

Chapter 1

Introduction

1.1 Perspective and Background

A high-speed road network is a crucial infrastructure requirement for rapid economic growth and social integration in a country. Road transportation has earned an increasingly higher share of passenger and freight movement than other modes of transportation as it provides easy accessibility, operational flexibility, door-to-door service, and reliability [1]. The other important modes of transportation, like railways, airports, and ports, are connected by road networks, increasing their economic importance [2]. India has the second largest road network in the world, spanning around 6.3 million km. Over 64.5% of all goods in the country are transported through roads, while 90% of the passenger use roads to commute [3].

1.1.1 Role of transportation in nation's economy

The transport sector contributes to an extent of 4% of India's gross domestic product (GDP) [4]. The inconsistencies and hindrances in the smooth functioning of transportation can reduce the GDP by 1 to 2%, equivalent to 16-32 billion US\$ [5]. As an estimation, 64.5% of all goods and 90% of total passenger traffic utilize road networks for transportation [6]. This shows that the mobility of humans, as well as goods, is majorly dependent on the road network in the country. Hence, proper pavement functioning is essential for the country's overall growth.

1.1.2 Development of highway infrastructure

The demand for superior-performing roads has been increasingly diversified due to the rapid growth of traffic volume and highway mileage. Understanding the immense need for road infrastructure, the government has accelerated the construction of various categories (asphalt and cement) in the past few years. Special attention has been given to the construction of national highways (NH), and nearly 80,000 km of NH have been constructed in the past eight years, as shown in Figure 1.1.

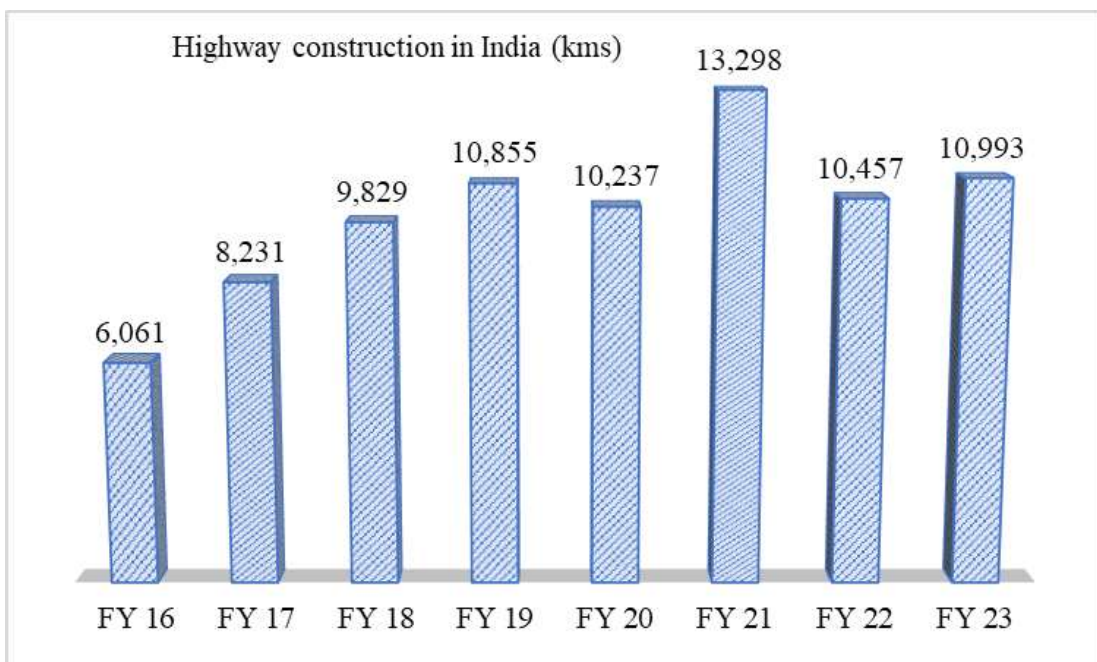


Figure 1.1. Highway construction in India during FY 16 to FY 23 [3].

Note: FY 16 means financial year 2015-16, and so on.

