ADDRESSING UNCERTAINTY ISSUES OF BITUMINOUS MATERIALS AT COMPONENT LEVEL WITHIN LINEAR VISCOELASTIC FRAMEWORK

The structural design of flexible pavement is a complex and tedious task. Variation in factors such as traffic loading, pavement material properties, climatic conditions, construction techniques and models, result in uncertainty. This in turn leads to significant deviation in the performance of pavements (when compared to design). One approach to reduce the errors in the performance prediction of pavement is through uncertainty quantification, while accepting the fact that uncertainty can never be eliminated completely. Quantifying uncertainty from the potential sources eventually result in pavements with minimum deterioration, resulting in savings in maintenance cost. However, the current pavement design methods will not account for uncertainty issues at design stage. Hence there is a pressing need for quantifying the uncertainty, from these sources, considering the efficiency and economical aspect of pavement design.

The overall objectives of the thesis include addressing uncertainty in two stages of pavement analysis-design framework namely, (i) constitutive modelling of viscoelastic framework, and (ii) pavement design level. The specific objectives, overall framework and results obtained are discussed below.

(1) <u>Characterization of uncertainty in asphalt mixture dynamic modulus</u>: The dynamic modulus ($|E^*|$) values of Asphalt Concrete (AC) are determined under laboratory conditions using frequency sweep-temperature sweep tests. Subsequently, mastercurve is constructed using the time-temperature superposition principle. Even under best quality control, significant scatter is found with results obtained with frequency sweep-temperature sweep tests. This scatter can be attributed to issues during fabrication

processes, testing, and analysis process. This part of research addresses the issue of scatter through uncertainty quantification techniques. For this purpose, $|E^*|$ mastercurves constructed using different specimens but with the same mixture were used. The $|E^*|$ values at a particular reduced frequency were analyzed using uncertainty quantification techniques. The results indicate that parameters used for quantifying uncertainty are dependent on testing frequency (in the range of 0.1 Hz, 0.2 Hz, 0.5 Hz, 1 Hz, 2 Hz, 5 Hz, 10 Hz, and 20 Hz), testing temperature (-10°C to 30°C at 10°C increments), and reduced frequency (1.0E-05 to 1.0E+05 Hz).

(2) <u>Quantification of uncertainty in the mastercurves of viscoelastic properties of asphalt concrete</u>: The prediction of AC behaviour using continuum damage mechanics approach requires viscoelastic properties like creep compliance, $D(t)$ and relaxation modulus, $E(t)$ values. Due to practical limitations, dynamic modulus ($|E^*|$) and phase angle (φ) measurements are used to construct $D(t)$ and $E(t)$ mastercurves. Due to issues during testing, fabrication processes and interconversion approximations, significant scatter can be found in $D(t)$ and $E(t)$ mastercurves constructed. This part of research proposes and compares quantification methods to address scatter found in $D(t)$ and $E(t)$ mastercurves. For this purpose, several AC specimens with identical volumetric properties were prepared and tested for $|E^*|$ and φ values. The results indicate that the choice of simulation technique affects the statistical parameters associated with the Probability Density Function (PDF) to a large extent. In other words, uncertainty found in $D(t)$ and $E(t)$ values are dependent on the choice of interconversion technique and time of interest.

(3) <u>Analysing the effect of construction methodology on uncertainty in asphalt concrete mastercurves</u>: This part of study critically evaluates the effect of (i) various temperature shift factor determination approaches (i.e. free shifting approach, Arrhenius type equation, William- Landel-Ferry (WLF) equation and Kaelble equation), and (ii)

functional form of mastercurve (symmetric and asymmetric) adopted on the resulting uncertainty in $D(t)$ and $E(t)$ responses. The results indicate uncertainty at any particular reduced time is dependent primarily on mastercurve construction method. Based on the uncertainty quantification parameters, various mastercurve construction methods were ranked. Based on this ranking, for a given sigmoidal function, use of Kaelble, Arrhenius, WLF and free shifting approach resulted in the least to highest uncertainty. Further, for a given temperature shift factor, symmetric sigmoidal function resulted in higher uncertainty when compared to asymmetric sigmoidal function.

