CHARACTERISATION OF CRACKING RESISTANCE OF POLYMER MODIFIED ASPHALT MIXTURES USING FRACTURE MECHANICS AND IMAGE ANALYSIS

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ABSTRACT

Most distresses in asphalt pavements are directly related to fracture. Thus, it becomes clear that identifying and characterising fracture properties of asphalt mixtures are critical steps towards a better pavement design. This study provides a detailed analysis of the crack resistance of the modified asphalt mixtures with crumb rubber and plastic waste. These modified mixtures have been introduced in road construction based on the basic understanding of the mechanical properties and lack of intensive studies on fracture mechanics. This study used the fracture mechanic concepts combined with the image analysis technique to evaluate the cracking behaviour of the asphalt mixtures. The asphalt mixtures were examined using semi-circular bending (SCB) test under different loading modes and levels, emphasising the impact of ageing and moisture. Digital image analysis technique was used to capture the crack initiation and propagation length. The crack length data were used to construct the resistance curve (R-curve) based on cumulative fracture energy for the control and modified asphalt mixtures. Crack mouth opening displacement (CMOD) data was used to analyse the crack initiation, crack propagation, and failure stages of the fatigue process. The digital image correlation (DIC) technique was successfully utilised in capturing the strain map of the SCB sample under monotonic and repeated load tests. Then, a two-dimensional finite element model using ABAQUS software was used to simulate the SCB test under monotonic load. The results showed that incorporating plastic and crumb rubber into the asphalt mixture increases the energy release rate by 10% and 20%, respectively. On the other hand, asphalt with crumb rubber expressed lower cracking resistance due to ageing and moisture conditioning than conventional and plastic modified mixtures. A different pattern was captured for the R-curve showing the impact of adding plastic and crumb rubber into the asphalt mixture. The R-curve showed that the rubberised mixture consumes 8% lower fracture energy at the crack initiation stage compared to the control and plastic modified asphalt mixtures. Moreover, the CMOD analysis showed that the rubberised asphalt mixture promoted crack propagation, whilst plastic waste modified asphalt mixture resisted cracking by delaying the crack initiation phase compared to the control asphalt. The digital image analysis of the modified asphalts indicates higher crack tortuosity and fractal dimension by 35% and 48%, respectively, compared to the control asphalt. This can be attributed to the increased cracking resistance of the modified asphalt mixtures. The DIC clearly emphasises the impact of crumb rubber in increasing the plastic deformation around the crack tip, while small fracture zones and high strain concentration were observed in the strain map of the mixture containing plastic waste. Additionally, the extended finite element method has successfully predicted the impact of change in notch length on the value of peak load and displacement.

