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Research Article

Comparison of Two Typical Professional Programs for Mechanical Analysis of Interlayer Bonding of Asphalt Pavement Structure

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The mechanical analysis of interlayer bonding problem of asphalt pavement is performed by the elastic layered system theory or finite element method (FEM); then, a lot of specialized programs based on the above theories emerged successively, of which BISAR3.0 and EverStressFE are quite representative. In order to further clarify the characteristics of BISAR3.0 and EverStressFE for investigating interlayer bonding problem of asphalt pavement, this paper will carry out a comprehensive comparison from the specific realization viewpoint, such as the principle of interlayer bonding, modeling, calculation processing, and result treatment, and a specific example will be given to compare and analyze their functions. The results indicate that the two programs have certain comparability in analyzing the interlayer bonding problem of asphalt pavement, which will contribute to the foundation for the rational selection of asphalt pavement structure mechanical analysis program.

1. Introduction

Asphalt pavement structure, as one of the main pavement forms, has been widely used for its advantages of great flatness, being seamless, short construction period, and convenient maintenance, while the distresses of asphalt pavement, such as slippage, rutting, and reflective crack, are especially serious. In 2007, after coring on SH 114 pavement in Texas, Walubita and Scullion found that the asphalt surface often showed interlayer interface separation, slip, and other phenomena. Besides, the National Highway Traffic Safety Administration once conducted a survey of 44 major highways, of which 13 roads were damaged by rutting, which is about 29.5% of the total survey [1–3].

The distresses of asphalt pavement not only depend on the mechanical parameters of each layer but also are significantly affected by the interlayer bonding condition. Lepert et al. stated that the serious damage of pavement caused by deterioration of interlayer bonding condition accounted for 5% of highway network at that time in France [4]. Kruntcheva et al. investigated the service life of asphalt pavement structure with different interlayer bonding conditions by BISAR3.0 and finite element programs, which concluded that the service life was reduced by more than 80% due to the poor bonding condition between layers [5]. The current design method is based on the continuous elastic layered system theory in most countries, which assumed that the adjacent layers of structure are continuous, but the assumption generally is not reached in real engineering because of the following factors: (1) the asphalt pavement structure is not formed at one time but is paved and compacted each layer from bottom to top, which result in debonding between layers; (2) the interface between layers is easy to be polluted by natural or human factors in construction process; (3) due to the significant difference in the construction material properties of adjacent layers, the interface between the layers becomes a weak link. In conclusion, the real interlayer bonding conditions between layers are inconsistent with the assumption that the layers of pavement structure are completely continuous in the design, which leads to unreasonable structure design and then distresses occur.

Obviously, it is greatly significant for design, construction, and maintenance of pavement to research the influence of interlayer bonding condition on asphalt pavement structure. Traditional researches focused on interlayer bonding problems were performed based on experimental methods. Uzan and Crispino investigated the mechanical properties of the interface between the asphalt layers of the specimens made in the laboratory and cored on-site [6, 7]. Donovan et al., Canestrari et al., and Raposeiras et al. investigated the effects of temperature, dosage, and type of tack coat on interlayer bonding of asphalt pavement [8–10]. Romanoschi et al., Kruntcheva et al., and Collop et al. studied the influences of interface treatment, material types, and other factors on the interlayer bonding of pavement structures through laboratory experiments, which found that the material type is the main factor affecting the interlayer performance [11–13]. Jaskula and Rys conducted field and laboratory tests, analyzed materials of tack coat in three sections, and summarized the reasons for the poor bonding quality between layers [14]. Obviously, the above research studies mainly depend on certain size specimens, which could not completely reflect the mechanical response of pavement structure and design index during road operation because of its small size and unreally boundary conditions.

With the development of computer technology, some programs are developed to calculate the mechanics behavior of asphalt pavement for numerical simulation, which can accurately account for the structural problems of asphalt pavement. At the same time, it can effectively respond to the design indexes and mechanical properties. Therefore, based on the elastic layered system theory, finite element method (FEM), and continuous finite layer method [15], the asphalt pavement professional programs emerged successively, including KENLAYER [16], BISAR [17], CIRCLY [18], EVERSTREES [19], EverStressFE [20], MICHPAVE [21], and 3D-Move Analysis [22], among which different mechanical models were adopted to simulate interlayer bonding condition, such as Goodman model [23], shear spring model [24], and Coulomb friction model [25]. And the above professional programs of asphalt pavement mechanical analysis have robust performance and overcome complexity and insufficient pertinency of the large general program, such as ABAQUS, ANSYS, and ADINA [26–28]. The BISAR3.0, developed by Bitumen Business Group based on the elastic layered system theory, and EverStressFE, developed by William G. Davids from University of Maine based on the finite element method (FEM), are most typical in professional programs for mechanical analysis of asphalt pavement. These two programs have been widely used in the field on the aspect of interlayer bonding problem of asphalt pavement. However, there is still a gap between the basic principle and computer modeling. Therefore, the research on the differences between the above two programs is important to build a foundation for the successful application and development of asphalt pavement structure professional programs.

Based on this, this paper selects the two typical professional programs, BISAR3.0 and EverStressFE, which can better solve interlayer bonding problem of asphalt pavement structure. The parallel comparison of the above programs is conducted from the aspects of principle and algorithm, and an example is given to discuss the influence of interlayer bonding condition on mechanical responses of asphalt pavement structure, including pavement surface deflection, flexural-tensile strain, and maximum vertical compression strain on the top of subgrade, which provides a valuable reference for the rational selection of analytical program.

2. Comparison of BISAR3.0 and EverStressFE

BISAR3.0 and EverStressFE are based on the elastic layered system theory and finite element method (FEM), respectively. The elastic layered system theory is a method to study the displacement and stress in the elastic system under load, which is a branch of elastic mechanics. In this theory, by establishing the relationship between the unknown and known quantities (equilibrium condition, geometric condition, and physical condition of the force), a set of equations can be derived. In the process of derivation, if various factors are considered accurately, the resulting equations will be extremely complicated and even unable to be solved. Therefore, in the process of analyzing the stress, strain, deflection, and other processes of pavement mechanics by using elastic layered system, the basic assumptions are generally introduced to facilitate the solution [29]. The finite element method (FEM) is an efficient numerical simulation method. Its basic idea is to divide the continuous whole into many elements connected only at the nodes and take the node displacement as the basic unknown quantity of the structure. On this basis, the finite element method (FEM) analysis process includes discrete, element characteristics analysis, integral analysis, and other steps, according to the basic mechanical theorem (virtual work principle and variational principle), equilibrium relationship, continuum conditions, and other analysis of the mechanical response of the structure under the given boundary conditions [15, 30]. Therefore, the two kinds of asphalt pavement analysis program will directly determine the differences of program in the treatment of interlayer bonding problem, modeling, solution process, and result postprocessing, which are based on the different research and development principles (as shown in Figure 1).

