

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

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
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WITHIN LINEAR VISCOELASTIC FRAMEWORK**

by

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Submitted

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to the



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DEDICATION

*My family and to my guide,
for their immense help and support that made this thesis
possible.*

CERTIFICATE

This is to certify that the thesis entitled “**Addressing uncertainty issues in bituminous materials at component level within linear viscoelastic framework**”, being submitted by **Mrs Aswathy Rema** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a bonafide record of the research work carried out by her under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard, fulfilling the requirements for the degree of Doctor of Philosophy.

The contents of this thesis, in full or in parts, have not been submitted to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

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) Characterization of uncertainty in asphalt mixture dynamic modulus: 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) Quantification of uncertainty in the mastercurves of viscoelastic properties of asphalt concrete: 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) Analysing the effect of construction methodology on uncertainty in asphalt concrete mastercurves: 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.*

सार

लचीली फुटपाथ का संरचनात्मक डिजाइन एक जटिल और थकाऊ काम है, जो इसके साथ जुड़े सभी कारकों की परिवर्तनशीलता और सन्निकटन के कारण है और परिणामी अनिश्चितता है। यातायात लोडिंग, फुटपाथ सामग्री गुण, जलवायु परिस्थितियों, निर्माण तकनीक और मॉडल जैसे कारकों में भिन्नता। ऐसी अनिश्चितता पैदा करें और फुटपाथों के प्रदर्शन की भविष्यवाणी में महत्वपूर्ण विचलन की ओर बढ़ें। फुटपाथ के प्रदर्शन की भविष्यवाणी में त्रुटियों को कम करने का एक संभावित समाधान अनिश्चितता का परिमाण हो सकता है, इस तथ्य को स्वीकार करते हुए कि अनिश्चितता को कभी भी पूरी तरह से समाप्त नहीं किया जा सकता है। संभावित स्रोतों से अनिश्चितता को कम करने के परिणामस्वरूप अंततः न्यूनतम पहनने और आंसू के साथ फुटपाथों में परिणाम होता है, जिसके परिणामस्वरूप फुटपाथ से संबंधित निर्माण परियोजनाओं के लिए आरक्षित राशि में बचत होती है। हालांकि, मौजूदा फुटपाथ डिजाइन के तरीके अनिश्चितता के कारक को इसके डिजाइन में नहीं मानते हैं। इसलिए फुटपाथ डिजाइन की दक्षता और किफायती पहलू पर विचार करते हुए, अनिश्चितताओं को निर्धारित करने के लिए एक दबाव की आवश्यकता है।

थीसिस के समग्र उद्देश्यों में फुटपाथ विश्लेषण-डिजाइन फ्रेमवर्क के दो चरणों में अनिश्चितता को संबोधित करना शामिल है, (i) विज़कोएलास्टिक फ्रेमवर्क का संवैधानिक मॉडलिंग, और (ii) फुटपाथ डिजाइन स्तर।

विशिष्ट उद्देश्यों, समग्र रूपरेखा और प्राप्त परिणामों की नीचे चर्चा की गई है।

- (1) डामर मिश्रण में अनिश्चितता की विशेषता डायनामिक मापांक: डायनेमिक मापांक ($|E^*|$) डामर कंक्रीट (AC) के मान को आवृत्ति स्वीप-तापमान स्वीप परीक्षणों का उपयोग करके प्रयोगशाला परिस्थितियों में निर्धारित किया जाता है। इसके बाद, टाइम-टेंपरेचर सुपरपोजिशन सिद्धांत का उपयोग करते हुए मास्टरस्क्यू का निर्माण किया जाता है। यहां तक कि सर्वोत्तम गुणवत्ता नियंत्रण के तहत, आवृत्ति स्वीप-तापमान स्वीप परीक्षणों के साथ प्राप्त परिणामों के साथ महत्वपूर्ण बिखराव

