MECHANICAL PROPERTIES OF RECLAIMED ASPHALT PAVEMENT MIXTURES WITH REJUVENATOR

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SCHOOL OF CIVIL ENGINEERING
UNIVERSITI SAINS MALAYSIA
2018

To my late father, my mother and the enlightenment of all sentient beings

MECHANICAL PROPERTIES OF RECLAIMED ASPHALT PAVEMENT MIXTURES WITH REJUVENATOR

By

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This dissertation is submitted to

UNIVERSITI SAINS MALAYSIA

As partial fulfilment of requirement for the degree of

BACHELOR OF ENGINEERING (HONS.)
(CIVIL ENGINEERING)

School of Civil Engineering,
Universiti Sains Malaysia

June 2018

UNIVERSITI SAINS MALAYSIA

SCHOOL OF CIVIL ENGINEERING
ACADEMIC SESSION 2017/2018

FINAL YEAR PROJECT EAA492/6
DISSERTATION ENDORSEMENT FORM

Title: MECHANICAL PROPERTIES OF RECLAIMED ASPHALT PAVEMENT MIXTURES WITH REJUVENATOR

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I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

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Date :

ACKNOWLEDGEMENT

Namo Amitabha. First of all, praise be to the Buddha and the Boddhisatva for Their wisdom and compassion in delivering me from avidyā, and guiding me towards enlightenment and knowledge.

I would like to express my heartfelt gratitude to my parents for my upbringing. Though difficult, they have toiled their entire life to keep a roof over my head and the food on the table. Their sacrifices and hardship will not be forgotten; I am eternally indebted to them for their unconditional love and kindness.

I would also like to convey my utmost respect and appreciation to my mentor and advisor, Professor Dr. Meor Othman Hamzah for his guidance, resources and encouragement. Without his trust, I may not be able to carry out my study independently, innovate and experiment with new ideas. Most importantly, under his guidance, I was taught the essence of research, and the value of diligence. May his legacy be commemorated, and his dedication to science and education remains an inspiration to all. Thank you Professor Meor and happy retirement.

Also, a special thanks to Dr. Lilian Gungat from Universiti Malaysia Sabah and Mr. Teh Sek Yee for sharing their research insight and resources with me. On top of that, I would like to acknowledge the technical staff, Mr. Fouzi Ali, Mr. Zulhairi Ariffin, Mr. Abdullah Md. Nanyan and the research assistant, Mr. Muhammad Samsul for their help.

Furthermore, my earnest thanks also go to my friends that have supported me along the way and were willing to part with their photographic equipment in the support of my study. A thousand credits to Louis Tan and Lee Sze Yee for making my study possible. Thanks for reminding me that asphalt is not the end of the world for the past six months. Last but not least, I would like to thank my country, university and sponsor (Public Service Department of Malaysia) that supported my undergraduate study.

ABSTRAK

Sejajar dengan peningkatan permintaan terhadap agregat dan bitumen baru, usaha penyelidikan telah beralih kepada teknologi turapan asfalt kitar semula (RAP) dalam pembinaan jalan berturap yang berasaskan kelestarian. Sebagai akibat daripada penggantian bahan asfalt baru dengan bahan kitar semula, campuran asfalt menjadi lebih terdedah kepada kegagalan retak. Justeru, bahan tambah pembalik muda digunakan untuk memulihkan prestasi campuran RAP. Objektif utama kajian ini adalah untuk menyiasat kesan bahan tambah pembalik muda terhadap sifat mekanikal campuran asfalt yang mengandungi 50% dan 70% bahan RAP dari segi kerentanan retakan dan ubah bentuk kekal. Kajian ini juga bertujuan untuk membandingkan prestasi campuran RAP dengan campuran asfalt baru yang mengandungi bahan tambah kalis pelucutan. Keseluruhannya, ujian konvensional seperti modulus kebingkasan, daya tegangan tidak langsung dan lenturan separuh bulatan bertakuk menunjukkan prestasi campuran RAP terpulih bersetanding dengan campuran asfalt baru, dan mengatasi campuran RAP biasa dalam konteks ketahanan retakan tegangan tulen dan retakan campuran tegangan-ricih serta ubah bentuk elastik. Pemodelan algoritma menunjukkan campuran RAP terpulih mengalami pelucutan awal berbanding campuran asfalt lain dalam ujian rayapan dinamik. Selain itu, kaedah inovasi seperti teknik pengimejan dwidimensi juga dilaksanakan untuk mengenalpasti kesan bahan tambah pembalik muda terhadap kekakuan campuran RAP dalam ujian-ujian retakan. Analisis pengimejan dijalankan dengan penggunaan perisian sistem maklumat geografi (GIS). Kajian analisis pengimejan dwidimensi membuktikan laluan retakan dan daya ketegangan campuran asfalt tertakluk kepada kekakuan lapisan mortar pada suhu ambien, tetapi lebih dipengaruhi oleh kekuatan agregat pada suhu rendah. Penggunaan bahan tambah pembalik muda didapati berkesan dalam mempengaruhi ciri permukaan retakan campuran RAP.

ABSTRACT

In view of the ever-escalating demand for virgin aggregates and bitumen, research efforts have now turned to reclaimed asphalt pavement (RAP) technology as the solution for sustainable bituminous road construction. However, substituting virgin materials with very high RAP contents would render the pavement vulnerable to cracking. Thus, rejuvenator is incorporated to recuperate the performance of RAP mixtures. The primary objective of this study is to investigate the effects of a rejuvenator on the mechanical properties of asphalt mixtures incorporating 50% and 70% RAP contents in terms of cracking and rut susceptibility. This study compares the performance of RAP mixture with virgin mixture imparted with a strong antistripping agent. Overall, conventional performance tests such as resilient modulus, indirect tensile strength and notched SCB tests indicated that the rejuvenated mixtures performed comparably with virgin mixtures, and outperformed non-rejuvenated RAP mixtures in the context of pure tensile and tensile-shear fracture toughness and elastic deformation. Through algorithmic modelling, it was also found that rejuvenated mixtures experienced relatively earlier stripping in comparison with virgin and non-rejuvenated RAP mixtures in the dynamic creep test. A new two-dimensional (2-D) imaging technique was innovated to better understand the effects of rejuvenator on the stiffness of RAP mixtures in various fracture tests. Image analysis was implemented with the use of geographic information system (GIS) software. From this study, 2-D imaging technique revealed that the fracture path and tensile strength of asphalt mixtures were governed by the stiffness of the mortar layer at intermediate temperature, but influenced by the strength of aggregates at low temperature. The effects of rejuvenator on the fracture surface characteristics of RAP mixtures were found to be significant.

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LIST OF ABBREVIATIONS

2-D	Two-dimensional
AASHTO	American Association of State Highway and Transportation Officials
ABR	Asphalt Binder Replacement
AC	Asphaltic Concrete
Adj. R^2	Adjusted Coefficient of Determination
ANOVA	Analysis of Variance
APA	Asphalt Pavement Analyser
ASTM	American Society for Testing and Materials
CIDB	Construction Industry Development Board
DBM	Dense Bituminous Mixture
DF	Degree of Freedom
DIC	Digital Image Correlations
DOSM	Department of Statistic Malaysia
EAPA	European Asphalt Pavement Association
ENVI	Environment for Visualizing Images
FEM	Finite Element Method
FHWA	Federal Highway Administration
GIS	Geographic Information System
HMA	Hot Mix Asphalt
HWTT	Hamburg Wheel Tracking Test
IL-SCB	Illinois Semi-circular Bending
ITS	Indirect Tensile Strength
LAS	Liquid Anti-strip
LC_{SN}	Stripping Number

LC_{ST}	Stripping Life
LTPP	Long Term Pavement Performance
NSE	North-South Expressway
OPC	Ordinary Portland Cement
PG	Penetration Grade
PMD	Pavement Modifier
PWD	Public Works Department
R^2	Coefficient of Determination
RAP	Reclaimed Asphalt Pavement
RAS	Reclaimed Asphalt Shingles
ROI	Region of Interest
SARA	Saturate, Aromatic, Resin and Asphaltene
SCB	Semi-circular Bending
SENB	Single-edge Notched Bending
SMA	Stone Mastic Asphalt
SS	Sum of Squares
TSR	Tensile Strength Ratio
USM	Universiti Sains Malaysia
UTM	Universal Testing Machine
WMA	Warm Mix Asphalt

CHAPTER ONE

INTRODUCTION

1.1 Background

Bitumen, an inextricable component of flexible pavement, is a derivative of crude oil. As one of the most highly prized natural resources, oil price movement becomes increasingly volatile coinciding with its imminent depletion, and fluctuates under the influences of global events (King et. al., 2012). Table 1.1 illustrates the collateral effects of rising oil price. Following the dearth of crude oil reserve in 2027 (Rahim and Liwan, 2012) and coupled with ever burgeoning motorised society (Abdelfatah et. al., 2015), Malaysia will find itself at the cusp of a new era; one that values reusability and necessitates sustainable pavement technology - reclaimed asphalt pavement (RAP).