2.1. Principle of Interlayer Bonding. Goodman model, shear spring model, and Coulomb model are the three commonly used models for the evaluation of interlayer bonding condition. The Goodman model is widely used in the analysis of pavement structure. Both BISAR3.0 and EverStressFE programs are based on Goodman model in the simulation of interlayer interface. The expression of this model is shown in Figure 2. Combining with the direct shear test, the interlayer average shear strength of the test piece under a certain condition can be obtained, which is expressed by the interlayer adhesion coefficient K. When the relative horizontal displacement between the layers is Δu, the interlayer adhesion coefficient K and the interlayer shear stress τ is expressed as follows:

$$\tau = K\Delta u. \quad (1)$$

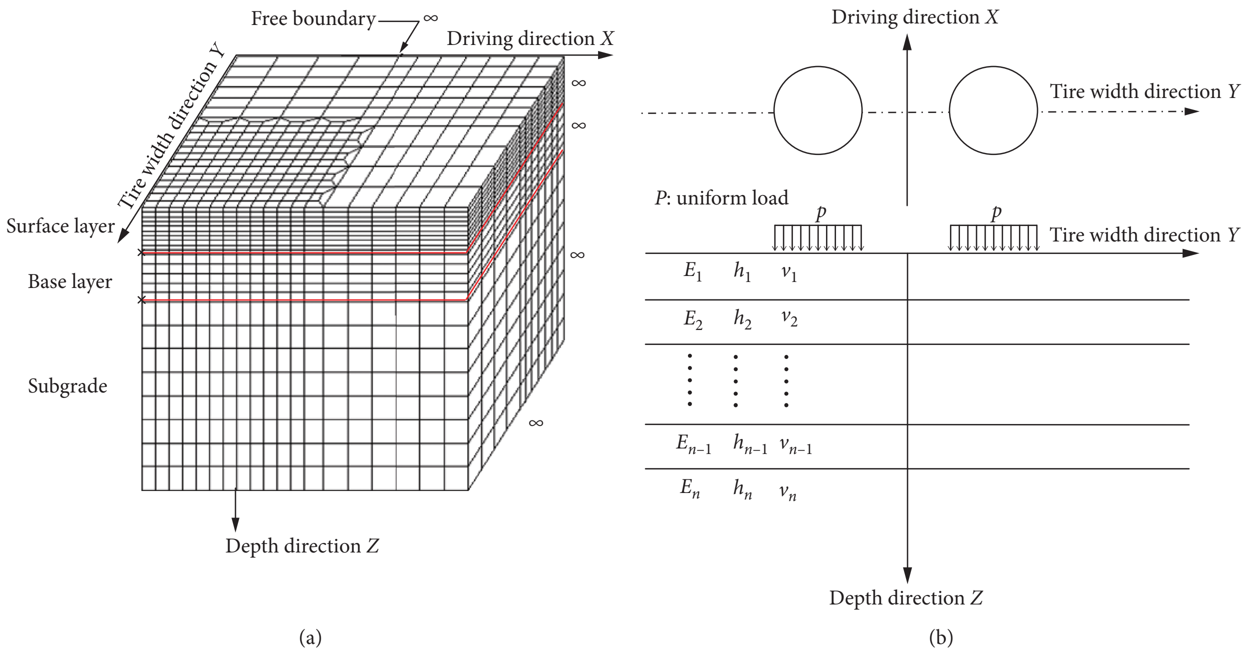

Figure 1: Schematic diagram of two programs of research and development principles: (a) three-dimensional finite element (3D FE); (b) elastic layered system theory.

It has a clear physical meaning to describe the interlayer bonding condition with the coefficient K. When $K \longrightarrow 0$, the interlayer tends to fully bonding. When $K \longrightarrow \infty$, the interlayer tends to be fully slipping. And when $0 < K < \infty$, the interlayer is the state between fully slipping and fully bonding.

BISAR3.0 program makes a slight change in simulating interlayer bonding, combining the basis of Goodman mechanical model. The interface between the upper and lower horizontal structural layers is regarded as an infinite thin interlayer. The strength of the interlayer is expressed by the standard shear spring compliance AK, and the value of interlayer bonding state is represented by AK, which is reciprocal to the interlayer bonding coefficient K of Goodman model. Physically, it is assumed that the shear stress acting on the interlayer interface causes the relative horizontal displacement between the upper and lower structural layers, which is proportional to the stress acting on the interlayer interface. The standard shear spring compliance AK is defined as follows:

$$\mathrm{AK} = \frac{\text{relative horizontal displacement of layers}}{\text{stresses acting at the interface}}. \tag{2}$$

In BISAR program, the introduction of standard shear spring compliance AK is not a well-known“classical”friction coefficient, which shows the interface bonding state in the pavement structure. It is generally known that the value of the friction coefficient is different in dynamic and static conditions. If the friction coefficient is used, BISAR is required to solve the problem of discontinuity (i.e., step function). However, the mathematical assumption of the BISAR model is continuous with all its parameters, which has never solved the problem of discontinuity, so the standard shear spring compliance AK is introduced instead in this case [17].

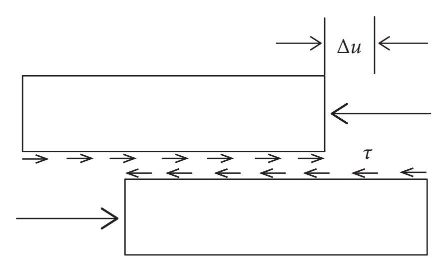

Figure 2: Goodman model.

The relationship between the standard shear spring compliance AK and the friction parameter α is expressed as follows:

$$\alpha = \frac{\mathrm{AK}}{\mathrm{AK} + ((1+\nu)/E)\cdot a}. \tag{3}$$

Here, α is the dimensionless friction parameter (α is between 0 and 1, when $\alpha = 0$ means full friction, when $\alpha = 1$ means complete slip), AK is the standard shear spring compliance (m^3/N), a is the radius of load circle, E is the elastic modulus of the layer above interface, and ν is Poisson's ratio of that layer. It should be noted that the friction parameter here is different from the friction coefficient K mentioned in the Goodman model, which not only is affected by the material properties, but also depends on the diameter of the load circle.

For the standard shear spring compliance AK, it is difficult to give it an accurate value in the theoretical analysis, so it is necessary to introduce another coefficient for sensitivity analysis. In this case, BISAR program defines another parameter to characterize the interlayer bonding condition, that is, the reduced shear spring compliance ALK (m). The relationship between the ALK and friction parameter α, shear spring compliance AK is expressed as follows:

$$\begin{aligned} \text{ALK} &= \frac{\alpha}{1-\alpha}\cdot a, \\ \text{AK} &= \text{ALK}\cdot\frac{1+\nu}{E}. \end{aligned} \tag{4}$$

The specific meaning of each variable symbol in the equation is the same as the above.