1.1.3 Asphalt concrete pavement

The most common pavement structure in India being constructed on a large scale is asphalt concrete (AC) pavement due to its lower initial cost and ease of maintenance [7]. It is a layered structure with an AC layer above good-quality granular materials known as the base and sub-base layer. The granular layers transfer the load to the existing ground, known as subgrade. The load in AC pavement is transferred using a grain-to-grain contact

mechanism [8]. Figure 1.2 shows a typical cross-section of AC pavement. In India, the AC layer, generally used as a combination of two sublayers (surface course and binder course), is laid over a granular base/sub-base layer. Generally, the AC layer is designed with no interconnected voids (air voids 4-8%) and thus mostly relies on surface runoff for drainage. The base and sub-base layer is either compacted aggregates, called 'granular', or utilizes binding agents like cement or bitumen emulsion, known as 'stabilized'.

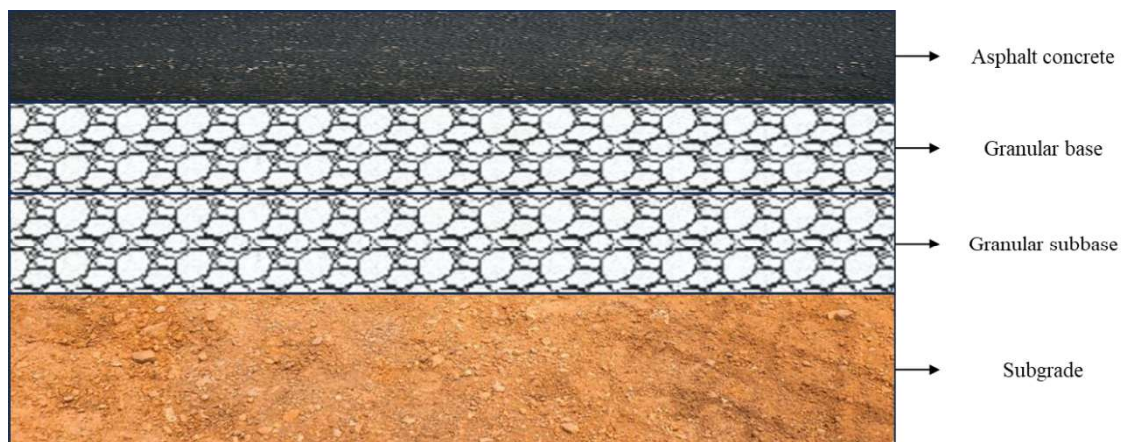


Figure 1.2. Typical cross-section of asphalt concrete pavement.

The layered nature of the pavement makes it complex to analyse the structure as a whole. Other than the layered structure of the asphalt pavement, several parameters associated with loading conditions and material properties complicate pavement analyses.

Over the years, the magnitude and variety of loading conditions on asphalt pavement have increased manyfold. The cumulative effect of stresses/strain on the pavement, especially from heavy trucks, results in early deterioration in pavement, such as plastic deformation in AC pavement. This is considered one of the main factors that results in premature stress-related failures before the pavement's design life. Asphalt pavement design is mainly based on two input parameters: - loading conditions and material properties. So, it is crucial to estimate the design standard axle load correctly and implement traffic policies related to overloading to limit premature stress-related failures. Another key

input parameter in pavement design is the material properties of different layers. Underestimating or overestimating material strength may lead to uneconomic pavement design or premature pavement failure. So, understanding material response to traffic load is crucial for estimating pavement performance and expected life. AC pavement layers are often considered linear elastic in pavement analysis and design. The elastic modulus and Poisson's ratio describe the elastic properties of materials in various layers.

1.2 Material properties of asphalt concrete

Asphalt pavement is a complex structure composed of various materials with different properties. In past studies, researchers have proposed several models to evaluate pavement response based on layered theory [9]. These models do not consider the heterogeneity of asphalt mixes. These are mostly based on linear elastic theory. The linear elastic theory assumes material is homogeneous, isotropic, and linear elastic.

1.2.1 Behaviour of asphalt concrete mix

The materials used in various layers determine the layered system's final performance. Therefore, understanding the material behaviour subjected to repeated traffic loading is important for pavement engineers. Researchers have tried different approaches to characterize these materials for evaluating pavement response to traffic loading.