Table 1.1: Average Bitumen, Crude Oil and AC14 Premix Prices in Malaysia

Year	Source	2008	2009	2010	2011	2012
Bitumen (RM/m^3)	CIDB, 2012	1616.67	1525.00	1729.16	1900.50	2195.00
Crude Oil (USD/barrel)	Statista, 2017	94.10	60.86	77.38	107.46	109.45
AC14 (RM/tonne)	DOSM, 2014	166.80	162.60	166.90	185.90	203.00

In conjunction with the impending depletion of crude oil reserves globally, the United States has leapfrogged the utilisation of RAP technology with resounding success. The nationwide survey indicates that more than 99% of reclaimed asphalt pavement material found itself back to productive use, predominantly as new asphalt pavement mixtures (Hansen and Copeland, 2017). The implication is applaudable as the application of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) alone has amounted to more than USD 2.1 billion cost savings in comparison with the use of virgin materials (Hansen and Copeland, 2017). In fact, European countries such as the Netherlands and Denmark have distinguished themselves with technological hegemony in RAP utilisation by achieving 100 percent RAP materials usage (Holtz and Eighmy, 2000). Evidently, the material is the principal cost category of pavement construction as shown in Figure 1.1. Hence, RAP technology might emerge as the turnkey solution for cost optimisation. Nevertheless, RAP technology in Malaysian pavement industry remains relatively unscathed and inert despite its mature establishment worldwide.

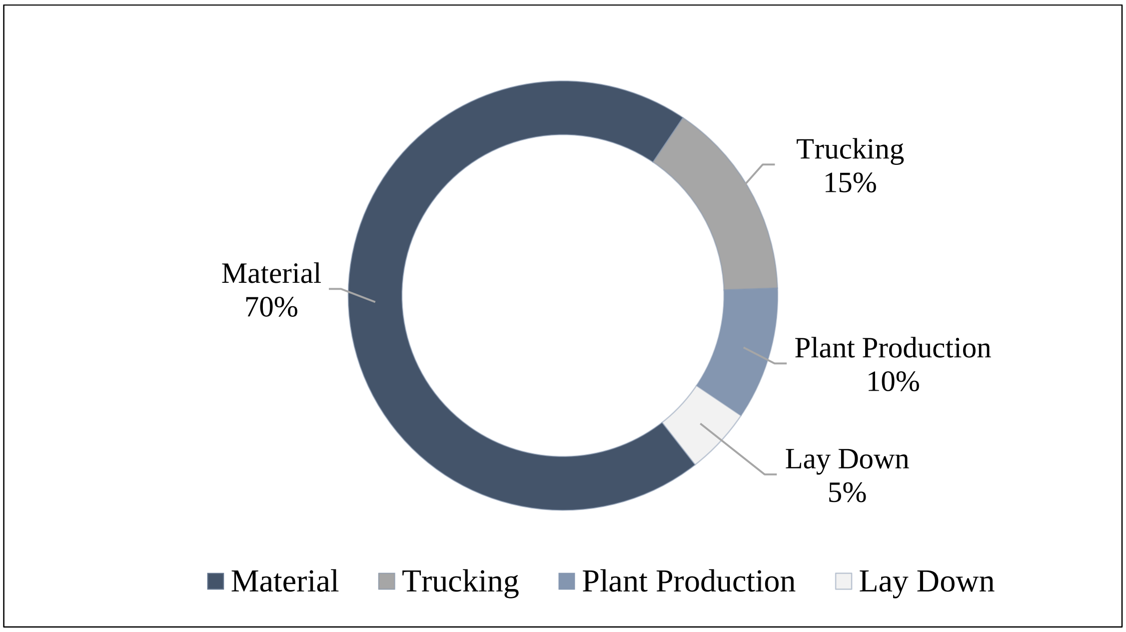


Figure 1.1: Estimated Asphalt Production Cost Categories (Copeland, 2011)

General key benefits of reclaimed asphalt pavement with high recycled content are (Copeland, 2011):

- energy conservation;
- economic savings;
- reduction of transportation cost with respect to procuring quality virgin aggregate;
- preservation of resources;
- providing environmentally sound solution.

Reclaimed asphalt pavement outweighs its drawbacks in strenuous design and production process in terms of cost savings when high recycled content is present (Izaks et al., 2015). RAP Expert Task Group from the Federal of Highway Administration (FHWA) defines ‘high RAP mixtures’ as those containing 25% or more RAP in an asphalt mixture by weight of the total mix (West et al., 2009). Low RAP content ranging from 10% to 25% has been comfortably adopted in the pavement industry (Zaumanis et al., 2014) and Long-Term Pavement Performance Program (LTPP) confirmed that pavement performance with RAP content up to 30% is similar with pavement constructed without RAP content (Copeland, 2011). Hence, the key interest of this research will solely pivot on the performance prospect of asphalt mixture using high RAP contents of 50% and 70%.

Research on 50% and 70% RAP contents is pragmatic as the ceiling content of RAP found in conventional drum plant only amounts to 70% (Kandhal and Mallick, 1997). As of now, researches on the performance of asphalt mixture containing RAP content up to 100% has been established widely with the aid of modern technologies and advancement of knowledge in mix design (Zaumanis et al., 2016). Currently, Germany and the United States are at the forefront of RAP technology with bituminous application incorporating RAP contents up to 87% and 94%, respectively (European Asphalt Pavement Association, 2018). The Malaysian Public Works Department (PWD) on the other hand, does not specify explicitly the allowable upper limit of RAP content in pavement construction (PWD, 2008).

Furthermore, according to Gibson (2011), utilisation of RAP will amount to 14% reduction in embodied carbon content with respect to conventional hot mix asphalt (HMA). Comparatively, Re-Road project inaugurated by the European Commission concluded that even at a low recycling rate of 15%, the recycling benefits of RAP application outweighs those that achieved by warm mix asphalt, from 165 ºC to 130 ºC (Waymen et al., 2012). Through life cycle assessment, relative impacts of recycling and warm mixing can be identified as portrayed in Figure 1.2. Undoubtedly, RAP remains as one of the dormant technologies with promising sustainable attributes in Malaysia, waiting to be explored and capitalised for green development.