In the BISAR model, when ALK increases from 0 to 100 a (a is radius of the loaded area), it represents the change process from fully bonding to fully slipping. It is noted that each layer of the BISAR program can be set as fully bonding, partially slipping, or fully slipping. If it is partially slipping or fully slipping, it needs to be reflected by setting the specific value of shear spring compliance AK or reduced shear spring compliance ALK.

The EverStressFE is also based on the Goodman model. It maintains the symmetry of the stiffness equation of the pavement system, and special interface elements are set to define the interlayer bonding condition of the pavement structure, which makes the solution and analysis process of the interlayer mechanical response of the pavement structure more concise.

There are two kinds of element types in the EverStressFE finite element model, namely, standard element with 20 nodes and interface element with 16 nodes [31]. The middle node on any side of all element types is strictly set at the center of the side, and the edge of element is always the first to contact and transfer stress. In order to maintain the matching degree and universality of different element types, all elements are equipped with equal parameter quadrilateral contact surface, and the Gauss integral of 8 integral points is used for numerical calculation. The shear stress between the structural layers is transferred by the specially treated 16-node interface element. In order to simulate the zero thickness transfer of shear stress as much as possible, the thickness of the interface element in EverStressFE is set to 1 mm. Different from the Coulomb friction model, the constitutive relation of the element is independent of the general stress to maintain the symmetry of the stiffness equation of the pavement system, which is very important for the realization of the preconditioned conjugate gradient method in EverStressFE distance. It is noted that the interface element is only used in the fully bonding or partially bonding condition between layers. When the interlayer is fully slipping, the two interfaces are separated and the shear stress cannot be transferred, leading to the fact that the interface element is not suitable.

In order to characterize the interlayer interface bonding condition and the transfer of shear stress, 16 nodes with special treatment are set at the interlayer interface, while the interface stiffness IS (N/mm^3) is introduced to parameterize the different bonding conditions of the interlayer interface of the pavement structure. The meaning of the interface stiffness IS can be expressed as the ratio of the shear stress τ (N/mm^2) at the top and bottom of the interface element to the relative shear displacement δ in the x or y direction between the nodes as shown in the following equation:

$$\text{IS} = \frac{\text{interlayer shear strain } \tau}{\text{relative shear displacement of interlayer nodes } \delta}. \tag{5}$$

As shown in equation (5), the larger the interface stiffness IS, the better the interlayer bonding condition, that is, the closer to the fully bonding state. Instead, the worse the interlayer bonding state, the more the inclination to the slipping state. When IS tends to 0 and ∞, the interlayer bonding is in two extreme states of fully slipping and fully bonding, respectively. When IS is a middle value, interlayer bonding is in a partial bonding state.

Similar to BISAR, it is necessary to define IS value to determine whether the interface is fully bonding, fully slipping, or partially bonding, while it sets the interlayer bonding condition in the EverStressFE. It is not necessary to input the IS value of interface stiffness when the interlayer is fully bonding. When the interlayer is fully slipping or partially bonding, input 0 or input IS value is greater than 0 according to the actual situation. And it is noted that the EverStressFE can define the bonding condition of two interfaces at most. If the pavement system is a 4-layer structure, the subbase-subgrade interface is defined as fully bonding by default.

2.2. Loads. BISAR program can consider both vertical force and horizontal force. The shape of tire-pavement contact surface must be circular, and the maximum number of wheel loads can reach 10 to simulate multiaxle and multiwheel groups. From the size, distribution radius, and contact stress of the circular distributed wheel load, only two factors are independent. It can be input by three modes: wheel load and load circle radius, contact stress and wheel load, and contact stress and load circle radius, while the specific area position (i.e., wheel spacing, axle spacing) is determined by setting the overall coordinates at the center of the circle. This program cannot directly specify the wheel axle configuration. If it is single axle dual-wheel group or tandem axle dual-wheel group, the wheel spacing and axle spacing size need to be realized by the number of wheel loads, relative plane position, etc. EverStressFE program is more convenient to set the wheel axle combination, which can directly set the wheel number, axle type, wheel spacing, axle spacing, single wheel load size, contact stress, and other parameters. The program can also set the shape and size of the tire-pavement contact surface by itself, such as circular distribution, rectangular distribution, and user-defined (considering the rectangular distribution of area reduction) and set the wheel load of specific format data file (suffix is Node) by clicking the *Save Custom Load* button. The biggest feature of EverStressFE program in wheel load is the embedded Tread Designer, which can easily set the number of tread patterns, the width of each tread pattern, the peak value of distribution force in each tread pattern, and the distribution form along the tire length direction (constant, parabolic shape or half sine wave shape, etc.). Users can even edit and generate the wheel data file with suffix of node in a certain format and then import the program for calculation.

2.3. Structural Layer and Calculation Point. For BISAR, a maximum of 10 layers of structural layers can be considered, among which the last layer from top to bottom is regarded as a semi-infinite space body, without inputting the thickness. The thickness of other structural layers can be specified separately. Each structural layer is regarded as a linear elastic body and needs to input elastic modulus and Poisson's ratio. EverStressFE program can consider up to four layers of structure and regard each layer as a linear elastic body with setting the thickness, elastic modulus, and Poisson's ratio. In order to avoid the influence of boundary conditions, the thickness of the subgrade is determined by checking calculation. BISAR can specify up to 10 calculation points, which can be determined by inputting the three-dimensional (3D) coordinates in the overall coordinate system. For the points that are just located in the interlayer interfaces, the user of the program also needs to determine whether it is the upper bottom or the lower top. EverStressFE does not need to specify calculation points in the preprocessing stage. For the interface between upper and lower layers, the program can be selected in the postprocessing of results.

2.4. Model Solution. After the BISAR model is established, it is calculated by saving the data and clicking *F*5 button or *Result-Calculate* menu. In EverStressFE, after modeling and saving the data, the solution process will be displayed on the screen by selecting *solve current model* menu and clicking *solve* button. In particular, by selecting *work with batch list* menu, the program can solve multiple models in batch and in order, which is beneficial to large-scale parallel operation.

2.5. Result Output. BISAR will display the calculation results in the form of *Block Report*, *Detailed Report*, *Block Table*, and *Detailed Table*. In the *Block Table*, it outputs three normal stresses and strains of each calculation point in one page and is expressed as *XX*/*YY*/*ZZ* according to the direction under the fixed Cartesian coordinate system, and three uniaxial displacements are expressed as *UX*/*UY*/*UZ*. The *Detailed Report* gives the calculation results with more detailed information of each calculation point on a page. When *Block Table* and *Detailed Table* are used, the data can be pasted to the clipboard for presentation.

