

**CHARACTERIZING THE VISCOELASTIC BEHAVIOR OF
ASPHALT BINDER AND MIXTURE THROUGH THE
CONTINUOUS SPECTRUM APPROACH**

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
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CONTINUOUS SPECTRUM APPROACH**

by

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Department Of Civil Engineering

Submitted

In fulfilment of the requirements of the degree of Doctor of Philosophy

to the



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DEDICATION

This thesis is dedicated to my family, guide and friends for their consistent support and encouragement throughout my academic endeavors. I hope this success will fulfill the dream they wished for me.

CERTIFICATE

This is to certify that the thesis titled “CHARACTERIZING THE VISCOELASTIC BEHAVIOR OF ASPHALT BINDER AND MIXTURE THROUGH THE CONTINUOUS SPECTRUM APPROACH”, submitted by Anjali Balan. L, 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 done 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 Institute or University for the award of any degree or diploma.

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Anjali Balan.L

ABSTRACT

Keywords

Asphalt binder; Asphalt mixture; Unmodified asphalt binder; Modified asphalt binder; Aging; Modification; Viscoelastic; Master curves; Complex modulus; Phase angle; Storage modulus; Storage compliance; Relaxation modulus; Creep compliance; Continuous spectrum; Relaxation spectrum; Retardation spectrum; Moments; Uncertainty; FTIR spectra; SARA fractions

The asphalt mixture is comprised of approximately 95% by weight of aggregates and 5% by weight of asphalt binder. Within the asphalt mixture, the asphalt binder is considered to have a significant effect on the overall performance of asphalt pavement since it acts as an adhesive material. The accurate determination of the properties of the asphalt binder and mixture is essential to analyze the response and performance of the pavements. Various viscoelastic properties such as relaxation modulus, creep compliance, complex modulus, and phase angle are commonly used to describe the linear viscoelastic behavior of these materials. The mechanical response of the asphalt materials will depend on the amplitude of stress or strain, the rate of loading and temperature. Further, creep compliance and relaxation modulus cannot predict the nonlinear features of the mechanical behavior of the material. Another fundamental properties such as relaxation spectra, $H(\tau)$, and retardation spectra, $L(\rho)$, can be used to characterize the relaxation modulus and creep compliance, respectively. Additionally, the relaxation modulus and creep compliance can be derived from the relaxation spectra and retardation spectra, respectively. One of the two spectra, i.e., relaxation or retardation spectra, is sufficient to describe linear viscoelasticity.

The continuous spectra are generally determined from the dynamic modulus tests, creep and stress relaxation tests data. Within the dynamic modulus test data, the continuous relaxation

and retardation spectrum are determined from the storage modulus and storage compliance master curve coefficients. Various functional forms and temperature shift factor techniques are used to construct master curves of these viscoelastic properties. As a result, even a small difference at the level of master curve construction will result in a substantial change in the developed continuous spectra. This study explores the effect of various construction methodologies on the development of continuous relaxation and retardation spectrum. Different combinations of both sigmoid functions (symmetric and asymmetric) and temperature shift factor approaches (free shifting, WLF equation, Arrhenius equation, and Kaelble equation) were used in this research. The present study also evaluated the applicability of three functional forms (Generalized Exponential function, Fraser Suzuki function, and Asymmetric Double sigmoidal function) to describe the continuous spectra of asphalt binders. Based on the obtained results, it was found that both the sigmoid functions (symmetric and asymmetric) coupled with the free shift approach resulted in the best construction methodology adopted for determining the G' and J' master curves. Further, both sigmoid functions coupled with the Kaelble equation resulted in the least construction methodology. Since the continuous spectra were developed using the G' and J' master curves, this result will reflect on generating the accurate continuous spectra. Therefore, the sigmoid functions in conjunction with the free shift approach can be considered as the best combination for developing the best continuous spectrum of asphalt binders. Among the various fitted functional forms, the asymmetric double sigmoidal function exhibited the best fit for describing the continuous spectra of asphalt binders. The major findings from this objective helped to identify the best construction methodology to obtain the continuous spectra.