ABSTRAK

Kebanyakan masalah turapan asfalt berkait secara langsung dengan retakan. Oleh itu, jelas bahawa mengenal pasti dan mencirikan sifat retakan campuran asfalt adalah langkah kritikal ke arah reka bentuk turapan yang lebih baik. Kajian ini menyediakan analisis terperinci mengenai ketahanan retakan campuran asfalt yang diubah suai menggunakan getah cebis dan sisa plastik. Campuran yang diubah suai ini telah diperkenalkan dalam pembinaan jalan raya berdasarkan pemahaman asas sifat-sifat mekanikal dan kekurangan kajian intensif mengenai mekanik retakan. Kajian ini menggunakan konsep mekanik retakan yang digabungkan dengan teknik analisis imej untuk menilai tingkah laku keretakan campuran asfalt. Campuran asfalt diperiksa menggunakan ujian lenturan separa bulat (SCB) di bawah mod dan tahap beban yang berbeza, dengan penekanan pada kesan penuaan dan kelembapan. Teknik analisis imej digital digunakan untuk menangkap permulaan retakan dan panjang perambatan. Data panjang retakan digunakan untuk membina lengkung rintangan (Lengkung R) berasaskan tenaga retakan kumulatif untuk campuran kawalan dan yang diubah suai. Data sesaran pembukaan mulut retakan (CMOD) digunakan untuk menganalisis permulaan retakan, perambatan retakan, dan peringkat kegagalan bagi proses kelesuan. Teknik korelasi imej digital (DIC) telah berjaya digunakan untuk merakam peta terikan sampel SCB di bawah ujian beban monotonik dan berulang. Kemudian, model elemen terhingga dua dimensi menggunakan perisian ABAQUS digunakan untuk mensimulasikan ujian SCB di bawah beban monotonik. Keputusan menunjukkan bahawa memasukkan plastik dan getah serbuk ke dalam campuran asfalt meningkatkan kadar pelepasan tenaga masing-masing sebanyak 10% dan 20%. Manakala, asfalt dengan getah cebis menunjukkan ketahanan keretakan yang lebih rendah kerana pendedahan terhadap penuaan dan kelembapan berbanding campuran konvensional dan campuran diubah suai plastik. Corak yang berbeza didapati untuk lengkung R yang menunjukkan kesan penambahan sisa plastik dan getah cebis ke dalam campuran asfalt. Lengkung R menunjukkan bahawa campuran getah menggunakan tenaga patah sebanyak 8% lebih rendah pada peringkat permulaan retakkan berbanding campuran asfalt kawalan dan diubah suai plastik. Tambahan lagi, analisis CMOD juga menunjukkan bahawa campuran asfalt diubah suai dengan getah menggalakkan perambatan retakan, manakala campuran asfalt yang diubah suai dengan sisa plastik menghalang retakan dengan melambatkan fasa permulaan retakan berbanding dengan asfalt kawalan. Analisis imej digital bagi campuran asfalt diubah suai menunjukkan lilitan retakan dan dimensi fraktal yang lebih tinggi masing-masing sebanyak 35% dan 48% berbanding asfalt kawalan. Ini boleh dikaitkan dengan peningkatan rintangan keretakan oleh campuran asfalt diubah suai. DIC dengan jelas menekankan kesan getah cebis dalam meningkatkan ubah bentuk plastik di sekitar hujung retakan, manakala zon retakan kecil dan kepadatan terikan yang tinggi dapat diperhatikan dalam peta terikan bagi campuran yang mengandungi sisa plastik. Tambahan pula, kaedah unsur terhingga lanjutan telah berjaya meramalkan kesan perubahan panjang takuk terhadap nilai beban puncak dan sesaran.

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LIST OF ABBREVIATIONS

AASHTO	-	American Association of State Highway and Transportation Officials
AC14	-	Asphaltic Concrete of Nominal Aggregate Size 14 mm
ACV	-	Aggregate Crushing Value
AIV	-	Aggregate Impact Value
APA	-	Asphalt Pavement Analyser
ASTM	-	American Society for Testing and Materials
BS EN	-	British Adoption of a European Standard
CSM	-	Creep Stiffness Modulus
CSS	-	Creep Strain Slope
CMOD		Crack Mouth Opening Displacement
CTOD		Crack Tip Opening Displacement
COV		Coefficient of Variation
DWT	-	Double Wheel Tracker
DCT		Disk-shaped Compact Tension Test
EI	-	Elongation Index
FI	-	Flakiness Index
FEM	-	Finite Element Method
Gmm	-	Maximum Specific Gravity
G_f	-	Fracture Energy
HMA	-	Hot Mix Asphalt
HWTT	-	Hamburg Wheel-Track Testing
IDT	-	Indirect Tensile
JKR	-	Jabatan Kerja Raya
Jc	-	Critical Strain Energy Rate
LEFM		Linear-Elastic Fracture Mechanics
LPFM		Elastic-Plastic Fracture Mechanics
LAAV	-	Los Angeles Abrasion Value
LTA	-	Long Term Ageing
LVDT	-	Linear Variable Differential Transducer

MQ	-	Marshall Quotient
M_R	-	Resilient Modulus
OAC	-	Optimum Asphalt Content
Pen.	-	Penetration
PG	-	Performance Grade
SCB		Semi-Circular Bending
SENB		Single Edge Notched Beam
SG	-	Specific Gravity
STA	-	Short-Term Ageing
TMD	-	Theoretical Maximum Density
VFA	-	Voids Filled with Asphalt
VTM	-	Void in Total Mix