The calculation results of EverStressFE are shown as standard 2D plot through depth, contour plot, and deformed mesh, which are drawn by Dplot Jr. The standard 2D plot through depth needs to specify the coordinates of the plane point and the program gives the distribution of three normal strains, three tangential strains, and three displacement components that should be vertically downward along the depth of the corresponding point. The contour plot gives nine mechanical response distributions on the *X*-*Y* section, *Y*-*Z* section, and *X*-*Z* section. The deformed mesh is given according to a certain displacement ratio. The program also gives the mechanical responses of some special points on the axis of symmetry, which is convenient to use for performance prediction.

2.6. Other Aspects. In order to reduce the calculation time and save the storage space, EverStressFE only considers 1/4 symmetrical structure, and the load-pavement contact model is also 1/4 symmetrical. For example, the circular load of single axle dual-wheel and tandem axle dual-wheel is shown in Figure 3. The horizontal direction and depth direction range of the model need to be determined by certain experimental calculation. In the aspect of mesh generation, the locally refined mesh or simple grid mesh can be selected in the horizontal direction. If it is the simple grid mesh, only the confirmation of the elements average number of tire width direction and driving direction for the plane is needed. If it is a locally refined mesh, the location and region of refinement area should be determined first, and then the elements average number of *X*/*Y* direction should be determined in this area. The number of equal elements is determined according to the thickness of each structural layer in the depth direction. In terms of model boundary, the left and front sides of the model are symmetrical planes, and the back, right, and bottom sides of the model are determined by the simulated infinite region and the finite region, which can realize the coupling between the finite element and the infinite element.

3. Example Analysis and Discussion

3.1. Problem Description. W. G. Davids and J. D. Clapp [20] provide an example of calculation with EverStressFE. After moderate modification on the basis of literature [20], a new example is provided for the EverStressFE and BISAR. In this example, there are three layers of pavement structure layer. And from top to bottom, asphalt surface layer, granular base layer, and subgrade are regarded as linear elastic model. Table 1 shows the thickness and material parameters.

3.2. Modeling. BISAR and EverStressFE models adopt circular vertical load of single axle and dual-wheel group (single wheel load of 50 kN), while tire pressure P is 0.70 MPa, equivalent circle diameter of single wheel pressure transmitting surface d is 21.30 cm, and center-to-center wheel spacing is 31.95 cm. In the BISAR model, based on the key calculation points in wheel gap center and single-circle load center and using the symmetry, it further increases the density of calculation points to 200 points with the interval of 0.125 d in plane, and 1/4 points are

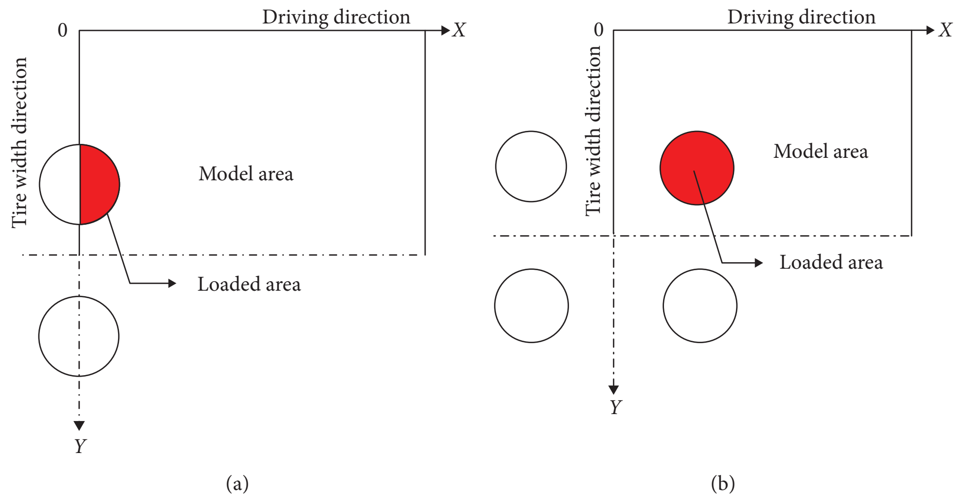

FIGURE 3: 1/4 symmetry of EverStressFE program model (circular load as an example): (a) single axle dual-wheel; (b) tandem axle dual-wheel.

TABLE 1: Pavement material parameters.

Material	Thickness (m)	Elastic modulus (MPa)	Poisson's ratio
Asphalt surface layer	0.1	3000	0.4
Granular base layer	0.3	300	0.35
Subgrade	1	100	0.35

taken to calculate to simplify the calculation steps. It is shown in Figures 4(a)–4(c), where $Ai\ Bi\cdots Ti$ represent the calculated points of each structural layer. The standard shear spring compliance AK is selected to simulate the interlayer bonding conditions. For the interface between base-surface layers, fully bonding and fully slipping AK are 0 and 4.92×10^{-9}, respectively. According to the symmetry of the structure and wheel load form as well as the characteristics of the EverStressFE program, it selects 1/4 model, in which geometric dimension is 1 m × 1 m × 1.4 m (driving direction × pavement cross section direction × depth direction). The right and bottom sides of the model are infinite boundaries, and the back side of the model is unconstrained free boundary, while the left and front sides of the model are symmetrical faces. The whole model is divided into 10010 elements and 45616 nodes. In order to improve the calculation accuracy, the mesh of local region (between 0 and 500 mm in X-axis and Y-axis direction) under wheel load is intensively divided into 15 elements along the X and Y directions, and the mesh far away from wheel load is sparse, with 9 elements along both the X and Y directions, as shown in Figure 5.

3.3. Result Analysis and Discussion. The results output of BISAR program is in the form of text, and its visual description uses a third-party software, while the results output of EverStressFE program can be directly shown in contour plot and 2D plot based on Dpolt Jr or in the form of text. In order to facilitate the visualization comparison between the two programs, third-party programs are used for the visualization processing of text results output. Under the traffic load, the mechanical responses of pavement structure, such as the pavement surface deflection value, the flexural-tensile strain, and the maximum vertical compression strain on the top of subgrade compared, are analyzed on the conditions of fully bonding and fully slipping of the interface between the base-surface layers.