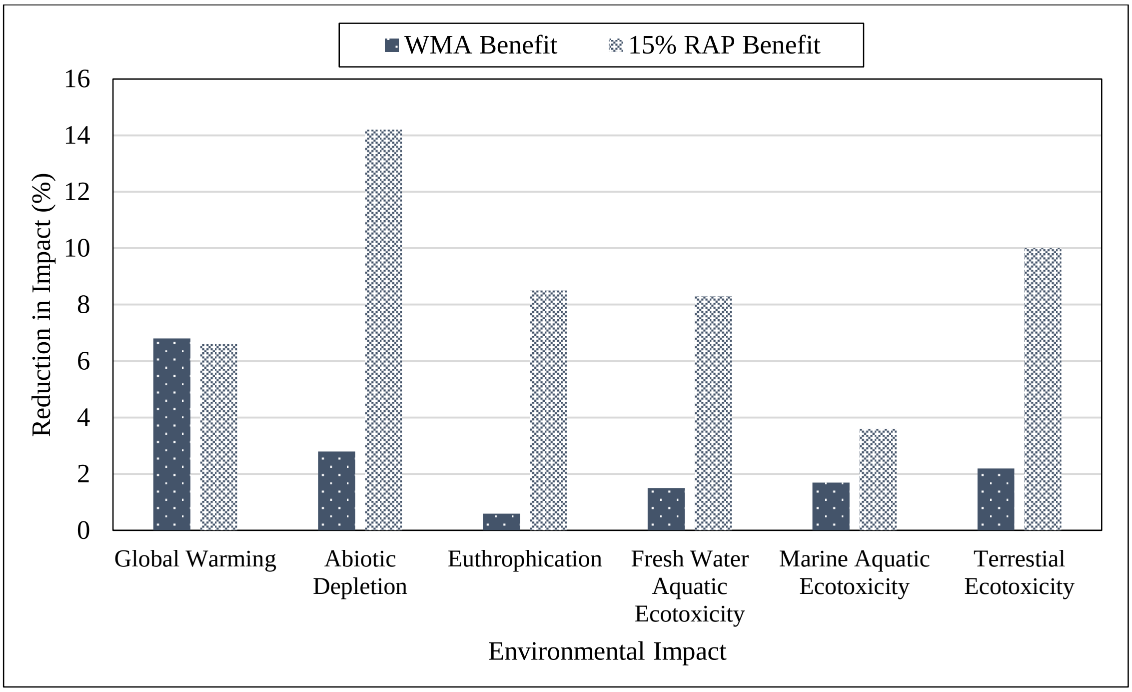


Figure 1.2: Relative Impacts of Recycling and Warm Mixing in Bound Layers of Flexible Pavement (Waymen et al., 2012)

In short, RAP technology is pivotal in the strive for sustainable development. It is sufficed to claim that the extent of the research in terms of RAP content is equitable and promising for the future prospect of the Malaysian pavement industry.

1.2 Problem Statement

Albeit RAP technology offers an array of pull factors for the pavement industry players that strive for financially and environmentally sound approach, applying a substantial amount of RAP content in road construction is not without its drawbacks. The

Federal of Highway Administration (FHWA) has successfully identified typical challenges in implementing pavement construction with high RAP content via LTPP. General key challenges of implementing reclaimed asphalt pavement with high recycled content are the (Copeland, 2011)

- consistency of RAP;
- mix design procedures;
- volumetric requirement;
- durability and cracking performance due to high stiffness;
- quality concerns;
- limitation of plant.

Corresponding with key challenges identified by Copeland (2011), other studies conducted on conventional asphalt mixture with high reclaimed content exhibit the following limitations (Newcomb et al., 2007; Howard et al., 2009; Copeland, 2011):

- pavement cracking failures engendered by properties of aged binder in reclaimed asphalt;
- degree of homogeneous bitumen blending and sufficient diffusion taking place between the virgin and RAP binder;
- aggregate properties of the RAP in terms of quality and fines content.

To address the stated drawbacks of high RAP content in asphalt mixture, studies and reviews by Bonaquist (2007), Zaumanis and Mallick (2015), Karlsson and Isacsson (2006) and Al-Qadi et al. (2007) opine that the following approaches are feasible:

- raising of mixing and compaction temperature;
- using warm mix additive, foamed bitumen;
- applying softer bitumen;
- adding softening agents or rejuvenators.

In the pursuit of a sustainable solution, raising of mixing and compaction temperature has been ruled out from this research. Addition of recycling agents or rejuvenators will be the prime highlight of this investigation. Instead of warm mix additive, a Dutch technology - Prephalt FBK rejuvenator is selected as one of the key ingredients in enhancing asphalt mixture performance with high RAP content. Prephalt FBK rejuvenator offers an edge in enhancing workability and to lower temperature necessary to facilitate homogeneous blending between virgin and aged binders. With the aid of Prephalt FBK rejuvenator, high recycling rate can be materialised in tandem with even higher recycling benefits in comparison with warm mix asphalt.

Nevertheless, rejuvenating agents are devised with distinctly formulated content and their dosages will yield indefinite ramifications on the asphalt mixture performance (Zaumanis et al., 2013). Zaumanis et al. (2013) have concluded the effects of various rejuvenators on the penetration grade of binders as demonstrated in Figure 1.3.

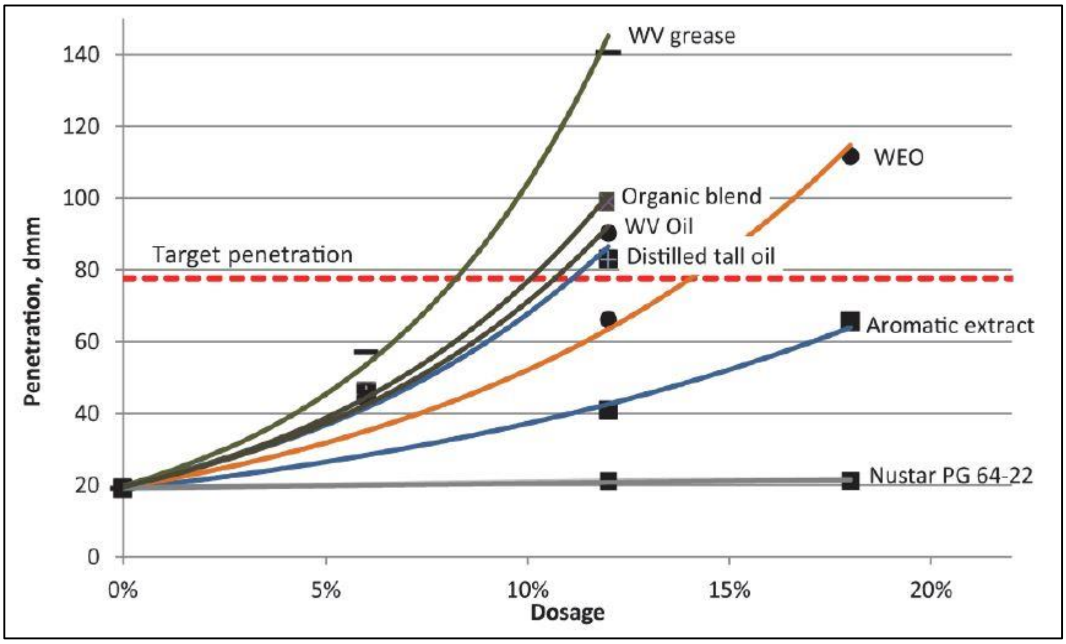


Figure 1.3: Softening Effects of Various Rejuvenators on Binder at 25ºC (Zaumanis et al., 2013)

Research and knowledge vis-à-vis the effects of Prephalt FBK on asphalt mixture performance are scarce as local research effort still remains at infancy. Without the establishment of performance yardstick for the selected rejuvenator, its wide acceptance as the solution for high RAP usage in Malaysia will nevertheless remain as a moot. Thus, various asphalt mixture performance tests to evaluate the cracking and rut performance of rejuvenated asphalt mixture containing high RAP content with Prephalt FBK are deemed imperative.

1.3 Objectives

It is tacitly known that the basis for the invention of rejuvenator is to soften aged binder. Considering the advent of problems stated in Section 1.2, rejuvenator's effectiveness in ameliorating the crack performance of bituminous mixture is crucial, but the unbridled nature of rejuvenators may result in aberrant performances and vagaries. Its effectiveness in doing so will dictate whether the asphalt mixtures will have the higher propensity to undergo rut failure or fatigue cracking. Hence, the objectives of this research are:

1. To investigate the effects of Prephalt FBK rejuvenator on the high temperature rut resistance, and fracture characteristics of asphalt mixtures with high reclaimed asphalt pavement content from low to intermediate service temperatures.
2. To evaluate the performance of typical and rejuvenated asphalt mixtures incorporating various high reclaimed asphalt pavement contents compared to equivalent conventional hot mix asphalt mixture imparted with antistripping agent.