This study further investigated on the continuous relaxation and retardation spectra determined from the frequency and time domain tests. As mentioned above, the relaxation modulus

and creep compliance values from the time-domain tests are used to establish the continuous relaxation and retardation spectra. Since the time and frequency domain functions are interrelated, the spectra obtained from these tests should be theoretically unique. However, both tests have failed to generate an identical relaxation and retardation spectrum. This study attempted to develop a new approach to determine the unique relaxation and retardation spectrum from frequency and time domain tests. In this study, the continuous spectra of unmodified asphalt binder (VG-30), modified asphalt (PMB-40), and asphalt mixture were determined using three approaches i) from the frequency domain test, ii) from the time-domain test, and iii) through the interconversion technique. The results indicated that the continuous relaxation and retardation spectra of all samples determined using the three approaches within the traditional methods (frequency domain test, time-domain test, and through interconversion technique) were completely different. This observation was further confirmed with the help of the shape characteristics of the spectra. Using the new approach, approximately the same relaxation and retardation spectra were determined for all the materials (for all three approaches). However, these spectra exhibited certain evident minor variations. These variations might be due to the fitting of the sigmoid function for experimental data, the effect of master curve model parameters on the shape parameters of the spectra, variations in the experimental data, and variations in the sample specimens.

This objective investigated the uncertainties and their sources associated with the continuous spectra. In order to obtain the continuous spectra, several viscoelastic parameters, including the complex modulus, phase angle, creep compliance, and relaxation modulus, are used, and it is expected to exhibit a considerable level of scatter within the experimental data. Since these parameters determine the spectra, this scatter will move towards the spectra. The scatter in continuous spectra will differ depending on the degree of scatter in these viscoelastic properties.

This study evaluated the uncertainty issues associated with the continuous relaxation and retardation spectra of asphalt binders. Further, the effect of the three approaches (time-domain and frequency domain tests, and through interconversion technique) and both sigmoid functions on developing the spectra was also evaluated. This study used the complex modulus and phase angle values from the frequency domain tests, the creep compliance and relaxation modulus values from the time domain tests, and interconversion techniques to determine the continuous spectra. The quantification of uncertainty in relaxation and retardation spectra revealed that the spectra derived from the frequency domain and interconversion have higher uncertainty than the time domain test. Further, less uncertainty was observed at intermediate relaxation/retardation times. Results also indicated that the asymmetric sigmoid function resulted in higher uncertainty on developing relaxation and retardation spectra.

This study explored how the aging and binder modification will affect the asphalt binder properties using the continuous spectrum approach. Further, the study developed mathematical expressions for the continuous relaxation and retardation spectrum using asymmetric sigmoid function. The present study used three case studies covering a wide range of material responses (with respect to the effect of the asphalt modifier and its dosage and aging) to show the efficacy of the proposed methodology. The results indicated that the continuous spectrum approach could capture the dosage effect reasonably. Significant changes in the peak of the spectrum were observed with different dosages of the asphalt modifier. The use of a stiffening modifier (WP) resulted in increased relaxation strength, while a viscosity-reducing modifier (WEO) resulted in the opposite trend. With regard to the retardation spectrum, the exact opposite trend was observed. Higher relaxation spectral strength values, broader relaxation spectrum, and horizontal shifts in relaxation spectra were observed with aging. However, the exact opposite trend was observed with

the retardation spectrum. These observations were confirmed with the shape parameters of the relaxation and retardation spectra.