The analysis of the above examples can draw a conclusion as follows: (1) It can be seen in Figure 6 that, under the condition of two kinds of interlayer bonding, the spatial distributions of the pavement surface deflection value calculated by the two programs are similar and symmetrical from macro perspectives. At the place of dual-wheel load, all of them are basin-shaped and downward denting with partial overlaps at the denting position, and the vertex is located at the load center of the two equivalent circles. In order to further observe the pavement surface deflection value under different interlayer bonding conditions from the specific value, the value ($x=0$) is selected in the cross section of the pavement for specific analysis, as shown in Figure 7. It can be seen that the pavement surface deflection values obtained by the two programs under the two interlayer bonding conditions are distributed in the form of "W", and the centers of the two wheel gaps are symmetrical. The maximum value occurs at $x=0.1$ m under any interlayer bonding condition, and the maximum pavement surface deflection values calculated by the BISAR and EverStressFE are 0.4805 mm and 0.44485 mm in the condition of fully bonding between the base-surface layers. And the values are 0.5445 mm and 0.54863 mm in the

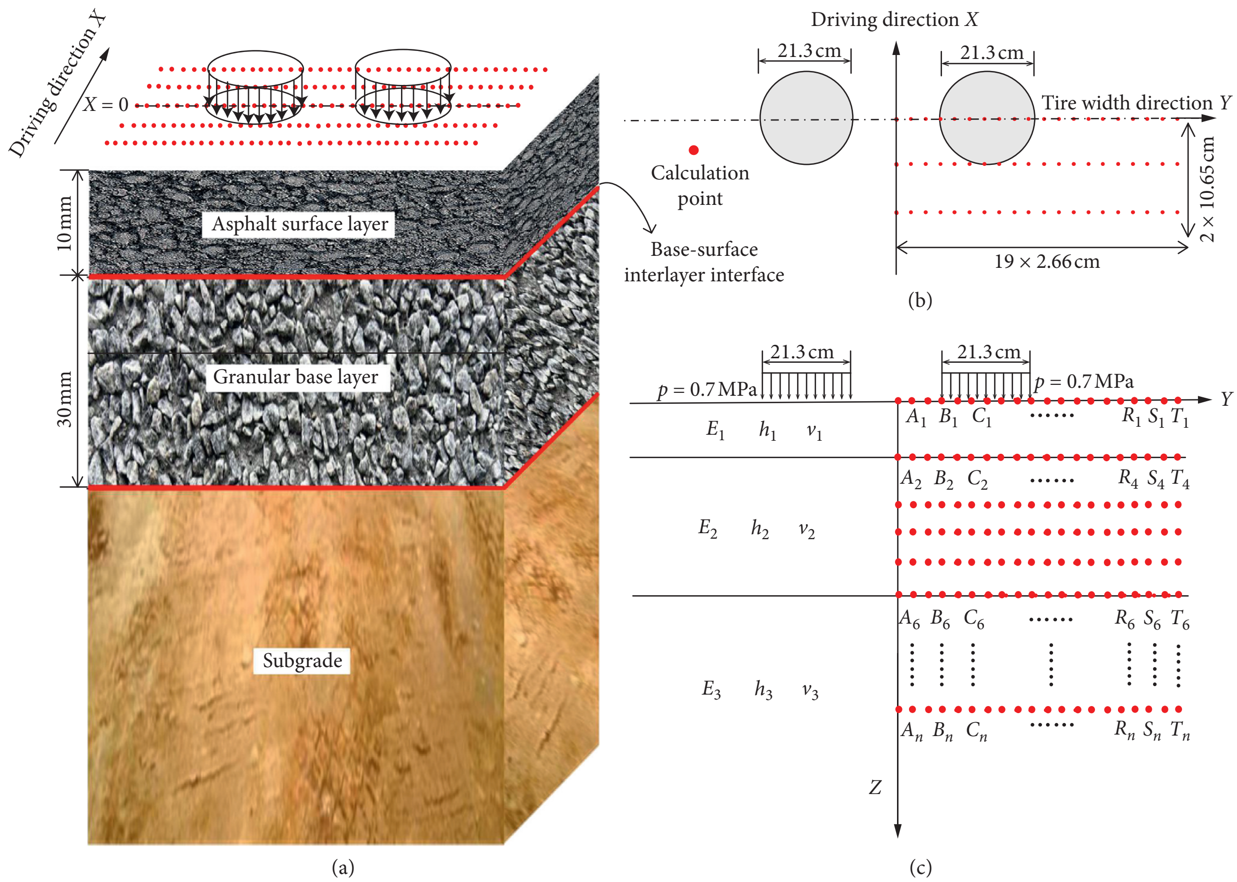

Figure 4: Pavement structure of BISAR (not to scale). (a) Pavement structure. (b) Plane calculation point. (c) Profile calculation point.

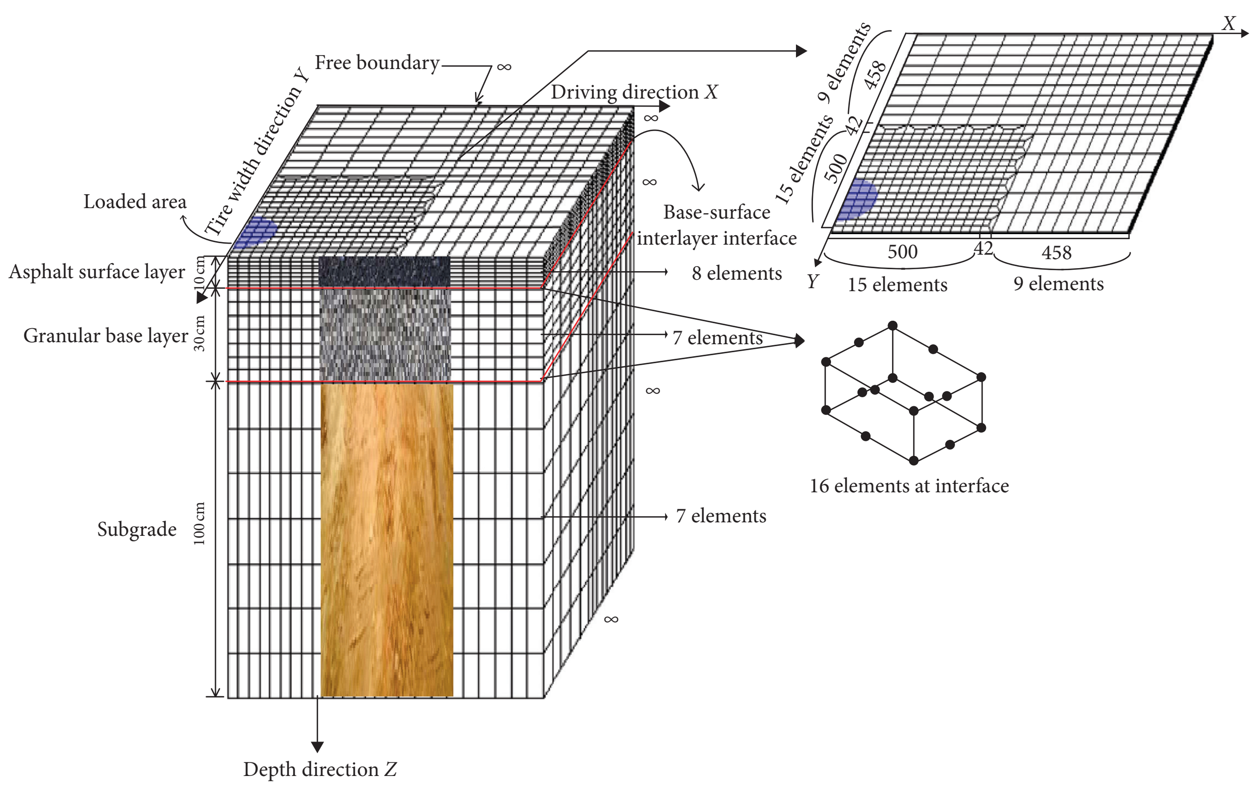

Figure 5: Pavement structure and finite element meshing of EverStressFE.

