strain at the bottom of PCC layer for different HMA thickness

HMA thickness (cm)	Tensile strain
10	0.000009775
12	0.000009179
15	0.000008583
18	0.000007749
20	0.000007629

Table 3. Tensile strain at the bottom of PCC layer for different PCC thickness

PCC thickness (cm)	Tensile strain
15	0.00001073
20	0.000008583
25	0.000006795
30	0.000005722
35	0.000004768
40	0.000003695

Table 4. Tensile strain at the bottom of PCC layer for different concrete elasticity modulus

PCC modulus (MPa)	Tensile strain
27430	0.000008583
30173	0.000008225
33190.3	0.000007749
36509.33	0.000007272

4. Fatigue Life

The fatigue life of the pavement is the number of times allowed to repeat the load before the occurrence of fatigue cracks. Fatigue cracks appear as alligator cracks in the pavement surface. Various models are provided by different regulations to determine this parameter. The mechanistic-empirical pavement design Guide (NCHRP 1-37A), based on the model of the Asphalt Institute, provides a fatigue transfer function to determine the fatigue life of the pavement. This relationship can be used for both flexible and composite pavements and predict the fatigue life of the pavement based on the tensile strain at the critical location. In this model, the fatigue life of the pavement is predictable for both types of cracks from bottom to top and from top to bottom. This model is shown in Eqs. (1) to (4) [16]. In this paper, fatigue cracks are predicted from bottom to top.

$$N_f = 0.00432(k_1')(C)\left(\frac{1}{\varepsilon_t}\right)^{3.291}\left(\frac{1}{E_{HMA}}\right)^{0.854} \qquad (1)$$

$$C = 10^M \qquad (2)$$

$$M = 4.84\left(\frac{V_b}{V_a + V_b} - 0.69\right) \qquad (3)$$

$$k_1' = \frac{1}{0.000398 + \frac{0.003602}{1+e^{(11.02-3.49H_{HMA})}}} \qquad (4)$$

where N_f is the fatigue life, ε_t is tensile strain at critical location, E_{HMA} is stiffness of HMA, k_1' is thickness correction term; dependent on type of cracking, H_{HMA} is total HMA thickness, V_b is effective binder content (%), V_a is air void (%) (the V_b and V_a are assumed to be 7 percent and 4 percent, respectively).

By placing the results obtained from dynamic analysis of composite pavement under moving load, the fatigue life of the pavement was obtained for different conditions and finally, the effect of different parameters on the fatigue life of the pavement was compared. In Figures 7-9, the effect of these parameters on the fatigue life of the pavement is shown. According to the results, it can be concluded that increasing the thickness and elastic modulus of asphalt and concrete layers increase the fatigue life of composite pavement. Among the parameters investigated, the effect of concrete layer thickness on fatigue life is higher than other parameters.

As seen in Figure 8, after the thickness of 30 cm, the extension of the fatigue life versus the thickness of the concrete layer increases with a steeper slope, so that it tends to infinity, As a result, the fatigue life of the pavement increases uneconomically. Therefore, it is possible to increase the resistance of the pavement to fatigue cracks by correctly choosing the thickness for the concrete layer. Of course, the project costs should be considered by the designers. Therefore, it is necessary to select a cost-effective thickness for the concrete layer.

The pavement would be destroyed due to fatigue cracks before the end of service life, if the thickness of the concrete layer is selected small. The pavement may also be destroyed by other factors, such as rutting and reflective cracks before the end of fatigue life if the thickness of the concrete layer is selected very large. Therefore, it is important that the thickness of the pavement be properly selected in such a way that the pavement is usable over the service life.