To understand the underlying mechanisms of asphalt binder, it is necessary to establish relationship between the FTIR indices and SARA fractions to the spectral shape parameters. It will be easier to comprehend the molecular changes in asphalt binders by relating the shape parameters of spectra with the chemical properties of the material. This study attempted to establish a relationship between the shape parameters of relaxation and retardation spectra with the chemical properties (in terms of SARA fractions and functional groups) of asphalt binders under different aging conditions. The results indicated that a linear function could describe the relationship between the shape characteristics of both spectra and the FTIR indices. At the same time, there was a poor correlation between the parameters when a logarithmic function was fitted to the peak position and FTIR index plots. Overall, the best correlation was exhibited between the peak value of both spectra and the FTIR indices. Linear, exponential, and logarithmic functions were used to establish the relationship between the shape parameters and SARA fractions. Further, the best correlation was exhibited between the spread of both spectra and the SARA fractions. Because of the complexity of the established relationships, multivariate regression analysis was also used to establish the correlation between the shape parameters of spectra and the chemical properties of the asphalt binder. The results indicated that the regression analysis in relaxation spectra was more statistically significant than the retardation spectra based on FTIR indices. Conversely, compared to the retardation spectra regression analysis, the relaxation spectra showed higher statistical significance in terms of SARA fractions.

सार

एस्फाल्ट मिश्रण का लगभग 95% भार से एग्रीगेट्स और 5% भार से एस्फाल्ट बाइंडर से मिलकर बना होता है। एस्फाल्ट मिश्रण के अंदर, एस्फाल्ट बाइंडर को सामान्यतः एक चिपकने वाली सामग्री के रूप में समझा जाता है, क्योंकि यह एक चिपकने वाली सामग्री के रूप में कार्य करता है। एस्फाल्ट रोड की समग्र प्रदर्शन में एस्फाल्ट बाइंडर की गुणधर्मों का सटीक निर्धारण, सड़कों की प्रतिक्रिया और प्रदर्शन का विश्लेषण करने के लिए महत्वपूर्ण है। इन सामग्रियों के रैखिक विस्कोइलास्टिक व्यवहार को वर्णित करने के लिए सामान्यतः अधिकांश विस्कोएलास्टिक गुणधर्म जैसे कि रिलैक्सेशन मॉड्यूलस, क्रीप कंप्लायंस, कॉम्प्लेक्स मॉड्यूलस, और फेज एंगल का उपयोग किया जाता है। एस्फाल्ट सामग्रियों की यांत्रिक प्रतिक्रिया ताकत या तन के अंश, लोडिंग दर और तापमान पर निर्भर करेगी। इसके अलावा, क्रीप कंप्लायंस और रिलैक्सेशन मॉड्यूलस सामग्री के यांत्रिक व्यवहार की गैररैखिक विशेषताएँ पूर्वानुमान नहीं कर सकतीं। रिलैक्सेशन स्पेक्ट्रा, एच(टौ), और रीटार्डेशन स्पेक्ट्रा, एल(रो), जैसी और महत्वपूर्ण गुणधर्म, रिलैक्सेशन मॉड्यूलस और क्रीप कंप्लायंस का वर्णन करने के लिए उपयोग किए जा सकते हैं। इसके अलावा, रिलैक्सेशन मॉड्यूलस और क्रीप कंप्लायंस को उसके रिलैक्सेशन स्पेक्ट्रम और रीटार्डेशन स्पेक्ट्रम से निर्धारित किया जा सकता है, उपयुक्त। दो स्पेक्ट्रा में से एक, अर्थात् रिलैक्सेशन या रीटार्डेशन स्पेक्ट्रम, रैखिक विस्कोएलैसिटी का वर्णन करने के लिए पर्याप्त है।