1.4 Significance of the Research

To produce credible outcomes, test parameters reflecting the realities and environmental elements of the localities are designated. These include the use of local materials that conform to local standards, namely RAP aggregates, asphalt binder, virgin aggregates, and aggregate gradation. The efforts invested in this research endeavour will unfold new knowledge and insight regarding the suitability of the rejuvenator in the local context to solve the aforementioned problems. The outcomes will then be benchmarked with performance characteristics of virgin mixtures. Collectively, these findings will enable policy and decision makers from both corporate and public institutions to opt for more sustainable alternatives when it comes to bituminous road construction.

An approach that conjoins conventional and novel tests on asphalt mixture with high RAP contents will be adopted to investigate the effects of rejuvenator. Performing conventional tests like indirect tensile strength test (ITS), resilient modulus test, semi-circular bending fracture test (SCB) and dynamic creep test, for example, will yield persuasive results for local pavement industry and government agencies. Exercising novel method such as imaging techniques on the other hand, will open up a new scientific front in analysing the effects of rejuvenators on the engineering properties of RAP mixtures. It will be a leap forward for RAP technology in terms of scientific contributions.

In layman's term, this research is an initiative to revitalise the Malaysian sustainable pavement industry via extensive utilisation of RAP. More importantly, it can be actualised with minimal interferences to the existing plant operations. Propelling sustainable development from stagnation requires unequivocal research evidence. Evidence, that will exemplify that RAP with rejuvenator can indeed utilise resources efficiently in meeting its engineering functionality, as well as to preserve the ecosystem in a cost-effective manner.

1.5 Scope of Study

The ambit of the research solely encompasses the study on the effects of the Dutch commercial grade rejuvenator – Prephalt FBK on the engineering properties of asphalt mixtures incorporating high RAP contents. The aggregate sources can be demarcated into two groups, namely crushed virgin granites native to the local quarry and RAP aggregates scarified from PLUS North-South Expressway. Aggregate gradation was apportioned in accordance with Asphaltic Concrete 14 (AC14) specification of the Malaysian Public Works Department (PWD) (PWD, 2008).

Hewing to their respective designated compositions, the mixture specimens fabricated can be delineated into five groups. They were specimens with 50% and 70% RAP contents infused with rejuvenator, 50% and 70% RAP contents without rejuvenator, and conventional AC14 hot mix asphalt (HMA). These mixtures were imparted with grade 80/100 asphalt binder and pavement modifier (PMD) fillers. All specimens fabricated adhered to PWD specifications. The specimens were compacted to approximately 4% percent air voids with Superpave gyratory compactor to simulate the final densification of in place asphalt pavement engendered by trafficking. Thus, the fabricated samples were intended to reflect the ideal infield performance under final consolidated state.

Conventional methods with recognised theoretical foundations from either American Society for Testing and Materials (ASTM) or American Association of State Highway and Transportation Officials (AASHTO) were performed to initiate the pioneer study. In order to magnify the distinction of the mixture performance, temperature was manipulated as the salient conditioning variable in this study. These tests were indirect tensile strength test (ITS), resilient modulus test, notched semi-circular fracture test (SCB) and dynamic creep test. Novel analysis method involving two-dimensional (2-D) imaging technique was also applied to inspect the fracture surfaces and crack paths of both SCB and ITS specimens. The details with regard to these tests will be further described in Chapter 3.

1.6 Dissertation Outline

1. Chapter One narrates the potential of RAP technology in alleviating imminent exhaustion of abiotic resources and highlights the problem statement, objectives, significance of the research, and scope of study.
2. Chapter Two outlines the cruces of recent findings unveiled by other researchers on asphalt technology and RAP in terms of binder behaviours, mixture performance, evaluation methods, mixing techniques, the effects of rejuvenator, and modelling approach.
3. Chapter Three characterises the materials, mixture fabrications, experimental methods and analytic procedures applied in this study.
4. Chapter Four deliberates the results and analytical outputs of the study on the effects of rejuvenator on asphalt mixtures with different RAP contents in terms of mechanical properties and performance.
5. Chapter Five concludes the findings, established facts and possible deductions emanated from this research in a summarised manner, and introduces pragmatic prospects for subsequent research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Chapter two articulates the established facts, reviews and reasoning that justify the basis for this research. Literature with regard to the performance of RAP mixtures, the effects of rejuvenators and performance evaluation methods will be highlighted. A short summary of the reviews is included at the end of each subchapter.

2.2 Rejuvenator and Mixture Performance

2.2.1 Rejuvenator

Embrittlement of asphalt binder is one of the prevalent failure causes for flexible pavement. Hardening and oxidation are inevitable for all asphalt pavement. As such, the concept of rejuvenation was conceived. It is devised as a means to instil asphalt materials with inherent ability to fully restore or partially reverse the ageing damage that might have taken place during its service life (Barrasa et al., 2015). Its primary objective is to resurrect asphalt pavement properties and preserve pavement longevity (Boyer, 2000).

However, a rejuvenating agent is often mistaken for a softening agent. Table 2.1 distinguishes the general differences between rejuvenating agent and softening agent. Nonetheless, Pradyumna et al. (2013) regarded recycling agent, rejuvenating agent and softening agent can be termed interchangeably. The terminology as defined in Table 2.1 is adopted for this dissertation. The focus of the study is emphasized solely on the effects of the rejuvenating agent, where the properties of the aged binder are recuperated chemically.

Table 2.1: Definition of Recycling agent, Rejuvenating Agent and Softening Agent (DeDene and You, 2014; Tran et al., 2012; Chen et al., 2007; Shen et al., 2007)

Type of Agent	Description
Recycling	Recycling agent is an additive that restores the rheological behaviour of binder. It can either be rejuvenating agent or softening agent that is typically derived from petroleum product.
Rejuvenating	Usually comprised of maltenes, rejuvenator restores the physical and chemical properties of aged binder by balancing the proportion of saturates, asphaltenes, resins and aromatics (SARA). Their function is to keep asphaltenes dispersed and lowers the rigidity.
Softening	Softening agent can lower the overall viscosity of oxidised binder For example, asphalt flux oil, lube stock and slurry oil are asphalt softeners.

2.2.2 Prephalt FBK

Stiffness and flexibility of the binder are dictated by the amount of polarised asphaltenes. Through SARA analysis, the composition of binder can be characterised (Rad, 2013). As exhibited in Figure 2.1, asphaltene percentage increases as ageing takes place.