पाया जाता है। इस प्रकीर्णन को निर्माण प्रक्रियाओं, परीक्षण और विश्लेषण प्रक्रिया के दौरान मुद्दों के लिए जिम्मेदार ठहराया जा सकता है। अनुसंधान का यह हिस्सा अनिश्चितता मात्रा का ठहराव तकनीकों के माध्यम से बिखराव के मुद्दे को संबोधित करता है। इस प्रयोजन के लिए ($|E^*|$) अलग-अलग नमूनों का उपयोग करते हुए मास्टरकुरव का निर्माण किया गया था लेकिन एक ही मिश्रण के साथ उपयोग किया गया था। ($|E^*|$) एक विशेष रूप से कम आवृत्ति पर मूल्यों का विश्लेषण अनिश्चितता परिमाणीकरण तकनीकों का उपयोग करके किया गया था। परिणाम इंगित करते हैं कि अनिश्चितता को बढ़ाने के लिए उपयोग किए जाने वाले पैरामीटर परीक्षण आवृत्ति, परीक्षण तापमान और कम आवृत्ति पर निर्भर हैं।

- (2) डामर कंक्रीट के विस्कोसैलेस्टिक गुणों के मास्टरस्कॉवर्स में अनिश्चितता की मात्रा: निरंतरता क्षति यांत्रिकी दृष्टिकोण का उपयोग करके एसी व्यवहार की भविष्यवाणी को रेंगना अनुपालन, $D(t)$ और विश्राम मापांक, $E(t)$ मूल्यों जैसे विस्कोसिस्टल गुणों की आवश्यकता होती है। व्यावहारिक सीमाओं के कारण, डायनेमिक मापांक ($|E^*|$) और चरण कोण माप का उपयोग $D(t)$ और $E(t)$ मास्टरस्कॉक्स बनाने के लिए किया जाता है। परीक्षण के दौरान मुद्दों के कारण, निर्माण की प्रक्रियाएं और इंटरकनेक्शन सन्निकटन, $D(t)$ और $E(t)$ मास्टरकेक्स में महत्वपूर्ण बिखराव पाया जा सकता है। अनुसंधान का यह भाग प्रस्तावित करता है और $D(t)$ और $E(t)$ मास्टरस्कॉक्स में पाए जाने वाले बिखराव को संबोधित करने के लिए मात्रात्मक तरीकों की तुलना करता है। इस प्रयोजन के लिए, समान वाष्पशील गुणों वाले कई एसी नमूनों को तैयार किया गया और उनका परीक्षण किया ($|E^*|$) और and मान। परिणाम बताते हैं कि सिमुलेशन तकनीक का चुनाव प्रोबेबिलिटी डेंसिटी फंक्शन (पीडीएफ) से जुड़े सांख्यिकीय मापदंडों को काफी हद तक प्रभावित करता है। दूसरे शब्दों में, $D(t)$ और $E(t)$ मूल्यों में मिली अनिश्चितता इंटरकनेव तकनीक और पसंद के समय की पसंद पर निर्भर है।

