CHARACTERIZATION OF PERMANENT DEFORMATION AND REPLICATE STOCHASTICITY IN ASPHALT CONCRETE MATERIALS USING BAYESIAN INFERENCE APPROACH

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Characterization of permanent deformation and replicate stochasticity in asphalt concrete materials using Bayesian inference approach

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Dedicated to

Varuni B R, Arnav M H and Ila M H

For your unending patience and unwavering faith in me

CERTIFICATE

This is to certify that the thesis entitled "**Characterization of permanent deformation and replicate stochasticity in asphalt concrete materials using Bayesian inference approach**" being submitted by Mr. Manoj K G to the Indian Institute of Technology Delhi is a record of bonafide research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the standard fulfilling the requirements for DOCTOR OF PHILOSOPHY degree. The research report and results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of any degree or diploma.

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ABSTRACT

This study proposes a modelling framework to characterise permanent deformation in asphalt concrete materials whose replicates are prepared using the Marshall compaction technique. In this relation, the models that are generally used are the viscoelastic and viscoplastic models. However, the viscoelastic modelling framework requires linear viscoelastic characterisation. The linear viscoelastic behaviour is not observed under the experimental conditions adopted in this study. In addition, viscoplastic models are not readily applicable under the loading conditions assumed in this study. Thus, the permanent strain is decomposed into creep and the viscoelastic strain components. The former component is characterised using the Kachanov-Rabotnov modelling framework using static creep tests, and the latter component is modelled using the differential equation form of viscoelasticity by adopting the state space approach using the dynamic creep test results. Further, upon replication, significant stochasticity is observed in the mechanical responses of the replicates due to the uncertainty in the specimen preparation method, test protocols and optimisation techniques. There exist methodologies to characterise this replicate stochasticity. However, these methods adopt the classical theory of probability. The classical probability theory is based on the law of large numbers and requires testing a significant number of samples under identical conditions. This requirement is because of the distinction between sample and population. The sample requirement to characterise a population is very high. Thus, Bayesian inference is adopted in this study to characterise the replicate stochasticity. A Bayesian model considers the distribution parameters to be stochastic, and it updates them with additional data. The stochastic characterisation is carried out in two conditions. In the first condition, the model parameters are considered stochastic and in the second, stochasticity in observed mechanical responses is considered directly. It was found that when stochasticity in model parameters is considered, the variation in model output is sensitive to variation in one or more model parameters. However, it can characterise the expected behaviours accurately. On the other hand, when stochasticity in model parameters is considered, the data requirement is extensive.

Keywords: Asphalt concrete, permanent deformation, modelling, static and dynamic creep tests, replicate stochasticity, Bayesian inference