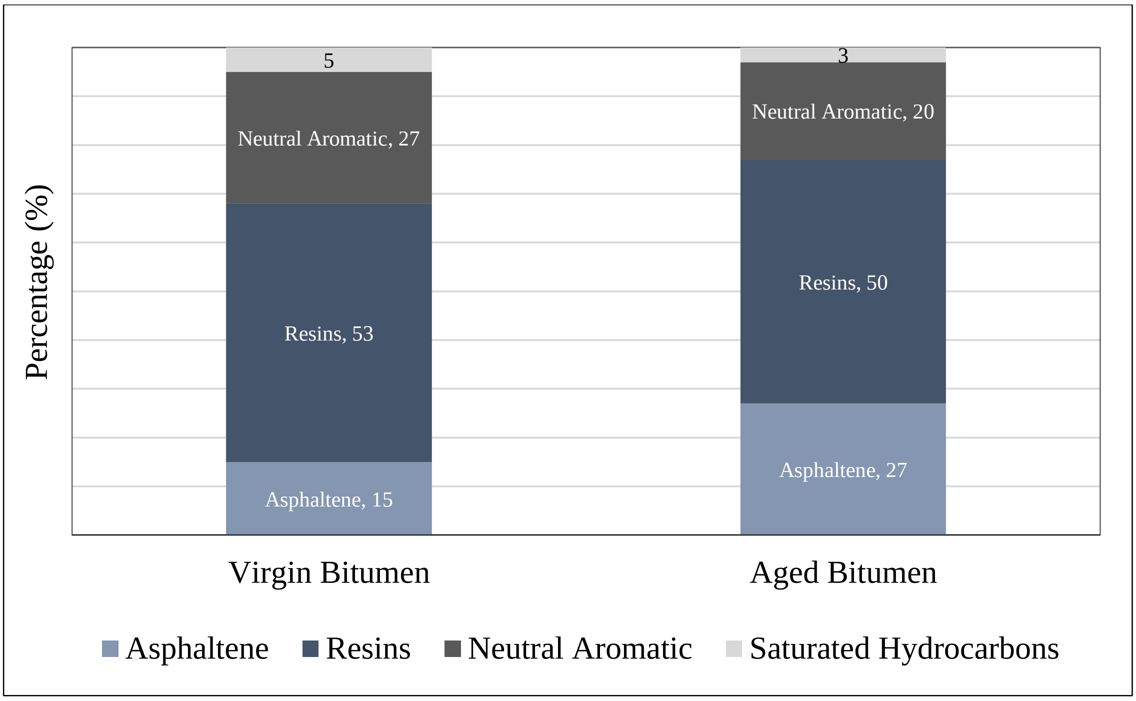
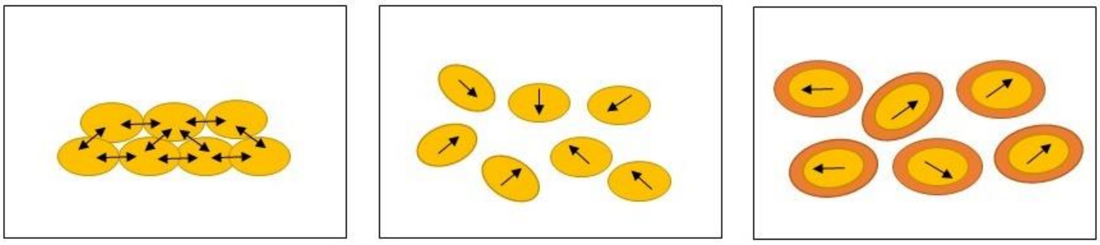


Figure 2.1: Compositions of Virgin and Aged Bitumen (Van Weezenbeek Specialties, 2017)

By imposing steric hindrance, a dosage of rejuvenator made up of resins will neutralise polarised asphaltenes and restore the original chemical composition of bitumen. Figure 2.2 illustrates the schematic sketch of the mechanism.

Figure 2.2(a) represents the cold and rigid state of aged asphalt (RAP), where asphaltenes are highly polarised and strongly bonded. Upon softening under high temperature, these bonds are disrupted as shown in Figure 2.2(b). Resins (Prephalt FBK) will then be injected to neutralise polar effects of the asphaltene by imposing steric hindrance. As portrayed in Figure 2.2(c), steric hindrance impedes the formation of polar bonds among asphaltenes and thus, the flexibility of the bitumen can be restored and preserved.



(a) Aged Binder (b) Disrupted Bond (c) Steric Hindrance

Figure 2.2: Chemical Effects of Prephalt FBK Rejuvenator on Aged Binder (Van Weezenbeek Specialties, 2017)

2.2.3 Mixture Performance of Rejuvenated Asphalt Mixture

The effects of rejuvenating agent on asphalt mixture performance will be the sole focal point of this literature review in conjunction with the objective of the research. From the review, it is evident that the rejuvenator exhibited softening effects on the virgin binder and mitigated the increase in air voids aside from reducing the stiffness (Mogawer et al., 2013). Mixtures incorporating 40% to 70% RAP were found to have significantly increased stiffness without fatigue resistance loss, unless at low temperature (Patiño et al., 2017). However, workability, fatigue resistance and ductility at low temperatures can be partially recovered with the use of rejuvenator (Patiño et al., 2017). Similarly, Silva et al. (2013), Oliveira et al. (2013) and Turner et al. (2015) found that rejuvenating additive enhanced crack resistance and workability. Furthermore, Tran et al. (2017) concluded that 50% RAP with rejuvenator has better intermediate-temperature cracking resistance than the 50% RAP mixture without rejuvenator. 50% RAP mixture with rejuvenator was ranked stiffer than control mixture but softer than 50% RAP mixture without rejuvenator at low temperature. (Tran et al., 2017). Moreover, effective blending for high RAP content mixes could be accomplished with recycling agent and hence, improved both rut and fatigue properties (Yu et al., 2017).

As a whole, researchers came to a consensus that rejuvenator is able to reduce the stiffness, increase the workability and improve the fracture resistance of the asphalt mixture with various high RAP contents. Some studies indicated that the effects of rejuvenator or bumped down binder on rut performance were not detrimental but evaluation of rut performance is still deemed necessary (Tran et al., 2012; Mogawer et al., 2013)

2.3 Asphalt Mixing Technique

Extensive investigations with regard to the optimisation of RAP asphalt mixing procedures were carried out to refine and standardise existing mixing techniques. In general, optimisation of mixing procedures has hitherto been made in terms of mixing sequence, duration, technique and temperature.

Theoretically, an effective RAP-virgin mixing technique is surmised to be able to curtail unsatisfactory blending and enable full activation of RAP materials. Otherwise, the products of intractable mixing processes will functionally behave as ‘composite black rock’ as shown in Figure 2.3 (Huang et al., 2005). Huang’s theory was later reinforced by Yu et al. (2017), where mixture with very high RAP content was accounted for low interaction between virgin and aged binders.

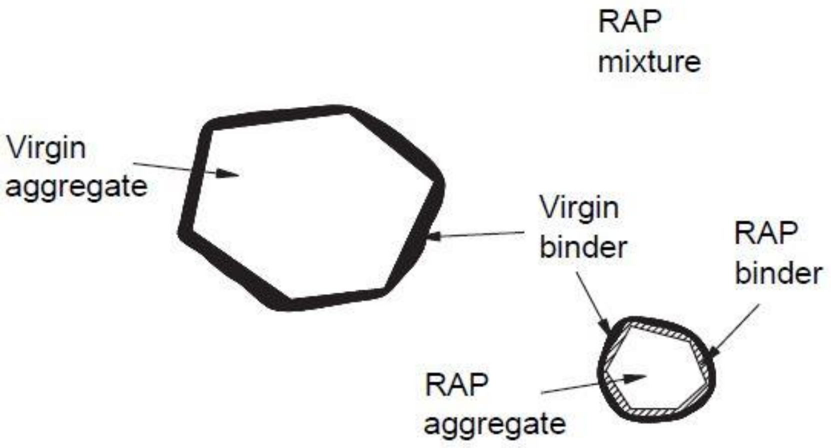


Figure 2.3: Illustration of ‘Black Rock’ RAP-virgin Mixtures (Huang et al., 2005)

Usually, the eclectic variety of procedures were engineered to simulate the processes practised in conventional plant operation. Optimum mixing time and temperature exercised by Huang et al. (2005) were 3 minutes and 190°C, respectively, but it was stated that the adopted values were well above conventional plant practices.

Back then, over-ageing of RAP aggregates and virgin bitumen due to high mixing temperature was not taken into account. Later on, concerns on further ageing under high temperature exceeding the range of 115 – 135°C were outlined by both Mallick et al. (2008) and Shao et al. (2017).

To enhance RAP mixture consistency, Shao et al. (2017) devised the novel double-drum mixing technique for mixing asphalt incorporating high RAP content and rejuvenator. The mixtures produced by novel technique were collated with those of conventional technique. Schematic setups for conventional and novel techniques reviewed in the comparative study are portrayed in Figures 2.4 and 2.5.