- (3) डामर कंक्रीट मास्टरस्कॉवर्स में अनिश्चितता पर निर्माण पद्धति के प्रभाव का विश्लेषण: अध्ययन का यह हिस्सा गंभीर रूप से (i) विभिन्न तापमान परिवर्तन कारक निर्धारण दृष्टिकोण (यानी मुक्त स्थानांतरण दृष्टिकोण, अरहेनियस प्रकार समीकरण, विलियम- लैंडेल-फेरी (डब्ल्यूएलएफ) समीकरण के प्रभाव का मूल्यांकन करता है। और कालबेल समीकरण), और (ii) $D(t)$ और $E(t)$ प्रतिक्रियाओं में परिणामी अनिश्चितता पर अपनाई गई मास्टरकूव (सममित और असममित) के कार्यात्मक रूप। परिणाम किसी विशेष रूप से कम समय पर अनिश्चितता का संकेत देते हैं जो मुख्य रूप से मास्टरकूव निर्माण विधि पर निर्भर है। अनिश्चितता परिमाणीकरण मापदंडों के आधार पर, विभिन्न मास्टरकूव निर्माण विधियों को रैंक किया गया था। इस रैंकिंग के आधार पर, किसी दिए गए सिग्मोइडल फंक्शन के लिए, कैबल, अरहेनियस, डब्ल्यूएलएफ और फ्री शिफ्टिंग दृष्टिकोण का उपयोग कम से कम उच्चतम अनिश्चितता के रूप में होता है। इसके अलावा, एक दिए गए तापमान परिवर्तन कारक के लिए, सममित सिग्मोइडल फंक्शन की तुलना में सममितीय सिग्मोइडल फंक्शन के परिणामस्वरूप उच्च अनिश्चितता हुई।
- (4) डामर बांधने की मशीन मास्टरकेस में अनिश्चितता की उपस्थिति और प्रसार का मूल्यांकन: काम का यह हिस्सा अंतिम इकाई प्रतिक्रिया मास्टरकूव्स में परिमाणित, प्रचार और अलग अनिश्चितता के लिए एक व्यापक ढांचे का प्रस्ताव करता है। इस अनिश्चितता मूल्यांकन ढांचे के प्रदर्शन के लिए, एक ही कंटेनर से नौ डामर बांधने की मशीन नमूने का एक सेट लिया गया था, जो अल्पकालिक आयु और इसकी विस्कोसैलेस्टिक गुणों के लिए परीक्षण किया गया था। बाद में, $J(t)$ और $G(t)$ मास्टरस्कूव्स का निर्माण किया गया (i) सीधे (प्रयोगात्मक रूप से निर्धारित जे $J(t)$ और $G(t)$ मूल्यों का उपयोग करके), और (ii) संख्यात्मक तकनीक के माध्यम से (उपयोग | अंतर्संबंध दृष्टिकोण के माध्यम से मान)। इसके अलावा, कई संकेतकों का उपयोग करके मास्टरस्कॉवर्स में अनिश्चितता का मूल्यांकन और मात्रा निर्धारित की गई थी। इन संकेतकों के संख्यात्मक मूल्यों ने दर्शाया कि मध्यवर्ती कम समय (और आवृत्तियों) की तुलना में उच्च अनिश्चितता कम और उच्चतर

- कम समय (और आवृत्तियों) पर मौजूद थी। इसके अलावा, विस्कोसैस्टिक मापदंडों में अनिश्चितता इंटरकनेक्शन प्रक्रिया में मध्यवर्ती चरणों के साथ बढ़ी। बाद में, $J(t)$ और $G(t)$ मास्टरस्कर्व्स में अनिश्चितता को महामारी और प्रेरक अनिश्चितता में अलग कर दिया गया था। इन सांख्यिकीय संकेतकों के संख्यात्मक मूल्यों ने दर्शाया कि मास्टरस्कर्व्स (एक विशेष रूप से कम समय (या आवृत्ति) पर अनिश्चितता भी निर्माण तकनीक, चुने हुए वितरण समारोह और नमूना आकार पर निर्भर थी।
- (5) लचीले फुटपाथ में महत्वपूर्ण स्थानों पर तनाव की भविष्यवाणी के लिए विभिन्न सरोगेट मॉडल की तुलना: लचीले फुटपाथ विश्लेषण (महत्वपूर्ण स्थानों पर तनाव का आकलन करने के लिए) में उपयोग की जाने वाली विभिन्न संख्यात्मक तकनीक कम्प्यूटेशनल रूप से महंगी हैं। ऐसी परिस्थितियों में, सरोगेट मॉडल (जो कम्प्यूटेशनल संसाधन की आवश्यकता को कम करते हैं) आसान हो जाते हैं। काम का यह हिस्सा तीन सरोगेट मॉडल की प्रभावकारिता का मूल्यांकन करता है; चार-स्तरीय प्रशस्त संरचना में तनाव की भविष्यवाणी के लिए प्रतिक्रिया सतह विधि, क्रिगिंग मॉडल और सपोर्ट वेक्टर रिग्रेशन (एसवीआर) मॉडल। सरोगेट मॉडल के निर्माण के लिए विभिन्न कर्नेल फ़ंक्शंस, लॉस स्कीम्स और ऑप्टिमाइज़ेशन विधियों से उत्पन्न होने वाले कई संयोजनों का उपयोग किया गया था। फुटपाथ संरचना में विभिन्न महत्वपूर्ण स्थानों पर तनाव का अनुमान इन सरोगेट मॉडल का उपयोग करके लगाया गया था, और विभिन्न सटीकता तकनीकों का उपयोग करके मॉडल सटीकता का मूल्यांकन किया गया था। अध्ययन से यह निष्कर्ष निकाला जा सकता है कि कर्नेल और अनुकूलन विधि का उचित विकल्प अंतिम रूप से सरोगेट मॉडल में एक महत्वपूर्ण भूमिका निभाता है। क्रिगिंग मॉडल को महत्वपूर्ण स्थानों पर तनाव की भविष्यवाणी के लिए एसवीआर और आरएसएम से बेहतर पाया गया।
- (6) बायेसियन मॉडल एवरेजिंग का उपयोग करके सरोगेट स्ट्रेन मॉडल की मॉडल अनिश्चितता का अनुमान लगाना: अधिकांश सरोगेट मॉडल सरलीकृत मॉडल के माध्यम से प्रतिक्रिया के साथ

