THE EFFECT OF CRUMB RUBBER MODIFICATION ON THE PHYSICAL PROPERTIES OF POROUS ASPHALT

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THE EFFECT OF CRUMB RUBBER MODIFICATION ON THE PHYSICAL PROPERTIES OF POROUS ASPHALT

ABSTRACT

Open graded friction course (OGFC) or porous asphalt (PA) system consists of a layer of porous asphalt, a layer of granular sub-base and a layer of crushed stone base course that acts as a reservoir. This allows water to infiltrate the surface course and stored at the base before the water reaches the subgrade. The popularity of this type of pavement is due to a number of advantages it have such as reduction in splash and spray, reduction of the risk of wet skidding and hydroplaning with lower noise generated from the traffic friction. In tropical counties such as Malaysia where the average monthly precipitation can be as high as 314mm, the use of open graded pavement system can be extremely beneficial. Due to its high porosity, porous asphalt can face problems such as faster oxidation rate of binder and loss of adhesion due to contact with water. Modified bitumen was utilised in the hope that it would further improve the performance of the porous asphalt. Crumb rubber modification by the wet process has been shown to have the ability to improve the rutting resistance, resilience modulus and fatigue cracking resistance of asphaltic mixes. This is due to the alteration to the property of the bituminous binder in terms of the viscosity, softening point, loss modulus and storage modulus. The outcome properties of crumb rubber modified bitumen (CRMB) is very sensitive and are highly governed by the mixing process which is dependent on external factors such as the mixing temperature, mixing duration and type; and internal factors such as type of bitumen, crumb rubber quantity, particle size, and type. This research studies the effect of particle size and crumb rubber content to the durability of an OGFC manufactured according to the Specifications for Porous Asphalt produced by the Road Engineering Association of Malaysia (REAM) modified with crumb rubber using the wet process. This study also conducted to determine the relations of rubber size, rubber content, and binder content in determination of optimum binder content (OBC) for OGFC with accordance to REAM specification. In order to analyse the performance of the binders and porous asphalt, a series of binder tests and bituminous mixtures tests were performed. In addition, multiple linear regression (stepwise method) was used for statistical analysis for which the main objective was to develop an equation (regression model) that could be used for predicting the performance of the mixtures for all factors engaged. A secondary purpose was to use regression analysis as a means of explaining the causal relationship among the factors (significant level). In the final analysis, the author found that rubber size, rubber content and binder content significantly affected the performance of porous asphalt. Moreover, this study showed that binder content between 6% and 6.5% is advisable to be used as the OBC to allow a certain level of tolerance when producing rubberized bitumen and at the same time ensuring a high quality product.

Keywords: Porous Asphalt, Bitumen, Crumb Rubber

KESAN PENGUBAHSUAIAN GETAH KE ATAS SIFAT- SIFAT FIZIKAL ASFALT POROS

ABSTRAK

Permukaan turapan gred terbuka (OGFC) atau sistem asfalt poros (PA) terdiri daripada lapisan asfalt poros, lapisan sub-butiran berbutir dan lapisan asas batu dihancurkan yang bertindak sebagai takungan. Ini membolehkan air menyusup ke permukaan dan disimpan di pangkalan sebelum air berada dilapisan tanah asas. Populariti jenis turapan ini adalah disebabkan oleh beberapa kelebihan yang ada seperti pengurangan percikan dan semburan, pengurangan risiko pengaliran basah dan hidroplaning dengan bunyi yang lebih rendah yang dihasilkan daripada geseran lalu lintas. Di kawasan-kawasan tropika seperti Malaysia di mana purata hujan bulanan boleh setinggi 314mm, penggunaan sistem turapan terbuka yang bergred adalah sangat bermanfaat. Oleh kerana keliangan yang tinggi, asfalt porus boleh menghadapi masalah seperti kadar pengoksidaan pengikat yang lebih cepat dan kehilangan ikatan kerana bersentuhan dengan air. Bitumen diubahsuai digunakan dengan harapan ia akan meningkatkan lagi prestasi asfalt poros. Pengubahsuaian getah oleh proses basah telah terbukti mempunyai keupayaan untuk meningkatkan rintangan, modulus daya tahan dan rintangan retak keletihan campuran asfalt. Ini disebabkan oleh perubahan kepada sifat pengikat bitumen dari segi kelikatan, titik pelembutan dan modulus storan. Ciri-ciri hasil bitumen diubahsuai getah serbuk (CRMB) sangat sensitif dan sangat ditadbir oleh proses pencampuran yang bergantung kepada faktor luaran seperti suhu pencampuran, tempoh campuran dan jenis; dan faktor dalaman seperti jenis bitumen, kuantiti getah serbuk dan saiz getah. Kajian ini mengkaji kesan saiz getah dan kandungan getah serbuk kepada ketahanan OGFC yang dihasilkan mengikut Spesifikasi Asfalt Poros yang dihasilkan oleh Persatuan Kejuruteraan Jalan Raya Malaysia (REAM) yang diubah suai dengan getah serbuk menggunakan proses basah. Kajian ini juga dijalankan untuk menentukan hubungan peratus getah, kandungan getah, dan kandungan pengikat dalam menentukan kandungan pengikat optimum (OBC) untuk OGFC mengikut spesifikasi REAM. Untuk menganalisis prestasi pengikat dan asfalt porus, ujian bitumen dan ujian campuran bitumen dilakukan. Di samping itu, regresi linear berganda (kaedah stepwise) digunakan untuk analisis statistik yang mana matlamat utama adalah untuk membangun persamaan (model regresi) yang boleh digunakan untuk meramalkan prestasi campuran untuk semua faktor yang terlibat. Tujuan sekunder adalah menggunakan analisis regresi sebagai satu cara untuk menerangkan hubungan kausal antara faktor (tahap signifikan). Dalam analisis akhir, penulis mendapati bahawa saiz getah, kandungan getah dan kandungan pengikat ketara mempengaruhi prestasi asfalt poros. Selain itu, kajian ini menunjukkan bahawa kandungan pengikat antara 6% dan 6.5% adalah dinasihatkan untuk digunakan sebagai OBC untuk membenarkan tahap toleransi tertentu apabila menghasilkan bitumen getah dan pada masa yang sama memastikan produk berkualiti tinggi.