LIST OF SYMBOLS

%	-	Percentage
cm	-	Centimetre
cm^{-1}	-	Reciprocal Wavelength
cm^2	-	Square Centimetre
cm^3	-	Cubic Centimetre
dmm	-	Decimillimetre
ε	-	Strain
g	-	Gram
hr	-	Hour
Hz	-	Hertz
kg	-	Kilogram
$KJ. Mol^{-1}$	-	Kilo Joule Per Mole
km	-	Kilometre
kPa	-	Kilo Pascal
L	-	Litre
mg	-	Milligram
mL	-	Millilitre
mm^2	-	Millimetre Square
$mmHg$	-	Millimetre of Mercury
MPa	-	Mega Pascal
N	-	Newton
nm	-	Nanometre
$^\circ C$	-	Celsius
sec	-	Second
θ	-	Angle
μ	-	Poisson Ratio
μm	-	Micrometre
σ	-	Stress

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

It is well known that cracking is the main factor contributing to asphalt pavement distortion, as the cracking developed in the pavement weakens the asphalt layer. The consequences of these cracks are water intrusion, rougher ride quality, higher fuel consumption, and traffic delays from rehabilitation efforts that cost users and agencies time, money, and resources [1]. Previously, researchers focused on improving the asphalt mix to resist the developed tensile stresses due to the thermal and traffic loadings [2]. In contrast, others focused on the quantification and the evaluation of the cracking resistance [3]. The correlation between the cracking resistance efficiency and empirical parameters is essential. It can be used to directly guide the pavement's design and construction to prevent severe cracking in asphalt concrete. Empirical research, however, is insufficient to comprehend the mechanisms behind the correlating factors. It is even more essential to know the main cause of the cracking due to the environmental factor, which always varies enormously.

In a more sophisticated phase of the research, studies have shifted to the fracture mechanics view to uncover the fundamentals of asphalt fatigue cracking. Recently, the fracture mechanic method and cracking-related index parameters used to quantify cracking resistance against fatigue have gained much attention among researchers. The fracture properties of asphalt mixture can be investigated experimentally by different fracture tests include monotonic fracture tests such as the Indirect Tensile (IDT) strength and the Semi-Circular Bending (SCB) test or conventional repeated fatigue tests such as the four-point bending beam test. The monotonic fracture tests can measure the toughness [4] or critical stress release rate as fracture resistance index [5]. Meanwhile, the repeated loading fatigue test method used either the energy dissipation ratio [6] or the number of cycles that a sample sustains before failure [7,8] as a fatigue resistance index. Furthermore, fatigue failure is an integrated system of three main phases: crack initiation, crack propagation, and failure stage. However, most of the studies focused on investigating one single phase [9–11]. Only limited studies explored the crack growth properties to understand the crack initiation and propagation using dynamic loading tests [12,13].

Nowadays, imaging technique plays an essential role in the analysis of material science. However, using imaging techniques as effective measuring devices is a difficult task. Though the tremendous ability of photographic techniques in advanced segmentation techniques for objects dividing and identifying (depending on their shape, pattern, and size), the accuracy of this technique is limited to the pixel level. Image and video recording with the aid of imaging software can be used as an effective evaluation device for the samples' displacement, surface changes, and deformation. Some efforts have been made to study the cracking performance of asphalt materials due to the previously highlighted issues. Scanning electron microscopy (SEM), X-ray scanning (CT), and Digital Image Correlation (DIC) techniques are currently the most commonly used [14–16]. The DIC can provide full real-time measurement of mechanical displacement and strain. This technique will allow for further investigation of the impact of the fatigue process on the structural integrity of the asphalt sample during the monotonic and dynamic load.