In such cases, different material characterization tests will be required. One of the important aspects that need to be incorporated is the time and temperature dependency of the pavement materials. Meanwhile, Dynamic shear rheometer (DSR) tests are often used to characterize binding materials' time/temperature dependency. However, no such tests are carried out for AC mixture, or they are scarcely used. Traditionally, AC materials in mechanistic analyses for asphalt pavements have been treated as purely elastic solids, though they behave like viscoelastic materials. The application of the theory of linear

viscoelasticity to the design and analysis of asphalt pavements has not been dominant to date, though it is conceptually old in origin. Unlike elastic solids, the behaviour of AC materials is strongly contingent on temperature and loading frequency. They behave more like elastic solids at low temperatures and higher frequency loading, whereas their behaviour is more like that of a viscous fluid at high temperatures and low loading frequency. At medium temperatures and loading frequencies, they behave like viscoelastic materials that normally exhibit a significant level of elastic solid stiffness while dissipating energy through frictional resistance, such as viscous fluids. Characterizing the temperature dependency of the asphalt mix is important for countries like India, where huge temperature variation across the region and in different seasons is observed. It is well recognized that AC material typically exhibits viscoelastic/visco-elasto-plastic behaviour depending on applied loading (including temperature) conditions. This study evaluated, both elastic and linear viscoelastic behaviour of asphalt mixes using resilient modulus and creep compliance tests, respectively.

The creep compliance test was used to characterize the viscoelastic behaviour of asphalt mixes using stress relaxation modulus. Stress relaxation modulus was further used to generate Prony series coefficients, which are used as input parameters in finite element modelling of pavement systems. Creep compliance data are time and temperature dependent. The asphalt mixes deform differently depending on loading time and temperature; thus, creep compliance also varies.

1.2.2 Behaviour of unbound granular materials

In India, building a flexible pavement system consisting of asphalt concrete lying on unbound granular materials (UGM) is a common practice. Failure of the granular materials used in pavement construction is formally known to cause unacceptable surface

deflection (rutting). The failure of granular materials is mainly governed by their shear strength and the state of stress. Therefore, geotechnical constitutive models representing this behaviour widely model granular layers (base, sub-base, and subgrade) in flexible pavement structures. It is also accepted that the characteristics of granular materials are subject to change as a function of loading cycles. The resilient modulus theory can illustrate this concept. Repeated cyclic triaxial tests investigate the progressive accumulation of plastic strain and permanent deformation in material test samples. It is generally accepted (even before failure) that the behaviour of granular material is not linear elastic. Laboratory experiments indicate that this type of material displays nonlinear stress-dependent behaviour [10].

Pavement researchers indicate that there is a need for an advanced constitutive model to be implemented in a comprehensive finite element (FE) analysis [11]. This inclusive FE analysis can consider static and dynamic loading, assuming complex nonlinear elastoplastic behaviour for granular layers. An adequate method of analysis to predict the structural response of the pavement, considering the complex material properties of individual layers, is necessary under actual loading conditions.

1.3 Mechanistic Empirical approach of asphalt pavement design

Direct/indirect empirical approaches in the current pavement design procedures may result in premature pavement failure or over-designed pavements [12]. However, these empirical approaches are still practiced in many developing countries worldwide. In modern days, many developing countries such as India are identifying an urgent need to shift their design practices from empirical to semi-mechanistic/mechanistic pavement design suited to their local requirements. Starting with a purely empirical method in which pavement design is based on observed field performance, researchers gradually employed

their analytical skills to expand the applicability of design procedures to a wide range of conditions, which led to the development of Mechanistic-Empirical (ME) design procedures. In the mechanistic part of the ME design approach, principles of continuum mechanics such as elasticity, plasticity, and viscoelasticity are applied to form a governing equation of the modelled medium which is usually the mechanical equilibrium of the system. Once this equation is obtained, different techniques, such as the finite element (FE) procedure, are applied to solve it. It is necessary to assume a constitutive model to predict the material behaviour to solve the equation. This constitutive model, then, has a significant role in the final solution of the system. This is why, in recent decades, researchers have been interested in introducing new constitutive models capable of more accurately predicting material behaviour. These constitutive models include linear and nonlinear elastic, elastoplastic (such as the Tresca or von Mises yield criterion), frictional elastoplastic (such as the Drucker-Prager or Mohr-Coulomb yield criterion), and hardening/softening elastoplastic behaviour [13–15].

In the next step, a load is usually broken down into increments, and the whole system is solved for each of these loading increments under the assumption of a selected constitutive model for the materials. The critical solutions in terms of maximum surface deformations, stresses below loading, tensile strain at the bottom of the asphalt layer, and vertical compressive strain at the top of the subgrade layer are obtained from the mechanistic analysis [16]. An appropriate prediction of these critical responses heavily depends upon the quality and capability of the assumed constitutive models for considering the realistic material properties. It was evident that each material used in construction, necessitates a different constitutive model.