Katakunci: Asfalt Poros, Bitumen, Serbuk Getah

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LIST OF ABBREVIATIONS AND NOTATIONS

ARR	Abrasion Resistance Ratio
ARR	Abrasion Retention Ratio
ASTM	American Society for Testing and Materials
BSI	British Standard Institute
CALTRANS	California Department of Transportation
CR	Crumb Rubber
CRM	Crumb Rubber Modified
CRMA	Crumb Rubber Modified Asphalt
CRMB	Crumb Rubber Modified Bitumen
DAL	Dry Abrasion Loss
DSM	Dry Stiffness Modulus
DTS	Dry Tensile Strength
FHWA	The Federal Highway Administration
Gbcm	Bulk Specific Gravity
Gmp	Theoretical Maximum Specific Gravity
ID	Identification Names
ISTEA	Intermodal Surface Transportation Efficiency Act
ITS	Indirect Tensile Strength
ITSM	Indirect Tensile Stiffness Modulus
JKR	Malaysia Public Works Department
OBC	Optimum Binder Content
Pav	Air Voids
RC	Rubber Content
REAM	Road Engineering Association Malaysia
RS	Rubber Size

RTFOT	Rolling Thin Film Oven test
SABITA	South African Bitumen Association
SMA	Stone Matrix Asphalt
SMR	Stiffness Modulus Ration
SP	Softening Point
SPSS	Statistical Package for the Social Sciences
TRL	Transport Research Laboratory
TS	Tensile Strength
TSR	Tensile Strength Ratio
UMATTA	Universal Material Testing Apparatus
VIM	Voids in Mix
WAL	Wet Abrasion Loss
WSM	Wet Stiffness Modulus
WTS	Wet Tensile Strength

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CHAPTER 1: INTRODUCTION

1.1 Overview

In the 1930's the Oregon's Department of Transportation first used the open graded design in an attempt to improve the skid resistance of its road. This triggered the use of open graded friction course (OGFC) which is also known as porous asphalt. Later in the 1940s, the California Department of Transportation (CALTRANS) utilized this type of surface course as drainage interlayer and as an alternative to chip seals and slurry seals (Caltrans, 2006). In 1974 the Federal Highway Administration agency published the first guide in designing porous asphalt mixes (Putman and Kline, 2012) followed by The Franklin Institute in Philadelphia design guide which includes considerations in soil conditions, load bearing capability and hydrological concerns of the design that was published in 1978 (Thelen and Howe, 1978).

The popularity of this type of pavement is due to a number of advantages it have such as reduction in splash and spray, reduction of the risk of wet skidding and hydroplaning with lower noise generated from the traffic friction. These benefits make it gains popularity with time and more authorities had started using the system until the present day. In tropical counties such as Malaysia where the average monthly precipitation can be as high as 314mm (Wong et al., 2009), the use of open graded pavement system can be extremely beneficial. A study by Dreelin (2006) shows that porous asphalt produced 93% less runoff on clay soil compared to dense asphalt while Takahashi (2013) stated that the durability of porous asphalt in Japan expressways can exceed the lifespan of dense asphalt surfacing provided that the binder course has good stripping resistance. However, the advantages also come with a list of disadvantages such as reduced structural and functional durability and higher construction and maintenance costs. This calls for continuous research (Younger et al., 1994; Alvarez et al., 2011) in this field in order to improve the shortcomings of the design.

Open graded friction course or porous asphalt system consists of a layer of porous asphalt, a layer of granular sub-base and a layer of crushed stone base course that acts as a reservoir (Thelen and Howe, 1978). This allows water to infiltrate the surface course and stored in the base before the water reaches the subgrade. Due to its high porosity, porous asphalt can face problems such as faster oxidation rate of binder and loss of adhesion due to contact with water. This accelerates the disintegration process which contributes to raveling problem. To solve these weaknesses, modified binder to be used as modified binder can improve the durability characteristics of the pavement. Polymer modified binder, (Chen et al., 2012) and crumb rubber modified bitumen (Partl et al., 2010) have been proven to increase the durability of the pavement in terms of moisture sensitivity, raveling and rutting.