On the other hand, an increase in traffic loading reduces the asphalt pavement service life. As a result, this increases the pavement maintenance work, which implies the need for relevant materials to improve asphalt mixtures' performance. In recent years, several studies on the use of dry process-modified asphalt pavement by utilising crumb rubber have increased due to the desirable crack resistance properties and high content of modifiers used in the mixtures. Most current studies [17–20] are based on the conventional laboratory tests or field observations. However, these studies are unable to provide mechanistic interpretations to justify the high resistance of a crumb rubber-modified asphalt mixture against fatigue compared with conventional Hot Mix Asphalt (HMA) [21,22]. Moreover, previous studies have reported that plastic waste has also been used to construct more than 2500 km of roads that were found to function well without ravelling, potholes, and rutting [23,24]. Accordingly, due to the desired mechanical contribution of these polymeric wastes when added using the dry process, conventional laboratory testing faces specific challenges in characterising their fracture properties. Therefore, a laboratory testing procedure that can quantify and evaluate the crack resistance of these modified asphalt mixtures must be established. The imaging technique will complement the fracture analysis from different perspectives and better predict the cracking behaviour using the established procedures. This study aims to characterise the cracking resistance of HMA modified with crumb rubber and plastic under SCB by using the R-curve method and digital imaging techniques.

1.2 Problem Statement

Most distresses in asphalt pavements are directly related to fracture. Hence, identification and characterisation of the fracture properties of asphalt mixtures are critical steps towards a better pavement design. However, the current studies are based on empirical approaches and rely on conventional laboratory tests [18,25]. These laboratory tests either evaluate the relationship between initial tensile stress or strain to the number of loading cycles to failure or the rate of dissipated energy during repeated loading action to assess the fatigue cracking. Previous studies have used the concept of fracture mechanics to express fatigue. However, the researchers have not adopted appropriate evaluation methods in terms of sample geometry, time-consuming, and test set up that can be costly due to the required equipment [2,26]. Moreover, in most studies, the evaluation methods are based on linear elastic behaviour assumption, which can be valid for low-temperature cracking evaluation of asphalt mixtures. At intermediate temperature (25^{o}C), the viscous behaviour should be considered when evaluating the asphalt mixtures [27,28]. Nowadays, the fracture characteristics of asphalt mixtures are being evaluated in the laboratory using the disc-shaped compact tension, single-edge notch beam and semi-circular bending tests. The SCB test has garnered an increasing interest by the research community for investigating fracture properties of asphalt mixtures due to several aspects and advantages, including repeatability, consistency and ease of sample preparation and testing [29–32]. Enhancing the necessary parameters for fracture assessment has resulted in emerging an SCB monotonic standard test [33,34]. The crack resistance curve (R-curve) was also used to predict the necessary conditions for crack initiation and propagation [35]. The critical energy release rate (Jc), fracture toughness ($K_{c)}$, and fracture energy G_f were used as cracking resistance parameters. However, few studies used R-curve in characterising the performance of asphalt mixtures against crack initiation and propagation [5,35]. In contrast to quantitative single-point failure, it is believed that the fatigue life of asphalt mixtures is more applicable to be determined by a progressive damage phenomenon that is qualitatively assessed through the skeleton deterioration [2,36]. Therefore, the most suitable method for the fatigue life evaluation is the analysis method linked to its impact on the skeleton integrity and subsequent mechanical behaviour during the fatigue life. Moreover, using imaging techniques for monitoring fatigue life can provide important information about the impact of modifiers on the cracking process. Several parameters can be captured with assessing image analysis that includes; crack length, fractal dimension, crack density, crack tortuosity, and strain fields.

On the other hand, in recent years, the use of dry process modified asphalt pavement using crumb rubber and plastic waste has increased due to the desirable crack resistance properties and polymer waste recycling. The fatigue assessment of those materials is extremely challenging due to the complex viscoelastic nature and the heterogeneous binding composition of the produced asphalt mixture. Thus, laboratory testing poses certain challenges in characterising their fracture properties. Therefore, it is essential to establish a laboratory testing procedure that can be used to quantify and evaluate the crack resistance of these modified asphalt mixtures. Although few studies have been conducted to understand the fatigue cracking of crumb rubber and plastic waste modified asphalt [37,38], limited studies have quantified the crack initiation and propagation using static and repeated loading mechanisms combined with digital imaging techniques. This is significant for predicting and understanding the cracking behaviour from different perspectives.