In the last step, the stress, strain, and deformation solution are transferred to the empirical/ME formula to calculate pavement damage, such as rutting or fatigue life of

asphalt pavement. A common trend is to use the values for critical responses to calculate pavement damage at selected locations. These distresses are compared with design life expectancy against rutting and fatigue failure of the pavement. The complete procedure of the ME design approach is detailed in the flowchart, as shown in Figure 1.3.

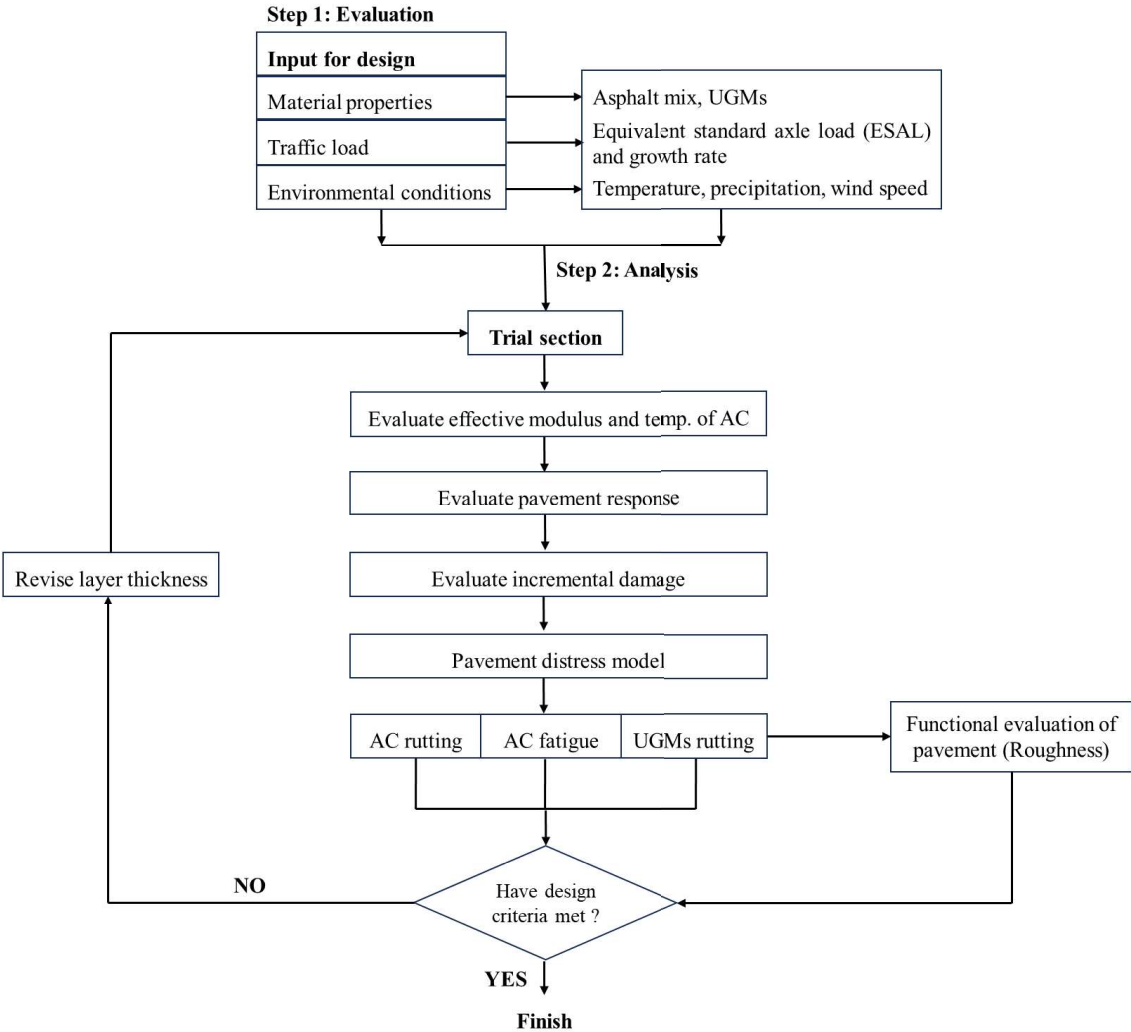


Figure 1.3. Flowchart of Mechanistic-Empirical pavement design approach.

