Chapter 7
Conclusions and future scope

7.1 Introduction

This research evaluated the structural response and service life (rutting and fatigue) of asphalt pavement subjected to differing loading and environmental conditions using FE-based analysis. The study utilized a three-dimensional FE model of a tire-pavement system, that considered LVE material properties of asphalt mixes and stress dependent response of UGMs. The FE model of a realistic solid tire was developed to simulate nonuniform contact stress distribution at the tire-pavement interface. Solid tires were utilized to simulate harsh environmental conditions and transportation of heavy loads. The tire was modelled as a rubber material because it is easy to model and determine properties in the laboratory.

The LVE properties of asphalt mixes were obtained using creep compliance tests at different temperatures and voids in total mix. Creep compliance data was converted to stress relaxation modulus, and Prony series constants were evaluated using GKM. The stress relaxation behaviour of UGMs was modelled using hypo-elastic material obtained from repeated load triaxial compression test data. The FE model of the solid tire was based on the hyper-elastic modelling of rubber material. The analysis was conducted in four phases, each to meet a specific objective of the study. Salient conclusions devised from the research are stated in subsequent sections.

7.2 Conclusions

The primary conclusions of the study are outlined as follows:

7.2.1 Material characterization of asphalt mixes

Linear elastic characterization:

- BC mixes exhibited higher stiffness at low temperatures than SMA mixes. However, the same is not true at higher temperatures. The stiffness of SMA mixes was found to be higher than BC mixes at higher temperatures. These findings encourage using SMA mixes at higher temperatures, where relatively higher deformations are expected.
- At lower temperatures, an increase of 10° C from 25 to 35° C, reduces the average M_r of mixes by 36.26%. In comparison, at higher temperatures, a similar increase in temperature from 60° C to 70° C, reduces the average M_r value by 41.81%. As discussed in past studies, temperature also plays a crucial role in selecting a suitable binder for the preparation of mixes, as the viscosity of the binder is significantly affected, resulting in the reduction of material stiffness.

LVE characterization:

- The gradient of the deformation-time graph steepens with time at higher temperatures while flattens at lower temperatures. The loading time affects mix response severely. The maximum vertical deformation in BC-2 mix at 2 seconds of loading was higher by 15.97% compared to 1 second at 25° C. When this load duration reaches 100 seconds, the vertical deformation increases by 324.92%. This gives the relative idea of pavement damage under increased load duration.

- The Prony and Power Law series was used to model the LVE properties of BC-2 mixes. The Power Law model was not a good fit for creep compliance data, while the Prony series yields a better exponential fit for mix response.

7.2.2 Material characterization of UGMs

- The response of various soil types (RS-1, RS-2, FAS, CS, and BCS) to cyclic loading differed. The RS-1 and RS-2 exhibited stress hardening behavior (M_r increases with an increase in cyclic stress), while CS and BCS showed stress softening behavior (M_r decreases with increased cyclic stress). The FAS exhibits a dual nature of stress softening and hardening behavior.
- Regardless of the gradation used, the aggregate materials in GSB and base layers exhibited unidirectional stress hardening behavior to cyclic loading.
- The M_r data of GSB and base materials obtained from repeated load triaxial compression testing were fitted to k-ϴ, Uzan, and NCHRP models to explain the nonlinear stress dependent response of UGMs. The NCHRP model was found to fit the experimental M_r test data best. However, a significant difference in M_r values obtained experimentally and predicted from the k-ϴ model was observed.
- The stress dependent response of soil material was fitted using the Bilinear model. A good agreement with experimental data (average difference of 3-4%) was found in the case of fine-grained cohesive soil. However, the Bilinear model is not a good fit for the stress dependent response of other soils that are not purely cohesive (an average difference of 7-11% was obtained).

7.2.3 FE modelling of tire-pavement system

A 3-dimensional FE model of pavement structure composed of asphalt concrete as a top layer, granular base, and sub-base layer over the top of the subgrade layer was developed in ABAQUS [271] (FE based software). A solid tire, considering hyperelastic rubber material was modelled to simulate nonuniform contact stress distribution at the tire-pavement interface.

The FE model was validated using the solutions obtained from 3D Move analysis and Boussinesq close form solution under similar conditions. The two results were in close agreement with each other, and the proposed FE model could predict pavement response by considering the complex material properties of mixes and UGMs under realistic loading conditions.

7.2.4 Parametric analysis of asphalt concrete pavement under overloading and different environmental conditions

Stage I: Linear elastic material properties and uniform loading – effect of various shapes (circular, square, rectangular, and rectangle with semi-circular ends) of loading contact area on the structural response of asphalt pavement was analyzed to see if it makes any difference as compared to circular contact area currently being practiced in the pavement design. No significant effect of these contact shapes was found. However, a rectangle with a semi-circular end result in the lowest deformation and normal strain in the pavement, while a circular shape yields the highest among all these contact shapes considered. The average difference in vertical deformation and normal strain considering these two shapes obtained from FE analysis was only 4.07% and 3.30%, respectively. The rectangular and square shape yields almost similar results.

The results were further compared with stage II simulation, where realistic tire model has been used to see the effect of nonuniform contact stress distribution. It was found that, maximum surface deformation considering circular loading area was 7.34% lower, compared to real tire model. It may due to, circular loading considers uniform distribution of the applied stress, while stresses in case of real tire is maximum at the centre, gradually decreasing to the edges.