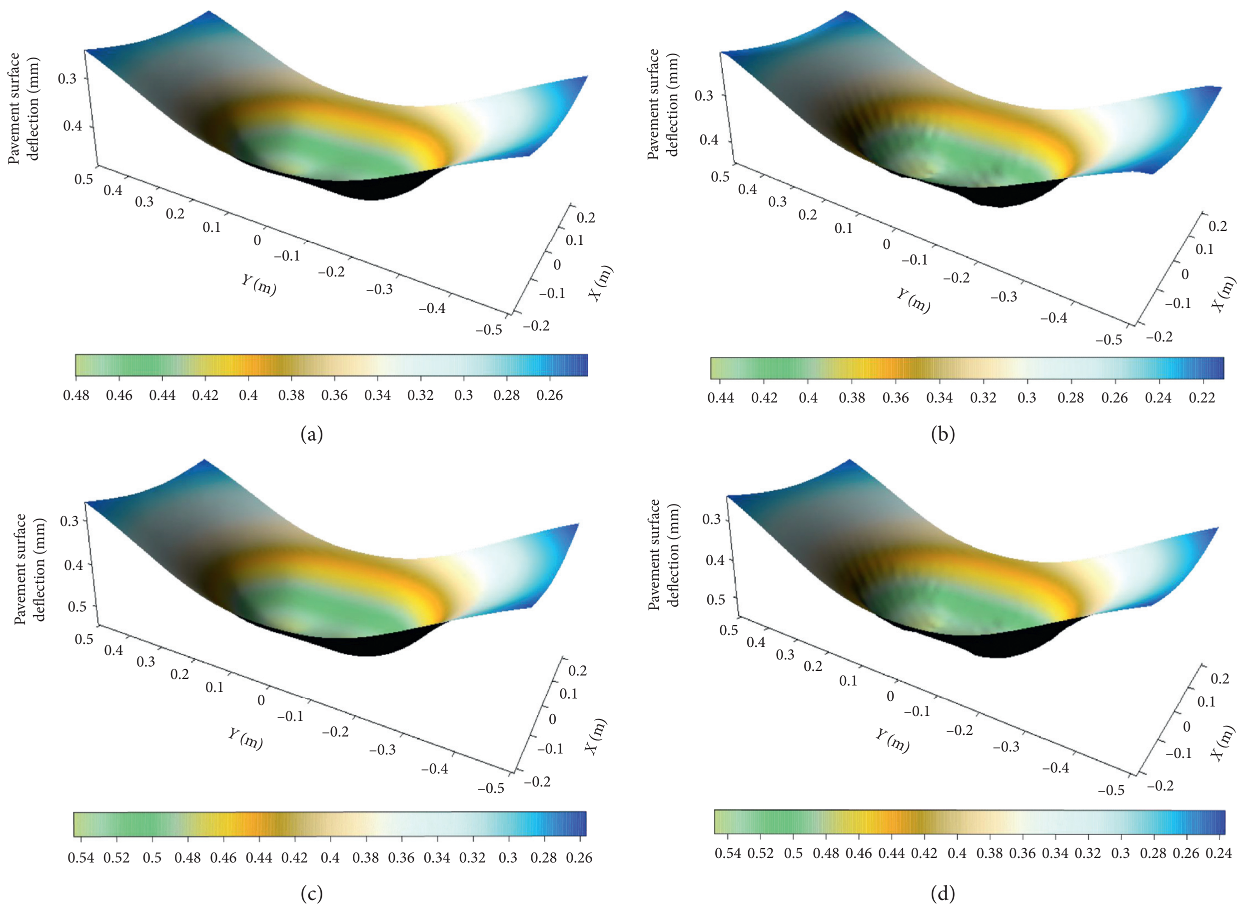

Figure 6: Spatial distribution of pavement surface deflections of the two programs (unit: mm): (a) BISAR (fully bonding of the interface between the base-surface layers); (b) EverStressFE (fully bonding of the interface between the base-surface layers); (c) BISAR (fully slipping of the interface between the base-surface layers); (d) EverStressFE (fully slipping of the interface between the base-surface layers).

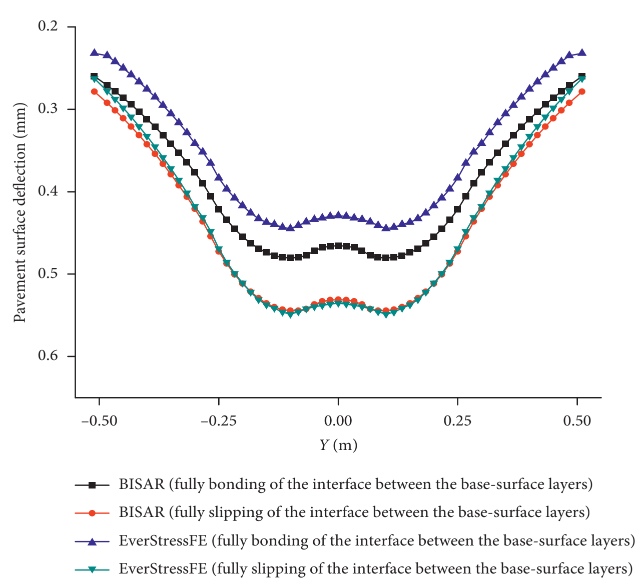

Figure 7: Distribution of pavement surface deflections of the two programs at $X = 0$ (unit: mm).