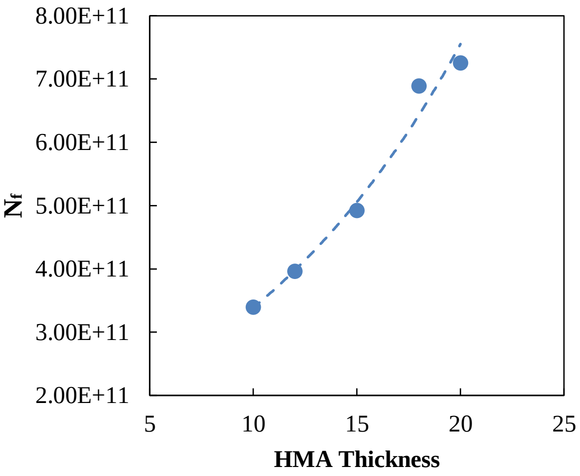

Figure 7. Fatigue life for different HMA thicknesses

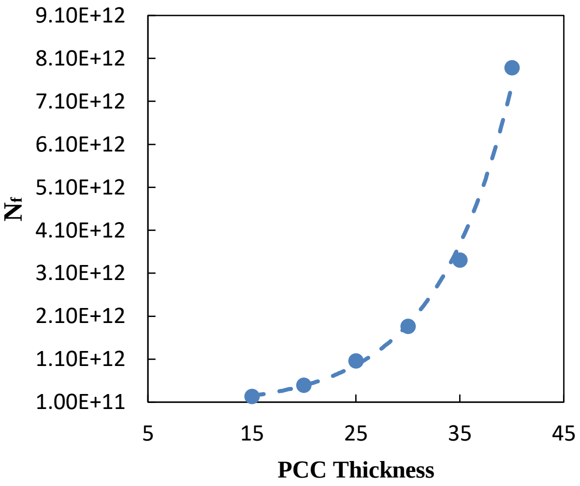

Figure 8. Fatigue life for different PCC thicknesses

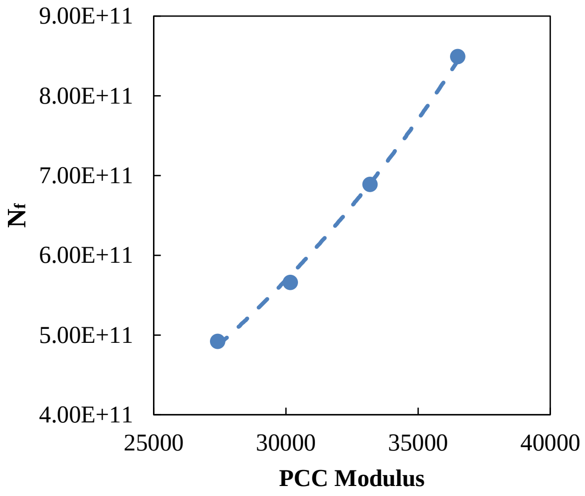

Figure 9. Fatigue life for various values of the PCC modulus

5. Conclusion

Using the finite element method, the dynamic analysis of the composite pavement under moving load was studied in this work. The dynamic analysis showed that the performance of the composite pavement is much more better compared with traditional pavements under traffic loads, and this pavement can be considered as a suitable option for carrying heavy traffic. In composite pavements, the strength of the pavement is measured based on the strength of the concrete layer,due to the higher stiffness of the concrete layer compared with the asphalt layer. Therefore, tensile strain of concrete layer is a critical factor in these pavements, and it is necessary that these strains should remain within the permissible limits in order to control fatigue failure and increase fatigue life. One of the methods to optimize the performance of the pavement against fatigue failure is to select the right and economical dimension of the thickness and properties of the asphalt and concrete layers materials in composite pavement.

In this study, the effect of various parameters such as the thickness of asphalt and concrete layers and the elastic modulus of concrete layer on the fatigue life was evaluated. The results indicated that the effect of concrete layer thickness on the fatigue life of the pavement is more than other parameters, and hence, designers need to select the right and economical thickness to improve the pavement performance against fatigue failure. It is worth mentioning that the thickness of the concrete layer should be selected at proper level so that the pavement is usable over the predicted service life and the pavement should not fail before the end of the service life. In addition to traffic loads, future works can study the environmental and thermal gradient effects on the performance of composite pavements.

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