कंटीन्यूअस स्पेक्ट्रा सामान्यतः डायनामिक मॉड्यूलस परीक्षण, क्रीप और स्ट्रेस रिलैक्सेशन परीक्षण डेटा से निर्धारित होते हैं। डायनामिक मॉड्यूलस परीक्षण डेटा के भीतर, स्टोरेज मॉड्यूलस और स्टोरेज कॉम्प्लायंस मास्टर कर्व कोइफिशिएंट्स से सतत रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रम को निर्धारित किया जाता है। इन विस्कोएलास्टिक गुणधर्मों के मास्टर कर्व की निर्माण के स्तर पर एक भी छोटा सा अंतर महत्वपूर्ण रूप से विकसित सतत स्पेक्ट्रम में परिणाम होगा। यह अध्ययन विभिन्न निर्माण पद्धतियों के प्रभाव की खोज करता है सतत रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रम के विकास पर। इस अनुसंधान में इस्तेमाल की गई विभिन्न सिगमॉइड फंक्शन्स (सममित और असममित) और तापमान शिफ्ट फैक्टर्स के तरीकों (फ्री शिफ्टिंग, WLF एक्वेशन, आरेनियस एक्वेशन, और केल्वल एक्वेशन) के विभिन्न संयोजनों का मूल्यांकन भी किया गया। वर्तमान अध्ययन ने एस्फाल्ट बाइंडर्स के कंटीन्यूअस स्पेक्ट्रम का वर्णन करने के लिए तीन कार्यात्मक रूप (गेनरलीज़ेड एक्सपोनेंशियल फंक्शन, फ्रेज़र सुजुकी फंक्शन, और असिमेट्रिक डबल सिगमोइडल फंक्शन) की अनुप्रयोगिता का मूल्यांकन भी किया। प्राप्त परिणामों के आधार पर, पाया गया कि दोनों सिगमॉइड फंक्शन्स (सममित और असममित) को फ्री शिफ्टिंग के साथ उपयुक्त करने पर जी-गोप्य और जेगोप्य मास्टर कर्व की श्रेष्ठ निर्माण पद्धति हुई। इसके अलावा, जोड़ी गई तीन कार्यात्मक रूपों में, असिमेट्रिक डबल सिगमोइडल फंक्शन ने एस्फाल्ट बाइंडर्स के कंटीन्यूअस स्पेक्ट्रम को वर्णन करने के लिए सर्वोत्तम मिलान प्रदान किया। इस उद्देश्य से प्राप्त मुख्य फिटिंग्स ने सहारा दिया कि कंटीन्यूअस स्पेक्ट्रम प्राप्त करने के लिए श्रेष्ठ निर्माण पद्धति की पहचान में मदद की।

इस अध्ययन ने और भी अध्ययन किया गया है कंटीन्यूअस रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रम पर जो फ्रीक्वेंसी और समय क्षेत्र के परीक्षणों से निर्धारित होते हैं। जैसा कि ऊपर उल्लिखित है, समय-क्षेत्र के परीक्षणों से रिलैक्सेशन मॉड्यूलस और क्रीप कंप्लायंस मानों का उपयोग कंटीन्यूअस रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रम स्थापित करने के लिए किया जाता है। क्योंकि समय और फ्रीक्वेंसी क्षेत्र के कार्यों में एक-दूसरे से संबंधित हैं, इन परीक्षणों से प्राप्त स्पेक्ट्रम को सिद्धांतिक रूप से अद्वितीय होना चाहिए। हालांकि, दोनों परीक्षणों ने एक समान रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रम उत्पन्न करने में असफल रहे हैं। इस अध्ययन ने कंटीन्यूअस रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रम को फ्रीक्वेंसी और समय क्षेत्र परीक्षणों से अद्वितीय रूप से निर्धारित करने के लिए एक नई दृष्टिकोण विकसित करने का प्रयास किया। इस अध्ययन में, तीन दृष्टिकोणों का उपयोग करके कंटीन्यूअस स्पेक्ट्रम का निर्धारण किया गया था: i) फ्रीक्वेंसी क्षेत्र परीक्षण से, ii) समय-क्षेत्र परीक्षण से, और iii) इंटरकंवरसिऑ तकनीक के माध्यम से। परिणाम दिखाए गए कि तीन दृष्टिकोणों (फ्रीक्वेंसी क्षेत्र परीक्षण, समय-क्षेत्र परीक्षण, और इंटरकंवरसिऑ तकनीक के माध्यम से) से प्राप्त सभी सैंपल्स का कंटीन्यूअस रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रम पूरी तरह भिन्न था। इस अवलोकन को स्पेक्ट्रम की आकृति विशेषताओं की सहायता से और भी पुष्टि की गई थी। नई दृष्टिकोण का उपयोग करके, लगभग सभी सामग्रियों के लिए यही समान रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रम निर्धारित हुआ। हालांकि, इन स्पेक्ट्रम में कुछ स्पष्ट सूक्ष्म विविधताएं थीं। ये विविधताएं प्रयोगात्मक डेटा