The accuracy of pavement response prediction mainly depends on design input parameters: material properties, traffic load, and assessment of environmental conditions. After estimating input parameters, the analysis method explained in the next section is selected based on experience and experimental/field data.

1.4 Structural analysis of layered system

Earlier, Boussinesq [17] solved the general elasticity equation for a semi-infinite elastic soil mass in which the whole mass was assumed to be homogeneous, isotropic, and linear elastic. Later, Burmister [18] developed solutions for two- and three-layered pavement systems based on different elastic modulus and Poisson's ratio for each layer. However, these solutions consider a uniform pressure applied at the surface over a circular contact area. Though these assumptions simplify the problem significantly, they don't simulate the real field conditions accurately. Contact stress distribution at the tire-pavement interface is nonuniform.

In addition to these simplified assumptions, the behaviour of materials in various pavement layers is considered linear elastic, which is not an ideal simulation. As reported in previous literature, it is well-known that AC material is viscoelastic, whereas material properties of unbound granular layers are stress-dependent. A single modulus value assigned to an unbound granular layer may not represent its stiffness characteristics correctly. Researchers proposed different material models to include viscoelastic and stress-dependent properties to accurately consider the material response of various layers.

The advent of modern high-speed computers facilitated the successful use of numerical methods, which can handle these material models for pavement analysis. These include finite difference and finite element methods. Both methods subdivide the tire-pavement structure into a finite number of elements of specific size using meshing. The finite difference method is based on making approximations to governing differential equations at each mesh point. In contrast, the finite element method assumes a displacement or stress pattern within each element defined by several mesh points. Each method solves many simultaneous equations to obtain the most accurate result. In the present study, the finite element method has been used to evaluate the structural response of the asphalt

pavement under different conditions, considering the viscoelastic properties of asphalt mixes and the stress-dependent behavior of unbound granular layers. Using the finite element method, these analyses modelled an actual, deformable solid tire to simulate non-uniform contact stress distribution at the tire-pavement interface. A four-layer pavement (asphalt concrete, base, subbase, and subgrade layer) was modelled in ABAQUS (finite element-based tool).

1.5 Problem statement

The finite element tools like ABAQUS are equipped with built-in nonlinear constitutive models to account for the nonlinear elastic behaviour of unbound granular layers as well as the viscoelastic behaviour of the AC layer. Since available nonlinear constitutive models in ABAQUS are based on strain rates, hypo-elastic models were developed to convert stress-dependent material response to strain-dependent behaviour.

The significance of this research is to incorporate complex material behaviour (viscoelastic AC and stress-dependent UGMs) of asphalt pavement in a three-dimensional FE model of a tire-pavement system. The FE model has been further used to evaluate the structural response of the pavement and its life under varying conditions of overloading and high temperature exposure. The results are expected to improve current pavement design procedures and result in more accurate and reliable design.

1.6 Research objectives

From the above literature studies, it can be concluded that asphalt concrete is a viscoelastic mixture, and materials in unbound granular layers can be characterized as nonlinear stress dependent. To accurately represent the material behaviour of these layers, representative tests on materials shall be conducted in the laboratory/field, and suitable material models shall be used to represent its behaviour. It was also noted that the

pavement design specifications in India are currently based on linear elastic material properties of various layers of the AC pavement. So, material characterization will help reach a more reliable pavement analysis and, hence, design at later stage. Also, the need to simulate actual tire load during pavement analysis was observed to consider non-uniform contact stress distribution at the tire-pavement interface. The need for the study was derived from an extensive literature review, as discussed in Chapter 2 of this thesis.

Based on these needs, the following objectives were defined for the present study:

- 1) Viscoelastic material characterization of dense graded asphalt mix using creep compliance test.
- 2) Nonlinear stress dependent material characterization of unbound granular layers using repeated load triaxial compression test.
- 3) The tire-pavement system's three-dimensional finite element model will be developed to consider the complex material properties and nonuniform loading conditions.
- 4) Parametric analysis and evaluation of the structural response of the asphalt pavement using finite element method to consider the effect of overloading, high-temperature exposure, and base layer stabilization.

In the first objective, a creep compliance test was conducted to understand the time and temperature dependency of the asphalt mixture. Based on the Marshall mix design, bituminous concrete (BC-2) samples were prepared and compacted at optimum binder content (OBC). A creep compliance test as per AASHTO T-322 on these samples was conducted to study the asphalt mixture's viscoelastic behaviour. This study used a generalized Kelvin model to represent the behaviour of asphalt mixture, which is mechanically approximated by five terms Prony series.