Stage II: Linear elastic material properties and nonuniform loading considering realistic tire

- Effect of overloading: An overloading of 25% (based on a standard single axle load of 80 kN) results in loss of subgrade rutting life by 62.42% while asphalt fatigue life by 32.53%. The overloading has a higher impact on the loss of subgrade life in rutting.
- Effect of mix type and temperature: BC mixes were found to be less sensitive to changes in temperature than SMA mixes at lower temperatures due to their denser gradation and, thus, relatively higher stiffness. However, a similar trend is not seen at higher temperatures; BC mixes were more sensitive to temperature change than SMA mixes, which results in higher pavement deformation and strains. These findings support the usage of SMA mixes in high temperature regions.
- Effect of layer thickness: The asphalt fatigue life was found sensitive to changes in asphalt layer thickness only. Any change in lower layer thickness showed no significant effect on the fatigue life of the AC layer. However, subgrade rutting life could be improved by changing the thickness of any layer (order of impact: AC > Base > GSB).
- Effect of base layer stabilization: The stabilized base layer showed huge potential in limiting ε_z and ε_t parameters. The base layer treated with 4% SS-2 emulsion could be used with 50 to 60 mm reduced AC thickness compared to conventional bases of similar thickness. It may result in cost savings as the construction of the asphalt layer is the costliest. However, the cost of emulsion

treatment needs to be worked out and further studied. The benefit of emulsion treatment in overloading allowances was also realized. Considering similar thicknesses of emulsion treated and conventional base, the pavement with emulsion treated base was found to have 17.5 to 27.5% higher load carrying capacity (based on similar ε_z and ε_t parameters) than conventional base pavement.

Stage III: Linear viscoelastic AC, linear elastic UGMs, and nonuniform loading considering realistic tire

- The LVE simulation based on static loading conditions resulted in higher vertical deformations, normal strains, and ε_z (at the subgrade top) while lower ε_t (at the bottom of the asphalt layer) compared to linear elastic simulations.
- The LVE simulation was found to estimate 21.52% higher maximum deformation, 16.28% higher maximum compressive strain in the pavement, and 15.94% higher ε_z (z = 800 mm) while 25.43% lower ε_t (z = 150 mm) compared to linear elastic simulations considering similar loading conditions. Similar trends were also obtained against other parameters (air voids in the mix, temperature, and layer thickness).
- Based on static loading conditions, it can be concluded that, the linear elastic approach overestimates material stiffness and yields lower stress and strains in the pavement.

Stage IV: Linear viscoelastic AC, stress dependent response of UGMs, and nonuniform loading considering realistic tire

- The solutions (structural response of the asphalt pavement) obtained from this analysis were higher than linear elastic UGMs in the case of stage II and stage III simulation.
- When stress dependent response of UGMs (WMM as a base layer, GSB grade V, and RS-1 soil as subgrade material) was considered, the maximum surface deformation and compressive strain in the pavement were found to be higher by 29.61% and 25.71%, respectively compared to linear elastic simulations.
- The study showed that the linear elastic properties of UGMs overestimate the material stiffness. Therefore, the analysis approach must be revised for better reliability and accuracy.

7.3 Contributions of the study

- The study explored the LVE characterization of BC-2 mixes at different air voids and test temperatures considering regional variation throughout the country.
- This study also explored the nonlinear stress dependent response of UGMs considering five different soils (RS-1, RS-2, FAS, CS, and BCS) as subgrade materials, two different grades (grade V and grade VI) of GSB, and WMM as base layer. Hypo-elastic material modelling technique was utilized to input UGMs response to cyclic loading in the FE model.
- The effect of various crucial parameters (overloading, mix type, layer thickness, base layer stabilization, and environmental conditions like temperature) on the structural response and pavement life has been studied. These analyses will help in understanding, numerically, how variation in these parameters influences pavement structural damage. Evaluating scenarios (loading, material properties,

and environmental conditions) can help achieve a better and optimum design of asphalt pavement.

7.4 Limitations of the study

- The present study considered static loading conditions likely to underestimate pavement strength and its life compared to realistic field conditions where the load duration is small.
- The LVE response of asphalt pavement is based on single mix type (BC-2); results may vary for other mixes and require further study.
- The present study considers the binder and surface course as a single layer, and FE analyses are based on the surface course's material properties. The binder course (Dense bituminous macadam) needs to be considered separately in future studies.

7.5 Recommendations for future study

- While this study utilizes a FE based approach to evaluate the structural response and pavement life under different conditions of overloading, environmental factors, etc., the transient loading behaviour can present a more realistic simulation.
- The FE model of the tire-pavement system has been validated using results obtained from 3D Move analysis and Boussinesq close form solution; validation of the FE model from the field study (based on similar loading conditions) will be helpful to understand the accuracy and reliability of the present model.

- The LVE response of asphalt pavement can be explored for gap-graded mixes like stone mastic asphalt (SMA-1 and SMA-2). The present study focuses to characterize LVE response of asphalt mixes using creep compliance test, however, at higher temperatures, dynamic modulus tests can be used for more comprehensive characterization of these materials. Additionally, nonlinear effect of temperature gradient and freeze-thaw on the LVE properties of the mixes can be also studied.
- The FE model of the tire body is based on a single rubber material to simplify modelling and analysis. However, other components, like bead, carcass, ply, reinforcement, etc., can be considered to model a more realistic tire, and its effect on contact stress distribution at the tire-pavement interface can be studied.