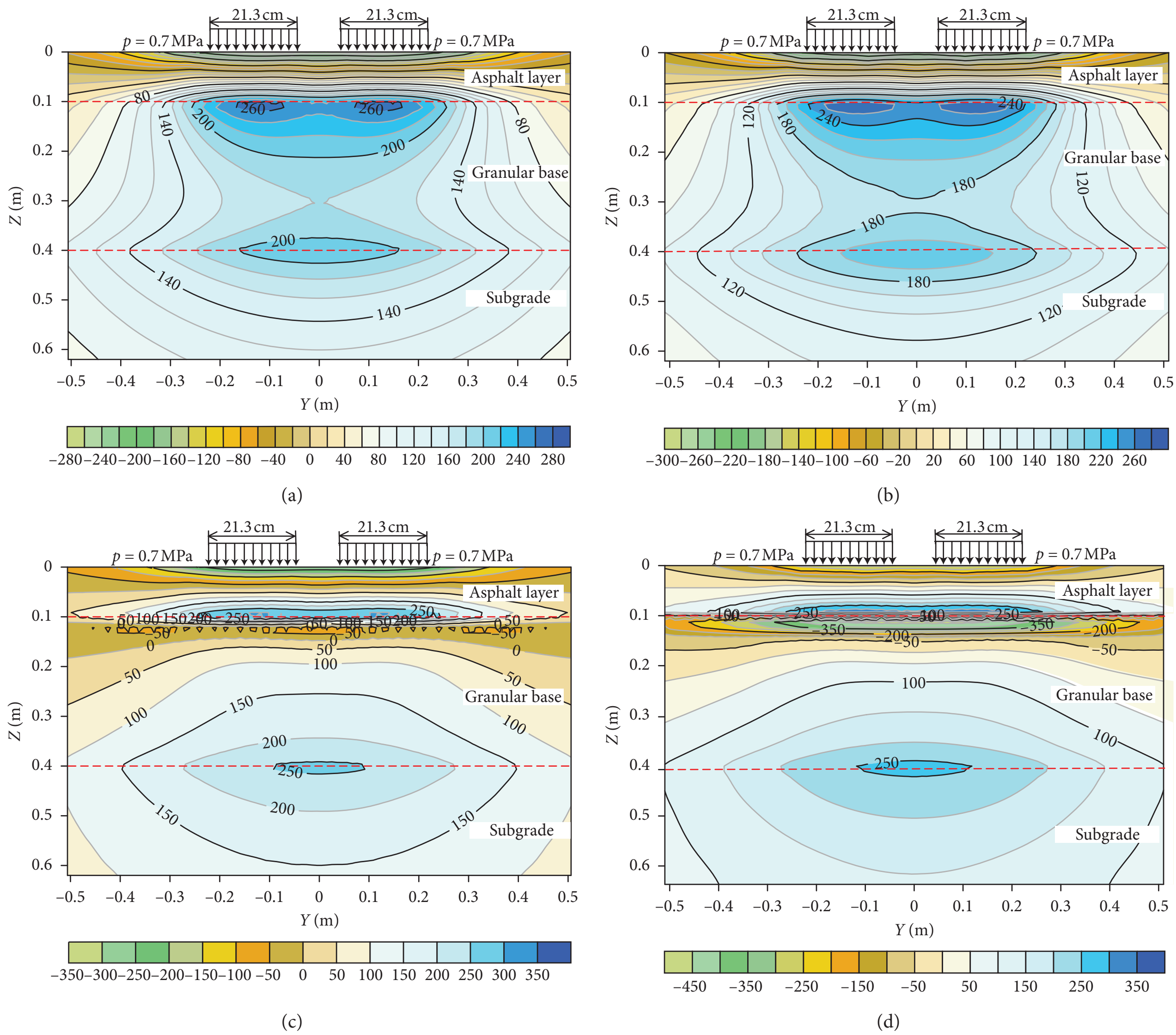

FIGURE 8: Contour map of cross section of flexural-tensile strain of pavement structure along driving direction ($x = 0$) (unit: 10^{-6}): (a) BISAR (fully bonding of the interface between the base-surface layers); (b) EverStressFE (fully bonding of the interface between the base-surface layers); (c) BISAR (fully slipping of the interface between the base-surface layers); (d) EverStressFE (fully slipping of the interface between the base-surface layers).

condition of fully slipping between the base-surface layers, respectively. The results show that the degree of coincidence is perfect. (2) In Figure 8, the spatial distributions of the flexural-tensile strain are similar and the distribution is relatively consistent under the two interlayer bonding conditions. There are extreme values in the base-surface interlayer interface and the base-subgrade interlayer interface. In the condition of fully bonding between the base-surface layers, however, there are slight differences due to the different modeling methods of the two programs' interlayer interfaces. (3) According to the results of Figure 9, at the condition of fully bonding, the maximum vertical compression strain on the top of subgrade calculated by EverStressFE is 217.7×10^{-6}, while it is 214.47×10^{-6} which is calculated by BISAR. The maximum vertical compressive strain on the top of subgrade calculated by EverStressFE is 260.9×10^{-6}, while it is 262.91×10^{-6} which is calculated by BISAR, both with the condition of fully slipping of the interface between the base-surface layers. The results show that the degree of coincidence is satisfactory.

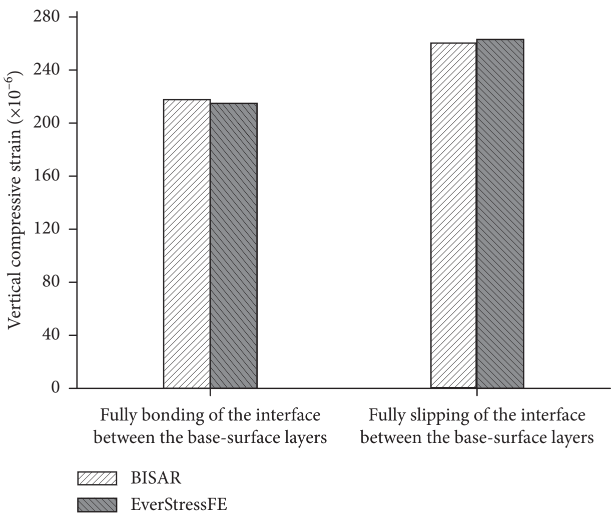

FIGURE 9: Maximum vertical compressive strain at the top of the subgrade (unit: 10^{-6}).

4. Conclusions and Suggestions

Based on different theoretical basis, BISAR and EverStressFE programs have their own characteristics in the principle of interlayer bonding, modeling, solution process, and result postprocessing, and a specific example is conducted to analyze and compare their functions. The conclusion is as follows:

(1) EverStressFE is mainly applied for the mechanical behavior analysis of flexible pavement under various wheel axle combinations and nonuniform load distributions. In the program, the interlayer bonding condition can be modeled as fully slipping and partially bonding by setting the interface stiffness IS, and the results output can be visualized by 2D plot and contour plot. The program adopts 20-node discrete elements, and the left and front sides of the model are all symmetrical surfaces. However, some parameters could be freely set by the user, including the specific 3D geometric dimensions of the model, the boundary conditions of the right, back, and bottom sides, and the density of the element meshing. It is advisable to enlarge the geometry of the model, reasonably setting the boundary conditions and meshing for higher computational accuracy.

(2) With the release of BISAR3.0, all functions of the initial program can be implemented under the Windows environment. The program is less influenced by users' subjectivity, and its calculation results are mainly limited by itself. The program not only can consider the multilayer pavement structure, but also can calculate the stresses, strains, deflection, and shear stresses between layers. The program can set specific values for standard spring compliance AK or reduced spring compliance ALK to describe the really interlayer bonding condition of pavement structure, including fully bonding, fully slipping, and partially bonding. If the results output can be visualized, it will be a more excellent professional mechanical analysis of asphalt pavement.