के लिए सिग्माइड फ़ंक्शन की फिटिंग, मास्टर कर्व मॉडल पैरामीटर्स के प्रभाव, स्पेक्ट्रम के आकृति पैरामीटर्स पर प्रभाव, प्रयोगात्मक डेटा में विविधताएं, और नमूना स्पीमन।

इस उद्देश्य ने कंटीन्यूअस स्पेक्ट्रम से जुड़े अनिश्चितताओं और उनके स्रोतों का अध्ययन किया। कंटीन्यूअस स्पेक्ट्रम प्राप्त करने के लिए, कई विस्कोएलास्टिक पैरामीटर, जैसे कि कॉम्प्लेक्स मॉड्यूलस, फेज एंगल, क्रीप कंप्लायंस, और रिलैक्सेशन मॉड्यूलस, का उपयोग किया जाता है, और यह प्रत्याशा है कि प्रयोगात्मक डेटा के भीतर एक काफी स्तर का छिद्र प्रदर्शित करेगा। क्योंकि ये पैरामीटर स्पेक्ट्रम को निर्धारित करते हैं, इस छिद्र का स्पेक्ट्रम की दिशा में होगा। कंटीन्यूअस स्पेक्ट्रम की छिद्र में भिन्नता इन विस्कोएलास्टिक गुणधर्मों की छिद्र की गुणस्तर पर निर्भर करेगी। इस अध्ययन ने एस्फाल्ट बाइंडर्स के कंटीन्यूअस रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रम के साथ जुड़े अनिश्चितता मुद्दों का मूल्यांकन किया। इसके अलावा, समय-क्षेत्र और फ्रीक्वेंसी क्षेत्र के परीक्षणों और दोनों ही सिग्माइड फ़ंक्शन्स के प्रभाव की भी मूल्यांकन किया गया। इस अध्ययन ने कॉम्प्लेक्स मॉड्यूलस और फेज एंगल मूल्यों का उपयोग फ्रीक्वेंसी क्षेत्र परीक्षणों से, क्रीप कंप्लायंस और रिलैक्सेशन मॉड्यूलस मूल्यों का उपयोग समय-क्षेत्र परीक्षणों से, और इंटरकंवरसिओं तकनीक से कंटीन्यूअस स्पेक्ट्रम को निर्धारित करने के लिए किया। रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रम में अनिश्चितता की मात्रा का मापन ने दिखाया कि फ्रीक्वेंसी क्षेत्र और इंटरकंवरसिओं तकनीक से प्राप्त स्पेक्ट्रम में समय-क्षेत्र परीक्षण की तुलना में अधिक अनिश्चितता है। इसके अलावा, स्पष्ट

रिलैक्सेशन/रिटार्डेशन समयों पर कम अनिश्चितता देखी गई। परिणाम ने यह भी दिखाया कि असममित सिगमॉइड फ़ंक्शन ने रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रम विकसित करने में अधिक अनिश्चितता पैदा की।