(4) Evaluating the presence and propagation of uncertainty in asphalt binder mastercurves: This part of work proposes a comprehensive framework to quantify, propagate and separate uncertainty in the finalized unit response mastercurves. For the demonstration of this uncertainty evaluation framework, a set of nine asphalt binder samples were taken from the same container, which was short term aged and tested for its viscoelastic properties. Subsequently, $J(t)$ and $G(t)$ mastercurves were constructed (i) directly (using experimentally determined $J(t)$ and $G(t)$ values), and (ii) through numerical technique (using $|G^*|$ and φ values through interconversion approach). Further, uncertainty in mastercurves was evaluated and quantified using several indicators. The numerical values of these indicators reflected that higher uncertainty existed at lower and higher reduced time (and frequencies) when compared to intermediate reduced time (and frequencies). In case of relaxation modulus, the numerical values of NUR corresponding to lower (1.0E-05s), intermediate (10s) and higher (1.0E+05s) reduced time values are 6.11E-01, 2.97E-01, 1.67E+00 respectively. Further, uncertainty in viscoelastic parameters increased with intermediate steps in the interconversion process. Subsequently, the uncertainty in the $J(t)$ and $G(t)$ mastercurves was separated into epistemic and aleatoric uncertainty. The numerical values of these statistical indicators reflected that the uncertainty in

mastercurves (at a particular reduced time (or frequency) was also dependent on the construction technique, chosen distribution function and sample size.

(5) Comparison of various surrogate models for predicting strain at critical locations in flexible pavement: Various numerical techniques used in flexible pavement analysis (for estimating the strain at critical locations) are computationally expensive. Under such circumstances, surrogate models (which reduce computational resource requirement) becomes handy. This part of work evaluates the efficacy of three surrogate models; response surface method, Kriging model, and Support Vector Regression (SVR) model for predicting strain in a four-layered pavement structure. Several combinations arising out of different kernel functions, loss schemes, and optimisation methods were used to construct surrogate models. The strain at various critical locations in pavement structure was predicted using these surrogate models, and the model accuracy was evaluated using various statistical techniques. From the study it can be concluded that the proper choice of kernel and optimisation method plays an important role in the finalized surrogate model. Kriging model was found to be superior to SVR and RSM for predicting strain at critical locations i.e. under one of the tyres and middle of the dual tyre.

(6) Estimating model uncertainty of the surrogate strain model using Bayesian Model Averaging: Most of the surrogate models rely on conventional approach of relating covariates with response through simplified models. Usually covariates are chosen on basis of experience, and data availability with ease. Further, form of the model is finalized based on statistical indicators and goodness of fit values. Thus concept of uncertainty in selecting the model is completely ignored. This often leads to overconfident results and an increased risk in the prediction. Under these circumstances, Bayesian Model Averaging (BMA) could be a potential model building tool. This part of study presents BMA based approach for choosing influencing variables and quantifying

uncertainty associated with the linear regression models used to predict strain in a four layered pavement structure. Initially, modulus and thickness of individual layers were used as input into surrogate model building exercise. Out of 128 possible models, best 100 models were used in conjunction with BMA technique to rank various models and variables. Further, model uncertainty was represented by plotting the marginal density function of the coefficients, Coefficient of Variation and Normalised Uncertainty Range. BMA exercise indicated that modulus and thickness of asphaltic layer, and modulus of binder layer accounted for majority of variability (upto 88%) associated with tensile strain in asphaltic layer. Similarly, thickness of asphaltic layer modulus and modulus of subgrade affected vertical compressive strain prediction models significantly (upto 38%). Also, ranking based on the posterior inclusion probability can be used as alternative for traditional sensitivity analysis.

Keywords: *Uncertainty Quantification, Constitutive modeling, Time-temperature superposition; Mastercurve, creep compliance, relaxation modulus; Surrogate models; transfer functions; Bayesian Model Averaging; Shift factor.*