सार

यह अध्ययन डामर कंक्रीट सामग्री में स्थायी विरूपण को चिह्नित करने के लिए एक मॉडलिंग ढांचे का प्रस्ताव करता है, जिसके प्रतिकृतियां मार्शल कॉम्पैक्शन तकनीक का उपयोग करके तैयार की जाती हैं। इस संबंध में, आमतौर पर इस्तेमाल किए जाने वाले मॉडल विस्कोइलास्टिक और विस्कोप्लास्टिक मॉडल हैं। हालाँकि, विस्कोइलास्टिक मॉडलिंग ढांचे के लिए रैखिक विस्कोइलास्टिक लक्षण वर्णन की आवश्यकता होती है। इस अध्ययन में अपनाई गई प्रायोगिक स्थितियों के तहत रैखिक विस्कोइलास्टिक व्यवहार नहीं देखा गया है। इसके अलावा, विस्कोप्लास्टिक मॉडल इस अध्ययन में ग्रहण की गई लोडिंग स्थितियों के तहत आसानी से लागू नहीं होते हैं। इस प्रकार, स्थायी तनाव रेंगना और विस्कोइलास्टिक तनाव घटकों में विघटित हो जाता है। पूर्व घटक को स्टेटिक रेंगना परीक्षणों का उपयोग करके काचनोव-रबोटनोव मॉडलिंग ढांचे का उपयोग करके चिह्नित किया जाता है, और बाद वाले घटक को गतिशील रेंगना परीक्षणों का संचालन करके राज्य स्थान दृष्टिकोण को अपनाकर विस्कोइलास्टिकिटी के अंतर समीकरण रूप का उपयोग करके मॉडल किया जाता है। इसके अलावा, प्रतिकृति पर, नमूना तैयारी विधि, परीक्षण प्रोटोकॉल और अनुकूलन तकनीकों में अनिश्चितता के कारण प्रतिकृतियों की यांत्रिक प्रतिक्रियाओं में महत्वपूर्ण स्टोकैस्टिसिटी देखी जाती है। इस प्रतिकृति स्टोकैस्टिसिटी को चिह्नित करने के लिए पद्धतियाँ मौजूद हैं। हालांकि, ये विधियाँ प्रायिकता के शास्त्रीय सिद्धांत को अपनाती हैं। शास्त्रीय प्रायिकता सिद्धांत बड़ी संख्या के नियम पर आधारित है और इसके लिए समान परिस्थितियों में बड़ी संख्या में नमूनों का परीक्षण करना आवश्यक है। यह आवश्यकता नमूने और पॉप्युलेशन के बीच अंतर के कारण है। पॉप्युलेशन को चिह्नित करने के लिए नमूने की आवश्यकता बहुत अधिक है। इस प्रकार, इस अध्ययन में प्रतिकृति स्टोकेस्टिसिटी को चिह्नित करने के लिए बायेसियन अनुमान को अपनाया गया है। बायेसियन मॉडल वितरण मापदंडों को स्टोकेस्टिक मानता है, और यह उन्हें अतिरिक्त डेटा के साथ अपडेट करता है। स्टोकेस्टिक लक्षण वर्णन दो स्थितियों में किया जाता है। पहली स्थिति में, मॉडल मापदंडों को स्टोकेस्टिक माना जाता है और दूसरी में, देखी गई यांत्रिक प्रतिक्रियाओं में स्टोकेस्टिसिटी को सीधे माना जाता है। यह पाया गया कि जब मॉडल मापदंडों में स्टोकेस्टिसिटी पर विचार किया जाता है, तो मॉडल आउटपुट में भिन्नता एक या अधिक मॉडल मापदंडों में भिन्नता के प्रति संवेदनशील होती है। हालांकि, यह अपेक्षित व्यवहारों को सटीक रूप से चिह्नित कर सकता है। दूसरी ओर, जब मॉडल मापदंडों में स्टोकेस्टिसिटी पर विचार किया जाता है, तो डेटा की आवश्यकता व्यापक होती है।

कीवर्ड: डामर कंक्रीट, स्थायी विरूपण, मॉडलिंग, स्थैतिक और गतिशील रेंगना परीक्षण, प्रतिकृति स्टोचैस्टिसिटी, बायेसियन अनुमान

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ABBREVIATIONS

(In the order of their appearance)

AC	Asphalt concrete
HMA	Hot Mix Asphalt (used interchangeably with asphalt concrete in some instances)
FN	Flow Number
FT	Flow Time
P_{t1}	Primary transition point
P_{t2}	Secondary transition point
RVE\REV	Representative Volume Element\ Representative Element Volume
IRC	Indian Roads Congress
SPT	Simple Performance Test
PMS	Pavement Management Systems
TTSP	Time-Temperature Superposition Principle
WLF	William-Landel-Ferry equation
TRS	Thermo-Rheologically Simple
CDM	Continuum Damage Model
CZM	Cohesive Zone model
ISV	Internal State Variable
DV	Damage Variable
HiSS	Hierarchical Single Surface
LTI	Linear Time Invariant
DE	Differential Equation
MoRTH	Ministry of Road Transport and Highways
VMA	Voids in Mineral Aggregates
VFB	Voids Filled with Bitumen
MCMC	Markov Chain Monte-Carlo
S-N	Stress-Number of cycles to failure
P-S-N	Probabilistic-Stress-Number of cycles to failure
MB-1	(Dense graded) Mix with Binder-1
MB-2	(Dense graded) Mix with Binder-2
CRMB	Crumbed Rubber Modified Bitumen
PMB	Polymer Modified Bitumen
MC	(Dense graded) Mix with Crumbed Rubber Modified Bitumen
MP	(Dense graded) Mix with Polymer Modified Bitumen
OBC	Optimum Binder Content
DTS	Dynamic Testing System
UTM	Universal Testing Machine
LVDT	Linear Vertical Differential Transducer
CDAS	Combined Data Acquisition System
TLD	Data file with *.tld* extension
AV4\4AV	Air Voids 4% specimen
AV7\7AV	Air Voids 7% specimen
RGB	Red-Green-Blue

2PP	Two-Point Probability functions
P1	Two-Point Probability function-1
P2	Two-Point Probability function-2
P3	Two-Point Probability function-3
P4	Two-Point Probability function-4
ANOVA	Analysis of variance
ACF	Auto Correlation Factor
ECDF	Estimated Cumulative Distribution Function
CDF	Cumulative Distribution Function
PDF	Probability Density Function
SD	Standard Deviation
MLE	Maximum Likelihood Estimation
DE	Differential equation