इस अध्ययन ने देखा कि बाइंडर का प्रौद्योगिकी और संयोजक संशोधन कैसे कंटीन्यूअस स्पेक्ट्रम दृष्टिकोण का उपयोग करके आस्फाल्ट बाइंडर गुणधर्मों पर प्रभाव डालेंगे। इसके अलावा, अध्ययन ने असममित सिगमॉइड फ़ंक्शन का उपयोग करके कंटीन्यूअस रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रम के लिए गणितीय अभिव्यक्तियाँ विकसित की। वर्तमान अध्ययन ने एक व्यापक सामग्री प्रतिक्रिया की विभिन्नता को दिखाने के लिए तीन मामलों का उपयोग किया (बाइंडर संशोधक और इसके मात्रा और प्रौद्योगिकी के प्रभाव के संदर्भ में) जो प्रस्तुत किए गए तरीके की प्रभावकारीता को दिखाने के लिए। परिणाम ने दिखाया कि कंटीन्यूअस स्पेक्ट्रम दृष्टिकोण से मात्रा के प्रभाव को यथासाम्यपूर्ण रूप से दर्शाया जा सकता है। एस्फाल्ट संशोधक के विभिन्न मात्राओं के साथ स्पेक्ट्रम के शिखर में विशेष परिवर्तन देखे गए। स्टिफ़निंग संशोधक (WP) का उपयोग से रिलैक्सेशन ताकत में वृद्धि हुई, जबकि एक दृवता कम करने वाले संशोधक (WEO) ने उल्टा परिवर्तन दिखाया। रिटार्डेशन स्पेक्ट्रम के संदर्भ में, विपरीत रूप में रुझान देखा गया। बढ़ी रिलैक्सेशन स्पेक्ट्रल ताकत मूल्य, बड़ा रिलैक्सेशन स्पेक्ट्रम, और रिलैक्सेशन स्पेक्ट्रम में क्षेत्रीय स्थानांतर दर्शित हुआ था। हालांकि, रिटार्डेशन स्पेक्ट्रम में विपरीत रूप में रुझान दिखाया गया। इन अवलोकनों की आकृति पैरामीटर्स के साथ भी यही विचार किया गया।

एस्फाल्ट बाइंडर के बुनियादी तंतुओं को समझने के लिए, FTIR इंडेक्स और SARA फ्रैक्शंस के बीच स्पेक्ट्रल आकृति पैरामीटर्स के बीच संबंध स्थापित करना आवश्यक है। सामग्री के रासायनिक गुणधर्मों के साथ स्पेक्ट्रा के आकृति पैरामीटर्स को जोड़कर एस्फाल्ट बाइंडर में आणविक परिवर्तनों को समझना सरल होगा। इस अध्ययन ने प्रयास किया कि विभिन्न प्रौद्योगिकी स्थितियों के तहत एस्फाल्ट बाइंडर के रिलैक्सेशन और रिटार्डेशन स्पेक्ट्रों के आकृति पैरामीटर्स के बीच एक संबंध स्थापित करने का प्रयास किया जाए। परिणाम ने दिखाया कि एक लीनियर फंक्शन और FTIR इंडेक्स दोनों स्पेक्ट्रम के आकृति पैरामीटर्स के बीच संबंध को वर्णन कर सकता था। इसी समय, जब पीक पोजीशन और FTIR इंडेक्स प्लॉट्स को लॉगारिदमिक समीकरण से फिट किया गया तो पैरामीटर्स के बीच एक गरीब सहमति दिखाई गई। कुल मिलाकर, सबसे अच्छा संबंध दोनों स्पेक्ट्रम के पीक वैल्यू और FTIR इंडेक्स के बीच दिखाया गया। लीनियर, एक्सपोनेंशियल और लॉगरिथमिक समीकरण का उपयोग आकृति पैरामीटर्स और SARA फ्रैक्शंस के बीच संबंध स्थापित करने के लिए किया गया। इसके अलावा, दोनों स्पेक्ट्रम के स्प्रेड और SARA फ्रैक्शंस के बीच सर्वश्रेष्ठ संबंध दिखाया गया। स्थापित रिश्तों की जटिलता के कारण, मुलतीवरीयते रिग्रेशन एनालिसिस का भी उपयोग इस आकृति पैरामीटर्स और एस्फाल्ट बाइंडर के रासायनिक गुणधर्मों के बीच संबंध स्थापित करने के लिए किया गया। परिणाम ने दिखाया कि FTIR इंडेक्स पर आधारित रिलैक्सेशन स्पेक्ट्रम में परिमाणिति विश्लेषण ने रिटार्डेशन स्पेक्ट्रम के तुलना में वाणिज्यिक रूप से अधिक सांख्यिक महत्वपूर्ण