The laboratory evaluated the stress-dependent material behaviour of unbound granular layers (base, subbase, and compacted subgrade) using repeated load triaxial compression testing to achieve the second objective. Stress-dependent resilient modulus has been fitted using $k-\Theta$, Uzan, NCHRP, and Bilinear constitutive models. Hypo-elastic material models were further developed to convert stress invariant models to strain invariant as the FE-based model uses strain invariant parameters.

The third objective is to develop a three-dimensional FE model of a multi-layered (AC, base, subbase, and compacted subgrade) asphalt pavement structure. A three-dimensional FE model of a solid tire composed of hyperelastic rubber material was developed to simulate vehicular loading and non-uniform contact stress distribution at tire pavement-interface. Finally, tire-pavement interaction was modelled to study pavement response subjected to different loading, material properties, and environmental conditions.

The fourth objective considers the effect of loading, material properties, layer thickness, temperature, and base layer stabilization on the structural response of AC pavement. A sensitivity analysis of these parameters on pavement performance in subgrade rutting and AC fatigue life was also done.

1.7 Thesis outline

The thesis consists of seven chapters. Chapter 1 briefly discusses the material characterization of asphalt concrete mix and unbound granular materials after the general introduction to asphalt concrete pavement. The later section discusses the mechanistic approach to asphalt pavement design and layered pavement system structural analysis. The last section of this chapter discusses an overview of this study's research significance and objectives.

In Chapter 2, an overview of the available literature on the viscoelastic material characterization of the AC layer has been discussed initially. This section discusses various experimental methods to capture asphalt mixes' time and temperature dependency. The significance and suitability of different models (Generalized Maxwell and Generalized Kelvin model) to fit these experimental data are further explained. Later, the stress dependency of unbound granular materials is discussed. The experimental method (resilient modulus test) to capture the stress dependency of these materials is further explained. The last part of this section presents various material models used to characterize these materials. Further, FE-based asphalt pavement and tire modelling techniques have been highlighted to study the complex material behaviour and nonuniform loading. The last section of this chapter introduces parametric analyses of the asphalt pavement under varying conditions of overloading, material properties, and environmental exposure.

Chapter 3 presents the research methodology for various experimental tests to characterize asphalt mixes and unbound granular materials. It further discusses the development of a finite element model of solid tires, which can simulate the nonuniform contact stress distribution at the tire-pavement interface. Later sections present finite element modeling of AC pavement and tire-pavement interaction. The material properties of various pavement layers as obtained in Chapters 4 and 5, were utilized in the FE model as an input. Next, the validation of the developed FE model is described.

Chapter 4 deals with the viscoelastic material characterization of AC mixture. It discusses the creep compliance test on AC mixes to evaluate the time and temperature dependency of the material. The conversion of creep compliance data to stress relaxation data and the utilization of the generalized Kelvin model to evaluate Prony series coefficients are presented. These coefficients are used as input parameters in the FE model.

Chapter 5 presents nonlinear stress-dependent material characterization of unbound granular layers. Resilient modulus using repeated load triaxial compression testing has been conducted on aggregate and soil materials to evaluate stress-dependent modulus values. The later section discusses Hypo-elastic material models to represent strain invariant parameters for further use in the FE model.

Chapter 6 deals with the structural response of asphalt pavement and its life subjected to varying overloading conditions, material properties (linear elastic, linear viscoelastic, and stress-dependent behavior), environmental exposure, base layer stabilization, and layer thicknesses. The stage I simulation considers linear elastic properties of the materials in various layers and uniform loading conditions considering different assumed footprints of the tires (circular, square, rectangular, and rectangle with semi-circular ends). The stage II simulation considers linear elastic properties of materials in various layers and nonuniform loading conditions using realistic tires. The stage III simulation considers linear viscoelastic properties of asphalt mix, linear elastic properties of UGMs, and nonuniform loading conditions using realistic tires. The stage IV simulation considers linear viscoelastic properties of asphalt mix, stress-dependent behavior of UGMs, and nonuniform loading conditions using realistic tires. It also discusses pavement performance in subgrade rutting and asphalt fatigue.

Chapter 7 summarizes the main conclusions drawn from this study and provides recommendations and directions for further research.