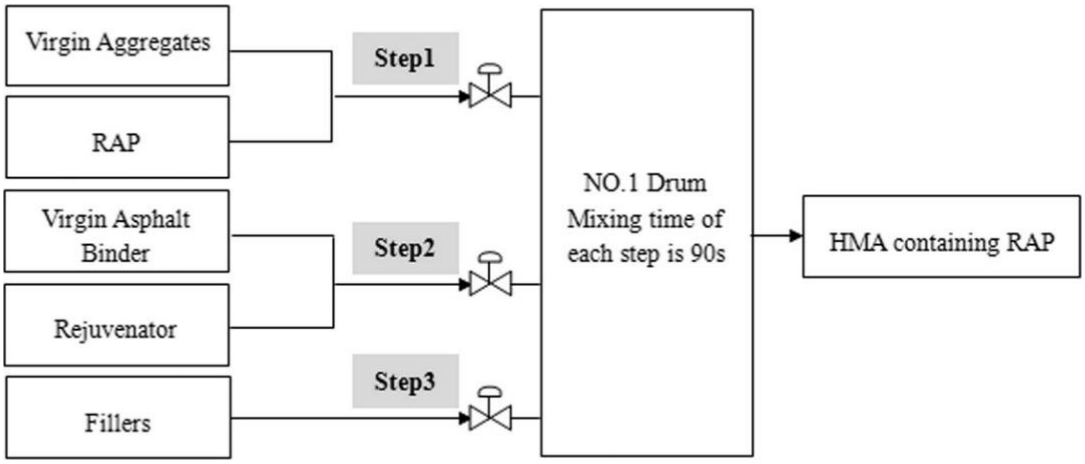


Figure 2.4: Schematic Setup of Conventional Mixing Process (Shao et al., 2017)

Preheating temperature highlighted in conventional mixing process for virgin aggregates was 180°C, while the recommended preheating temperature for RAP aggregates was below 110°C to mitigate over-ageing. The total accumulated mixing time was 270 seconds. Such practice was undesirable as extended mixing time would further oxidise both aged and virgin binders. According to the authors, the rejuvenator was underutilised and not predominantly consumed by RAP aggregates, but shared with virgin materials.

With reference to Figure 2.5, RAP-rejuvenator and virgin materials were blended simultaneously in a separate environment for 90 seconds in Step 1. The RAP-rejuvenator and virgin mixes were then further mixed in a common mixer in Step 2 for another 90 seconds while the fillers were fed concurrently. Blending condition with optimal 3-minute total mixing duration was met. As a result, the mechanical performance of these mixtures was encouraging. Noticeable improvements were observed in indirect tensile strength, loose mix coating, rut resistance, low-temperature failure strain and dynamic stability.

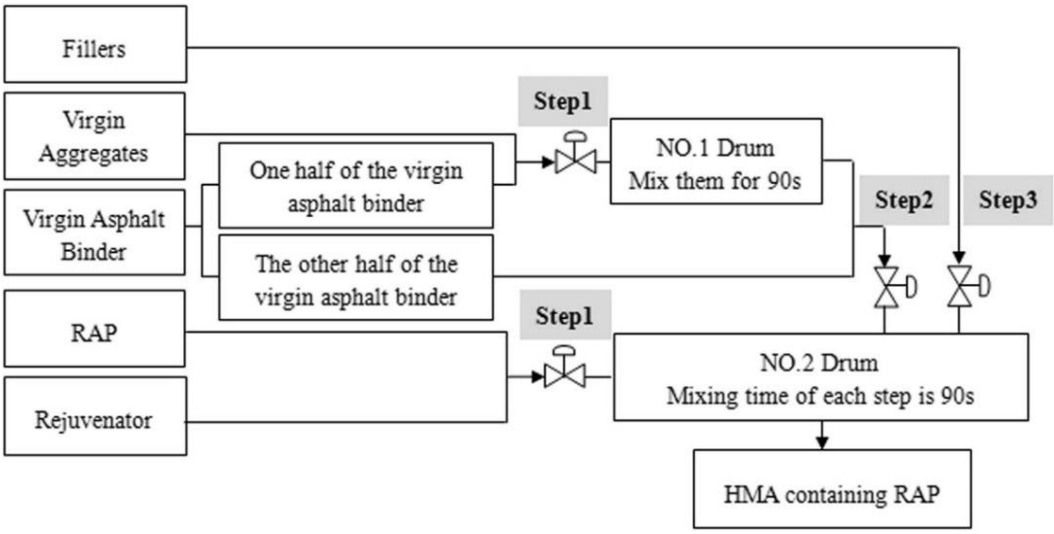


Figure 2.5: Schematic Setup of Novel Double-drum Mixing Process (Shao et al., 2017)

To summarise, the strengths of each mixing technique should be capitalised with minimal changes to existing setup or plant mixing conditions. Though the blending conditions endorsed by Shao et al. (2017) were highly advantageous, it would require the laboratory or conventional mixing plant to be retrofitted with a dual drum mixer. This poses a financial drawback for RAP technology practitioners in Malaysia. Hence, two-stage mixing approach by Gungat (2017) was integrated with the best practices developed by other researchers. The schematic setup and details of the process adopted are elaborated in Section 3.3.2.

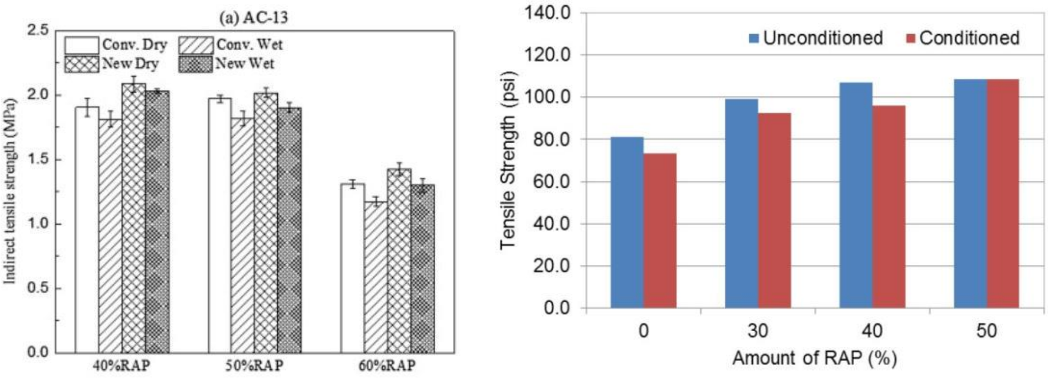
2.4 Fracture Potential and Crack Propagation

The fracture characteristics of asphalt mixtures are both time and temperature dependent (Al-Qadi et al., 2015). Indicators for crack potential are customarily measured in terms of fracture toughness or tensile strength, where the specimens are subjected to various loading rates and test temperatures.

2.4.1 Indirect Tensile Strength

The indirect tensile strength test is a standard test favoured by many transport agencies globally. Despite its shortcomings, it is valued for its simple setup and consistency in quantifying the relative quality of asphalt mixtures in terms of rut and crack potentials.

As a whole, researchers are in accord on the trend of tensile strength performance of RAP mixtures. Al-Qadi et al. (2012), West et al. (2013), Shao et al. (2017), and Gungat (2017) found RAP mixtures would normally result in equal or higher tensile strength than conventional HMA mixtures. Higher stiffness of RAP mixtures was credited as the rationale behind the enhancement of tensile strength performance. However, tensile strengths may not necessarily increase along with the increase of RAP contents. As depicted in Figure 2.6, the tensile strength increment appears to have an upper limit. Exceeding certain RAP content, the tensile strength of the RAP mixtures may even experience a slight decline or remain constant (Al-Qadi et al., 2012; West et al., 2013; Putman and Xiao, 2012; Shao et al., 2017). Such phenomena were claimed to be influenced by binder grades, RAP qualities, aggregate sources and test temperatures as demonstrated in Figure 2.7. (Putman and Xiao, 2012; West et al., 2013; Khan, 2016).