संबंधित कोवरिएट्स के पारंपरिक दृष्टिकोणों पर भरोसा करते हैं। आमतौर पर कोवरी को अनुभव के आधार पर चुना जाता है, और आसानी से डेटा उपलब्धता। इसके अलावा, सांख्यिकीय संकेतकों और फिट मूल्यों की अच्छाई के आधार पर मॉडल के रूप को अंतिम रूप दिया जाता है। इस प्रकार मॉडल के चयन में अनिश्चितता की अवधारणा को पूरी तरह से नजरअंदाज कर दिया गया है। यह अक्सर अति आत्मविश्वास परिणाम और भविष्यवाणी में एक बढ़ा जोखिम की ओर जाता है। इन परिस्थितियों में, बायेसियन मॉडल एवरेजिंग (बीएमए) एक संभावित मॉडल निर्माण उपकरण हो सकता है। अध्ययन का यह हिस्सा BMA आधारित दृष्टिकोणों को प्रभावित करने वाले चर को चुनने के लिए प्रस्तुत करता है और एक चार स्तरित फुटपाथ संरचना में तनाव की भविष्यवाणी करने के लिए उपयोग किए जाने वाले रैखिक प्रतिगमन मॉडल से जुड़ी अनिश्चितता को निर्धारित करता है। प्रारंभ में, अलग-अलग परतों के मापांक और मोटाई का उपयोग सरोगेट मॉडल बिल्डिंग व्यायाम में इनपुट के रूप में किया गया था। 128 संभव मॉडल में से, सर्वश्रेष्ठ 100 मॉडल विभिन्न मॉडलों और चर को रैंक करने के लिए BMA तकनीक के साथ संयोजन में उपयोग किए गए थे। इसके अलावा, मॉडल अनिश्चितता को गुणांक, भिन्नता के गुणांक और सामान्यीकृत अनिश्चितता सीमा के सीमांत घनत्व समारोह की साजिश रचने के द्वारा दर्शाया गया था। बीएमए व्यायाम ने संकेत दिया कि डामर और डामर की परत की मोटाई, और बाइंडर परत के मापांक को डामरिक परत में तन्यता तनाव से जुड़े परिवर्तनशीलता (88% तक) के बहुमत के लिए जिम्मेदार है। इसी तरह, डामर की परत के मापांक और सबग्रेड के वर्टिकल प्रभावित वर्टिकल कंप्रेसिव स्ट्रेन प्रेडिक्शन मॉडल (38% तक) को प्रभावित करते हैं। इसके अलावा, पीछे हटने की संभावना के आधार पर रैंकिंग का उपयोग पारंपरिक संवेदनशीलता विश्लेषण के विकल्प के रूप में किया जा सकता है।