(3) The two programs can completely simulate the problem of asphalt pavement interlayer bonding after simplifying and abstracting the actual problems. The mechanical response of specific examples indicates that the overall distribution trends are the same and the specific values are similar. In carrying out mechanical analysis, there is no doubt that the two professional typical programs are both excellent and available calculation tools.

Data Availability

The data used to support the findings of this study are included within the article. All the data were obtained by BISAR3.0 and EverStressFE based on the parameters in this paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] Y. H. Huang, *Pavement Analysis and Design*, Pearson Prentice Hall, Upper Saddle River, NJ, USA, 2nd edition, 2004.

[2] X. Hu and L. F. Walubita, "Effects of layer interfacial bonding conditions on the mechanistic responses in asphalt pavements," *Journal of Transportation Engineering*, vol. 137, no. 1, pp. 28–36, 2011.

[3] A. Das, *Analysis of Pavement Structures*, CRC Press, Boca Raton, FL, USA, 2015.

[4] P. Lepert, J. P. Poilane, and M. Bats-Villard, "Evaluation of various field measurement techniques for the assessment of pavement interface condition," in *Proceedings of the 7th International Conference on Asphalt Pavements*, pp. 224–237, Nottingham, UK, August 1992.

[5] M. R. Kruntcheva, A. C. Collop, and N. H. Thom, "Effect of bond condition on flexible pavement performance," *Journal of Transportation Engineering*, vol. 131, no. 11, pp. 880–888, 2005.

[6] J. Uzan, M. Livneh, and Y. Eshed, "Investigation of adhesion properties between asphaltic-concrete layers," *Journal of the Transportation Research Board*, vol. 47, pp. 495–521, 1978.

[7] M. Crispino, B. Festa, P. Giannattasio et al., "Evaluation of the interaction between the asphalt concrete layers by a new dynamic test," in *Proceedings of the 8th International Conference on Asphalt Pavements*, pp. 741–754, Seattle, Washington, USA, August 1997.

[8] E. P. Donovan, I. L. Al-Qadi, and A. Loulizi, "Optimization of tack coat application rate for geocomposite membrane on bridge decks," *Transportation Research Record: Journal of the*

Transportation Research Board, vol. 1740, no. 1, pp. 143–150, 2000.

[9] F. Canestrari, G. Ferrotti, M. Partl et al., "Advanced testing and characterization of interlayer shear resistance," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1929, no. 1, pp. 69–78, 2005.

[10] A. C. Raposeiras, D. Castro-Fresno, A. Vega-Zamanillo, and J. Rodriguez-Hernandez, "Test methods and influential factors for analysis of bonding between bituminous pavement layers," *Construction and Building Materials*, vol. 43, pp. 372–381, 2013.

[11] S. A. Romanoschi and J. B. Metcalf, "Characterization of asphalt concrete layer interfaces," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1778, no. 1, pp. 132–139, 2001.

[12] M. R. Kruntcheva, A. C. Collop, and N. H. Thom, "Properties of asphalt concrete layer interfaces," *Journal of Materials in Civil Engineering*, vol. 18, no. 3, pp. 467–471, 2006.

[13] A. C. Collop, M. H. Sutanto, G. D. Airey, and R. C. Elliott, "Shear bond strength between asphalt layers for laboratory prepared samples and field cores," *Construction and Building Materials*, vol. 23, no. 6, pp. 2251–2258, 2009.

[14] P. Jaskula and D. Rys, "Effect of interlayer bonding quality of asphalt layers on pavement performance," *IOP Conference Series: Materials Science and Engineering*, vol. 236, 2017.

[15] R. V. Siddharthan, N. Krishnamenon, and P. E. Sebaaly, "Finite-layer approach to pavement response evaluation," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1709, no. 1, pp. 43–49, 2000.

[16] Y. H. Huang, *Pavement Analysis and Design*, Pearson Prentice Hall, Upper Saddle River, NJ, USA, 1993.

[17] Bitumen Business Group, *BISAR 3.0 User Manual*, Bitumen Business Group, Moscow, Russia, 1998.

[18] L. J. Wardle, *Program CIRCLY Theory and Background Manual*, Mincad Systems, Richmond, Australia, 2004.

[19] Washington State Department of Transportation, *EVERSERIES User's Guide Pavement Analysis Computer Software and Case Studies*, Washington State Department of Transportation, Olympia, WA, USA, 2005.

[20] W. G. Davids and J. D. Clapp, *EverStressFE 1.0 Software for 3D Finite Element Analysis of Flexible Pavement Structures: Summary of Features and Capabilities", Advanced Structures and Composites Center AEWC*, University of Maine, Orono, ME, USA, 2009.

[21] R. S. Harichandran, M. S. Yeh, and G. Y. Baladi, "MICH-PAVE: a nonlinear finite element program for the analysis of flexible pavements," *Journal of the Transportation Research Board*, vol. 1286, pp. 123–131, 1990.

[22] R. Nitharsan, "Development of windows-based version of the 3d-move analysis software for pavement response analysis," Dissertations thesis, University of Nevada, Reno, NV, USA, 2011.

[23] R. E. Goodman, R. L. Taylor, and T. L. Brekke, "A model for the mechanics of jointed rock," *Journal of Soil Mechanics and Foundations Division*, vol. 94, pp. 637–659, 1968.

[24] A. S. Kuo, "A two-dimensional shear spring element," *AIAA Journal*, vol. 22, no. 10, pp. 1460–1464, 1984.

[25] Z. Dai, "Mechanics analysis of asphalt pavement structure," Dissertations thesis, Transportation College Southeast University, Nanjing, China, 2004.

[26] S. B. Ma, K. Wang, Y. F. Wu, L. Y. Wei, and M. W. Zhang, "Reliability analysis of asphalt pavement structure based on Three-Dimensional Finite Element," *Advanced Materials Research*, vol. 255-260, pp. 3421–3425, 2011.

[27] H. Ziari and M. M. Khabiri, "Interface condition influence on prediction of flexible pavement life," *Journal of Civil Engineering and Management*, vol. 13, no. 1, pp. 71–76, 2007.

[28] J. W. Tedesco, J. C. Powell, C. A. Ross et al., "A strain-rate-dependent concrete material model for ADINA," *Computers and Structures*, vol. 64, no. 5-6, pp. 1053–1067, 1997.

[29] K. Wang, "Analysis and calculation of stresses and displacements in layered elastic systems," *Acta Mechanica Sinica*, vol. 3, no. 3, pp. 251–260, 1987.

[30] Y.-H. Cho, B. F. McCullough, and J. Weissmann, "Considerations on finite-element method application in pavement structural analysis," *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1539, no. 1, pp. 96–101, 1996.

[31] X. Jiang, C. Zeng, X. Gao et al., "Three-dimensional FEM analysis of flexible base asphalt pavement structure under non-uniform tyre contact pressure," *International Journal of Pavement Engineering*, vol. 20, pp. 1–13, 2019.