था। उलटे, रिटार्डेशन स्पेक्ट्रम के परिमाणिति विश्लेषण की तुलना में, रिलैक्सेशन स्पेक्ट्रम ने SARA फ्रैक्शंस के संदर्भ में अधिक सांख्यिक महत्वपूर्णता दिखाई।

कीवर्ड्स : एस्फाल्ट बाइंडर; एस्फाल्ट मिश्रण; असंशोधित एस्फाल्ट बाइंडर; संशोधित एस्फाल्ट बाइंडर; प्रौद्योगिकी; संशोधन; विस्कोइलास्टिक; मास्टर कर्व्स; कॉम्प्लेक्स मॉड्यूलस; फेज एंगल; स्टोरेज मॉड्यूलस; स्टोरेज कंप्लायंस; रिलैक्सेशन मॉड्यूलस; क्रीप कंप्लायंस; कंटीन्यूअस स्पेक्ट्रम; रिलैक्सेशन स्पेक्ट्रम; रिटार्डेशन स्पेक्ट्रम; मोमेंट्स; अनिश्चितता; एफटीआईआर स्पेक्ट्रा; सारा फ्रैक्शंस।

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LIST OF ABBREVIATIONS

LVE	Linear Visco-Elastic
SARA	Saturate-Aromatics-Resins-Asphaltenes
FTIR	Fourier Transform Infrared
DSR	Dynamic Shear Rheometer
FS	Free Shifting
WLF	Williams-Landel-Ferry
AE	Arrhenius equation
KS	Kaelble shifting
GEX	Generalized Exponential
FSF	Fraser Suzuki Function
ADS	Asymmetric Double Sigmoidal
GoF	Goodness of Fit
SER	Standard Error Ratio
F.D.	Frequency Domain
T.D.	Time Domain
I.T.	Interconversion Technique
PG	Performance Grade
PMB-E	Polymer Modified Bitumen (Elastomer)
RTFO	Rolling thin film oven
PAV	Pressure Aging Vessel
COV	Coefficient of Variation

WEO	Waste Engine Oil
WP	Waste Polyethylene
HDPEHP	High-Density Polyethylene Homo-Polymer
SBS	Styrene-Butadiene-Styrene
LT	Limiting temperature

LIST OF SYMBOLS

$H(\tau)$	Relaxation spectrum
$L(\rho)$	Retardation spectrum
τ	Relaxation time
ρ	Retardation time
$J(t)$	Shear Creep compliance
$D(t)$	Creep compliance
$G(t)$	Shear Relaxation modulus
$E(t)$	Relaxation modulus
f	Test frequency
$ G^* $	Complex shear modulus
φ	Phase angle
G'	Storage modulus
G''	Loss modulus
$ E^* $	Dynamic modulus
J'	Storage compliance
f_r	Reduced frequency
a_T	Temperature shift factor
T	Testing temperature
T_{ref}	Reference temperature
t_r	Reduced time
α_i	Regression coefficients in symmetric sigmoidal function
β_i	Regression coefficients in the asymmetric sigmoidal function
C_1, C_2	Constants in Williams-Landel-Ferry equation

E_a	Activation energy
K_1, K_2	Constants in Kaoble shift equation
G_g	Glassy modulus
G_e	Equilibrium modulus
J_g	Glassy compliance
J_e	Equilibrium compliance
$adj R^2$	Adjusted R^2
I_c	Carbonyl Index
I_s	Sulphoxide Index
I_{Al}	Aliphatic Index
I_{Ar}	Aromatic Index