कीवर्ड: अनिश्चितता मात्रा का ठहराव, कांस्टीट्यूशनल मॉडलिंग, टाइम-तापमान सुपरपोजिशन;
मास्टरक्यूव, रेंगना अनुपालन, विश्राम मापांक; सरोगेट मॉडल; स्थानांतरण कार्य; बायेसियन एवरेजिंग
मॉडल; पारी कारक।

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LIST OF ABBREVIATIONS

AC	Asphalt Concrete
AIC	Atkins Information Criteria
BBM	Box Behnkem Method
BFGS	Broyden Fetcher Goldfarb Shanno
BIC	Bayesian information Criteria
BMA	Bayesian Model Averaging
CDF	Cumulative Distribution Function
COV	Coefficient of Variation
CMAES	Covariance Matrix Adaptation Evolution Scheme
DoE	Design of Experiments
DSR	Dynamic Shear Rheometer
HMA	Hot Mix Asphalt
IQR	Inter-Quartile Range
LEA	Linear Elastic Analysis
LHS	Latin Hypercube Sampling
LVDT	Linearly Variable Differential Transducers
MAPE	Mean Absolute Percentage Error
MCS	Monte Carlo Simulation
MCMC	Markov Chain Monte Carlo
MEPD	Mechanistic Empirical Pavement Design
NHDOT	New Hampshire Department of Transportation
NUR	Normalised Uncertainty Range
PIP	Posterior Inclusion Probability
PM	Posterior Mean
PMP	Posterior Model Probability
PSD	Posterior Standard Deviation
QR	Quantile Regression
QoI	Quantity of Interest
RBF	Radial Basis Function

RMSE	Root Mean Square Error
RSM	Response Surface Methodology
SVR	Support Vector Regression
UP	Uncertainty Propagation
UQ	Uncertainty Quantification
WLF	William Landel Ferry

LIST OF SYMBOLS

a_T	Temperature shift factor
C_P	Center points.
$D(t)$	Creep compliance
$J(t)$	Shear creep compliance
$ E^* $	Dynamic modulus
E_{HMA}	Resilient modulus of Hot Mix Asphalt layer
E_{WMM}	Resilient modulus of Wet Mix Macadam layer
E_{GSB}	Resilient modulus of Granular Subbase
E_{SG}	Resilient modulus of Subgrade
$E(t)$	Relaxation modulus
f_R	Reduced frequency
f	Testing frequency
$G'(\omega_r)$	Storage modulus as a function of reduced angular frequency
$ G^* $	Complex shear modulus
G'	Storage modulus at various reduced frequency
$G(t)$	Shear relaxation modulus
$G(t_r)$	Relaxation modulus as a function of reduced time
h_{HMA}	Thickness of Hot Mix Asphalt layer
h_{WMM}	Thickness of Wet Mix Macadam layer
h_{GSB}	Thickness of Granular Subbase
$J(t)$	Shear creep compliance
K_1, K_2	Constants in Kaelble shift equation
K	Number of independent variables
N	Number of combinations
N_f	Number of repetitions to fatigue cracking
N_r	Number of repetitions to rutting failure

p	Property of interest
t_r	Reduced time
T_r	Reference temperature
T_d	Defining point for inflection point in Kaelble shift equation
b	Offset parameter to be estimated
σ	Scale parameter
μ	Location parameter
n	Local slope of storage modulus mastercurve
λ'	Adjustment factor
w	Vector of weight coefficients
$\langle \rangle$	Dot product
φ	Phase Angle
μ_i	Poisson ratio
α_i	Regression coefficients describing symmetric sigmoidal function
β_i	Regression coefficients describing asymmetric sigmoidal function
ω_r	Angular frequency
β_i	Coefficients describing shape of asymmetric sigmoid function.
Γ	Gamma function
$\epsilon_{t,s}$	Horizontal tensile strain at middle of one of tyres
$\epsilon_{v,s}$	Vertical compressive strain at middle of one of tyres
$\epsilon_{t,d}$	Horizontal tensile strain at middle of dual tyres
$\epsilon_{v,d}$	Vertical compressive strain at middle of dual tyres