(a) Shao et al. (2017) (b) Al-Qadi et al. (2012)

Figure 2.6: Effects of RAP Contents and Conditioning on Tensile Strength of RAP Mixtures (Shao et al., 2017; Al-Qadi et al., 2012)

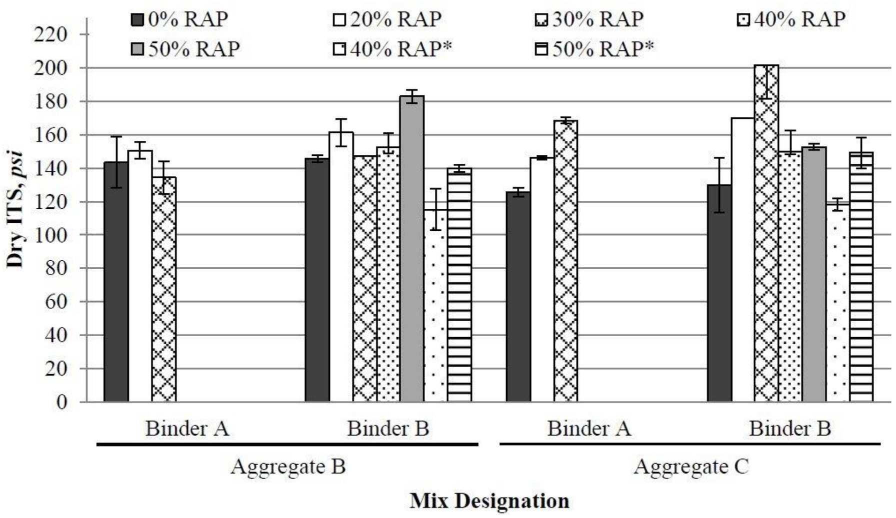


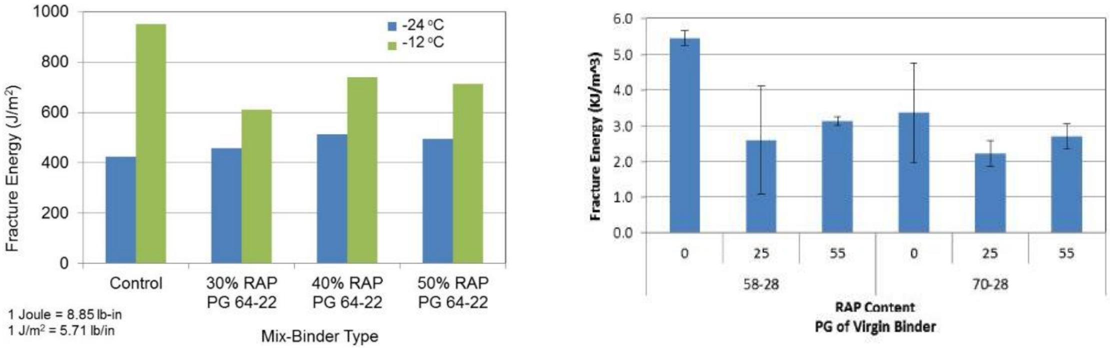
Figure 2.7: Effects of Binder Types, Aggregates Sources and RAP Contents on the Indirect Tensile Strength of Asphalt Mixture (Putman and Xiao, 2012)

The most commonly highlighted drawbacks were the effects of rut imposed by the loading strip, and the occurrences of mixed-mode fracture (instead of pure tensile fracture) (Arabani and Ferdowsi, 2008). At high temperature, loss of structural capacity may attribute to premature bulk failure and hence, affecting the accuracy of measurement (Khan, 2016).

To conclude, a good agreement was met among the researchers regarding the trend of tensile strengths in relation to RAP contents. Nevertheless, ITS test is a common method to measure the tensile strength of asphalt mixture but it is not without its flaws.

2.4.2 Fracture Energy and Toughness

Alternatively, fracture potential of asphalt mixtures can be quantified in terms of fracture energy via load-displacement graphs of ITS and SCB tests. Researchers found common ground on the trend of fracture energy for RAP mixtures. Altogether, incorporation of RAP into asphalt mix will usually result in stiffer mixture. Stiffer asphalt mixture tends to be brittle and has relatively lower fracture energy as depicted in Figure 2.8 (Al-Qadi et al., 2012; West et al., 2013; Braham, 2008; Tran et al., 2012).

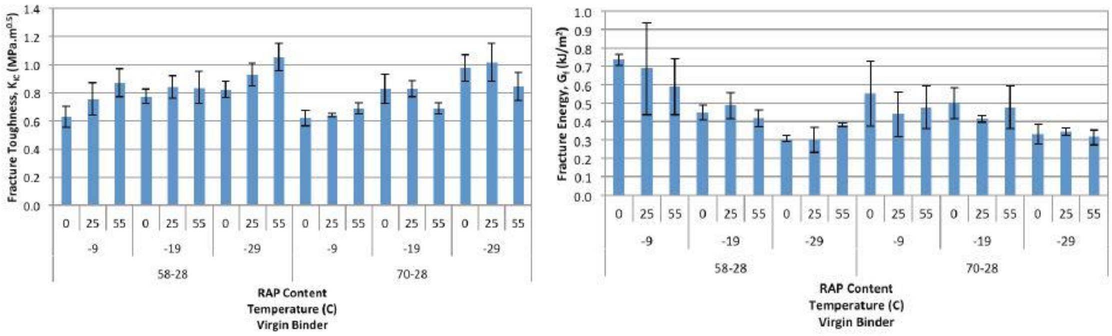


(a) Al-Qadi et al. (2012)

(b) West et al. (2013)

Figure 2.8: Effects of RAP Contents on Fracture Energy (Al-Qadi et al., 2012; West et al., 2013)

In any case, fracture toughness measured in Pascal tends to exhibit an inverse trend in comparison with computed fracture energy. As documented in New Hampshire mixture fracture test, high fracture toughness resulted in low fracture energy. The trends are showcased in Figure 2.9.

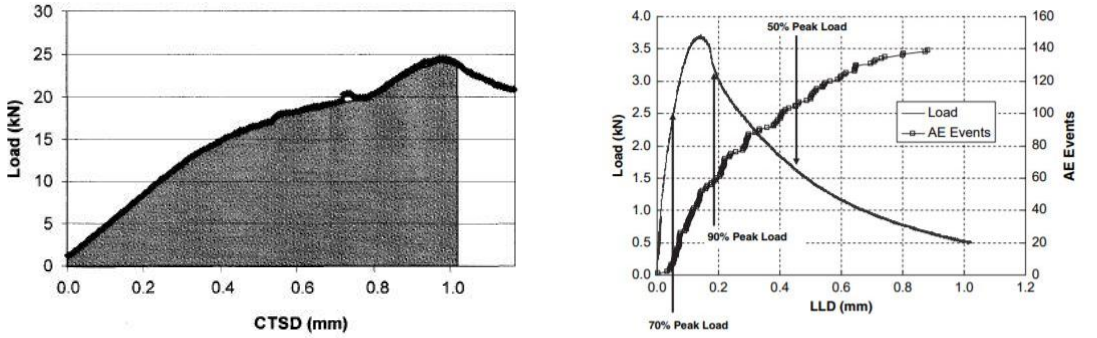


(a) Fracture Toughness (MPa)

(b) Fracture Energy (kJ/m^2)

Figure 2.9: Comparison of Fracture Toughness and Fracture Energy for RAP Mixtures (West et al., 2013)

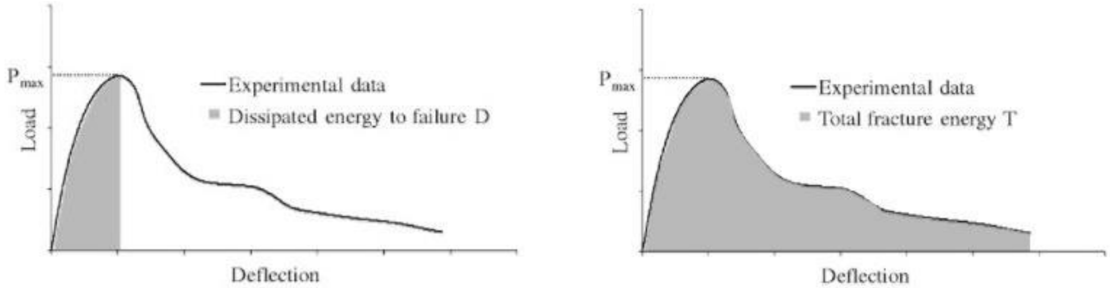
Nevertheless, methods to quantify crack potential with respect to toughness or fracture energy have long been debated. Existing standard such as BS EN 12697-44:2010 (BSI, 2010), computes fracture toughness via stresses computed from peak load. On the contrary, Braham (2008) alongside with Wagoner et al. (2005), Li et al. (2006) and Nguyen et al. (2008) described crack initiated at the vicinity of 95% post-peak load as shown in Figure 2.10. An investigation by Li et al. (2006) indicated that destructive crack commenced only when macro-cracks were detected just right after the peak load. Energy dissipation for crack potential was measured until post-peak load.