1.3 Aim and Objectives

The research aims to characterise the cracking resistance of hot mix asphalt modified with crumb rubber and plastic. The objectives are as follows:

(a) To design the asphalt mixtures containing crumb rubber and plastic waste as modifiers using the dry process method.

(b) To characterise the resistance of modified asphalt mixture against cracking using semi-circular bending test for different loading modes, stress levels, ageing, and moisture conditions.

(c) To analyse the fracture properties of asphalt mixtures, including crack initiation and propagation using fracture parameters and digital image analysis technique.

(d) To model and simulate the fracture failure of modified asphalt mixtures using the extended finite element method.

1.4 Scope of the Study

The mixture design of dense-graded AC14 was prepared using granite aggregate, 60/70 PEN bitumen, and filler (hydrated lime). The optimum asphalt content was determined using the Marshall mix design method. Three different types of mixtures were evaluated in terms of fracture resistance, including, i.e., conventional asphalt, modified asphalt with crumb rubber, and modified asphalt with plastic waste. Both modified asphalts were prepared using the dry process method, where the modifiers were added at 1% by weight of the aggregate prior to mixing with the bitumen. Several factors were considered in the evaluation, including load level, moisture conditionings, and ageing condition. The characterisation of the cracks/fracture was combined with both digital imaging techniques (with imaging software-ImageJ and digital image correlation) and fracture mechanics analysis. The parameters involved in the measurements are fracture energy, strain energy release rate

(J-integral), cumulative energy resistance curve (R-curve), crack mouth opening displacement, crack tortuosity, fractal dimension, crack density, and strain field measurement. Results captured using the SCB and digital image analysis were correlated for further evaluation. Based on the data obtained from the mechanical testing and imaging techniques, the fracture failure of the tested samples was modelled and simulated using the Extended Finite Element Method (XFEM) with commercial finite element software ABAQUS software. The finite element model of the fracture provided a better view in terms of the loading condition and stress concentration within the loading region. All the laboratory tests were conducted at the Transportation Laboratory, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia.

1.5 Significance of Study

The correlation between cracking performance and the empirical parameters can be used to design asphalt mixtures with improved resistance to cracking. This is essential to provide a detailed understanding of the fundamental cause of cracking due to the environment that the asphalt concrete works in and the material itself. It is necessary to study the crack initiation and propagation stages during the fatigue life of asphalt mixtures in addition to the failure stage. Hence, such studies can provide information and mechanistic description of crack growth properties of the modified asphalt mixtures. Besides that, applying the R-Curve method on the rubberised asphalt and plastic waste modified asphalt mixtures can provide important knowledge on the crack resistance of these materials and the phenomenon associated with cracking behaviour over many material properties mixtures. In addition, image and video recording with the aid of imaging software can be an effective evaluation device for capturing the mechanical response of modifiers on the full field strain map of the sample during the fracture test. The XFEM model can effectively predict the fracture behaviour of the modified asphalt mixtures under different loading and fracture modes. Fracture characterisation and modelling help to identify the influence of modifiers on the fracture resistance of the produced asphalt mixtures, consequently guiding the asphalt pavement designer to control the durability and efficiency.

1.6 Thesis Outline

This thesis is composed of the following six chapters:

Chapter 1 provides a background to this research and descriptions of the problem statement, objectives, scope, and significance of the study.

Chapter 2 discusses previous research performed in the field of fracture mechanics and imaging techniques. The testing procedures, parameters, and related findings are comprehensively described in this chapter.

Chapter 3 details the research plan and the procedure, which encompasses the following three stages of work: materials preparation and properties evaluation, semi-circular bending test for assessing the fracture performance, and modelling of the semi-circular bending test.

Chapter 4 presents the performance of the conventional and modified asphalt mixtures, including the impact of crumb rubber and plastic waste on the fracture properties of asphalt mixtures.

Chapter 5 covers the conclusions and recommendations for future research.

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