(a) Crack Initiation at 95% Peak Load (b) Crack Initiation at 90% Peak Load

Figure 2.10: Crack Initiations at Post Peak Load (a) Braham (2008), (b) Li et al. (2006) (Braham, 2008; Li et al., 2006)

On the other hand, Canestrari et al. (2012) and Lee (2008) classified energy dissipation until peak load as an indicator for crack initiation, while total fracture energy derived from the entire load-displacement graph as fracture toughness as illustrated in Figure 2.11. Toughness in this scenario was interpreted with the inclusion of crack propagation resistance. In IL-SCB test, Al-Qadi et al. (2015) computed fracture energy by considering the entire area under the load-displacement graph.



(a) Energy Dissipation for Crack Initiation (b) Energy Dissipation for Toughness

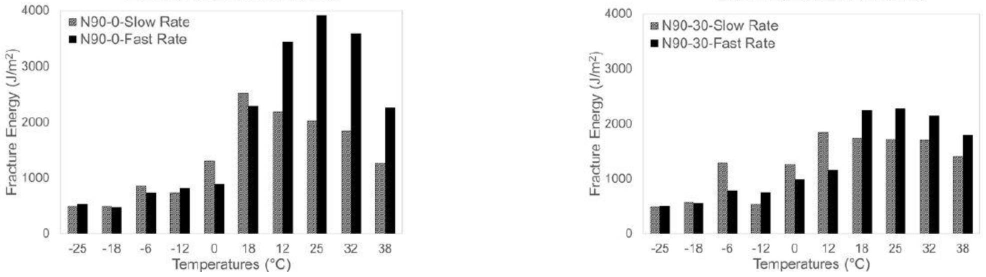
Figure 2.11: Energy Computation for Crack Initiation and Toughness (Canestrari et al., 2012)

To summarise, the literature regarded the behaviours of post-peak load-displacement graph crucial to the comprehension of fracture potential for asphaltic material. Therefore, post-peak fracture energy is indispensable in this study to amplify the effects of rejuvenator on high RAP content mixtures.

2.4.3 Loading Rate and Temperature

Asphalt material is known to crack under low temperature. Hence, fracture tests for bituminous mixtures were commonly practised at low temperature, and sometimes even at sub-zero temperature. Suitability of test temperatures and loading rates remains a disputable subject. However, a recent discovery by Al-Qadi et al. (2015) revealed that at an extremely low temperature (-12°C), statistical differences in fracture energy for SCB fracture test were minimal despite distinct variation in mixture types. At the same time, Tang (2014) documented minimal differences in fracture energy for RAP mixtures with 30% to 50% RAP contents at sub-zero temperature.

Comparison in Figure 2.12 was made between laboratory control mixture and asphalt mixture incorporating 30% asphalt binder replacement (ABR). Research outcome in Figure 2.12 deduced that intermediate test temperatures ranging from 12°C to 25°C accompanied by fast loading rate of 50 mm/min would yield unambiguous fracture energy for comparison (Khan, 2016).



(a) Conventional HMA Mixture (b) HMA Mixture with ABR

Figure 2.12: Comparative Effects of Temperature and Displacement Rate on Fracture Energy (Khan, 2016)

Al-Qadi et al. (2015) opted 25°C as SCB fracture test temperature to determine fracture potential and it was incorporated into AASHTO TP 124 test standard. It was selected on the basis of easing test temperature control. Moreover, other researchers such as Mohammad et al. (2012) also concluded that SCB test at the intermediate service temperature of 25°C demonstrated a good correlation with field cracking performance data. However, it was sometimes found that fracture energy alone was unable to discriminate asphalt mixtures with different compositions as denoted in Figure 2.13. Thus, the slope of post-peak inflection point should be included in the characterisation of fracture potential (Al-Qadi et al., 2015).

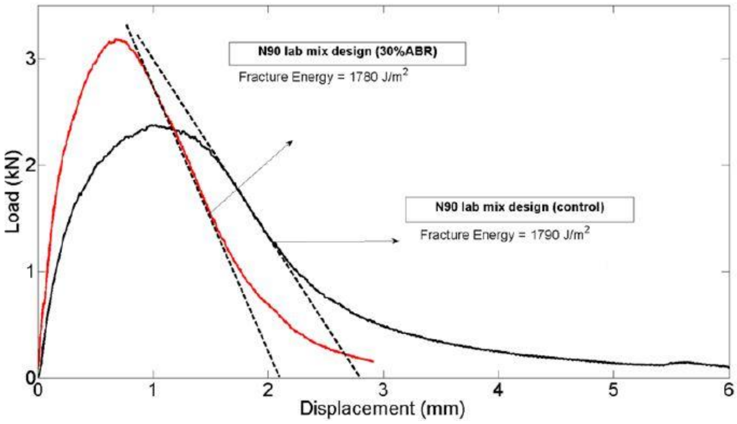


Figure 2.13: Comparison of Fracture Energy between Control and ABR Mixtures (Al-Qadi et al., 2015)

On the other hand, studies by Braham (2008) indicated that at a lower test temperature, fracture energy trend was closer to aggregate fracture energy, while at a warmer temperature, binder strain tolerance took precedence.

Overall, literature principally concurred that low-intermediate (10 to 25°C) test temperatures with the loading rate of 50 mm/min are ideal to differentiate fracture potentials of bituminous mixtures. Extreme low temperature would render most mixtures brittle, and thus resulting in low and similar fracture energy. Their differences are consequently unapparent for comparison. To ensure consistency, selection of test temperature should also tailor to test ambient condition. Lastly, fracture potential should be evaluated with the consideration of post-peak inflection slope as stipulated in AASHTO TP 124 (AASHTO, 2016).

2.4.4 Performance Evaluation for Fracture Toughness

The behaviours of composite materials that encompass heterogeneous properties differ from circumstances to circumstances. Currently, fracture mechanics of materials has long evolved from investigation of linear elastic fracture mechanics to nonlinear material behaviour of viscoplasticity and viscoelasticity. One of these composite materials is asphalt mixture, and fracture behaviours of asphalt mixture remain complex until the present day.

Like any other materials, asphalt mixture experiences different forms of cracking. Anderson (2005) categorised fracture modes into three conventional modes of loading namely, mode I (tensile stress), mode II (in-plane shear stress) and mode III (out-of-plane shear stress). Table 2.2 describes the characteristic of crack propagations experienced by asphalt mixture in the context of fracture mechanics.

Table 2.2: Characteristics of Crack Propagations (Anderson, 2005)

Fracture Category	Fracture Type	Type of Stress	Description
Mode I	Opening	Tensile	Stress acting perpendicularly to the plane of the crack.
Mode II	Sliding	In-plane Shear	Applied stress is parallel to the plane of the crack and normal to the crack front.
Mode III	Tearing	Out-of-plane Shear	Applied stress is parallel to the plane of the crack and crack front.

According to Braham (2008), thermal distress of asphalt pavement will result in mode I loading while mode II loading can be caused by repeating wheel loads. Lastly, mode III will only occur when the pavement is subjected to torsion (Aliha et al., 2015).