Crumb rubber (CR) modification by the wet process has been shown to have the ability to help improve the rutting resistance, resilience modulus and fatigue cracking resistance of asphaltic mixes. This is due to the alteration to the property of the bituminous binder in terms of the viscosity (Nah and Kim , 1997), softening point (Lougheed and Papagiannakis, 1996), loss modulus and storage modulus (Ali et al., 2013) . The improvement however, is governed by the swelling process of rubber particles that were interacted with bitumen. Rubber crumbs can swell up to 3 to 5 times its original size due to the absorption of maltenes component of the bitumen (Vonk and Bull,1989;Peralta et al., 2010). This left a higher proportion of asphaltenes in the binder therefore increasing its viscosity and bitumen with higher viscosity will generally have a higher failure temperature and therefore have a longer service life due to higher temperature stability. Researchers had recommended different percentages of crumb rubber to be added into bitumen ranging from 10% to 25% (Shen and Amirkhanian, 2005, Jeong, 2010; Wang et al., 2012). Khalid and Artamendi (2003) highlights that an addition of crumb rubber of more than 10% would a binder that is too viscous for field mixing operations.

The outcome properties of crumb rubber modified bitumen (CRMB) however, is very sensitive and are highly governed by the mixing process which is dependent on external factors such as the mixing temperature, mixing duration and type; and internal factors such as type of bitumen, crumb rubber quantity, particle size, and type (Billiter et al., 1997). Accurate selection of the processing variables such as bitumen type, rubber particle size and content, mixing temperature and duration are the keys to successful CRMB production.

Crumb rubber mesh size is one of the important factors that govern the rubber depolymerisation rate along with mixing time and temperature (Leite and Soares, 1999). Crumb rubber with finer particles swell faster due to a larger specific area and therefore give higher viscosities compared to coarser size. CRMB produced from fine rubber particles will also have a quicker viscosity reduction in the heating process due to its faster swelling rate and thus a faster depolymerisation (FHWA, 1993). Sun and Li (2010) mentioned that the factors that influences the viscosity of CRMB according to their order of significance are crumb rubber content, curing temperature, rubber particle size and mixing time.

Smaller particle size produces modified bitumen that have higher viscosity, softening point and resilience due to a higher surface area (Billiter, 1997; Neto et al., 2006; Putman and Amirkhanian , 2006; Sun and Li ,2010) and aspect ratio (Navarro et al.,2002). Wang et al.(2012) and Wong et al. (2007) reported that finer crumb rubber attains higher viscosity at high temperature and lower creep stiffness at low temperature and this leads to a better rutting resistance. However, Liu et al. (2009) mentioned that there is no significant difference between basic performances of bitumen modified with different crumb rubber size.

Cao and Bai (2007) on the other hand, showed that larger crumb rubber size gives a better high temperature performance and similar low temperature cracking resistance between CRMB manufactured with smaller crumb rubber particle size. Similar results are demonstrated by Sebaaly et al. (2003) where he mentioned that while crumb rubber size does not have a significant effect on the low temperature properties of bitumen, different combinations of crumb rubber size and content can either improve or jeopardize the low temperature performance grade of the CRMB.

In terms of tensile strength (TS) and the stiffness modulus or modulus of resilience (Mr), Xiao and Amirkhanian (2008) concluded that adding crumb rubber reduces the resilient modulus and tensile strength values of the mix, Kim (2001) on the other hand, concludes that adding rubber reduces the resilience modulus, but it increases its tensile strength. In a research using terminal blend mix, Navarro and Gámez (2011) shows that adding crumb rubber will increase the reliance modulus and decrease the tensile strength of the mix. However, it is important to note that all these researches use different method and parameters in the preparation of crumb rubber modified asphalt (CRMA).

Specifications around the world (Presti et al.,2012; Cheng and. Hicks, 2012) recommended varying values of crumb rubber addition percentage and size probably due the different base bitumen suggested to produce the CRMB and the type of climate that that design are expected to serve. For instance, CALTRANS recommended 120-150dmm penetration grade bitumen as a base and crumb rubber sizing up to 2.36mm with rubber content of 18% to 22% addition. South African Bitumen Association

(SABITA) recommended rubber addition ranging between 18% and 24% and rubber crumb sieve size 1.18mm with 60-100dmm bitumen and Ausroads (2007) on the other hand recommended crumb rubber sizing up to 2.36mm with rubber content from 15% to 18% with 85 to 100dmm penetration grade bitumen.

1.2 Problem Statement

In general, the studies above show that a slight change of parameter such as crumb rubber size and percentage used in the design of CRMB can significantly affect the properties of the outcome product. However the specifications, bitumen type, rubber size and content used in the studies varies quite significantly and the results can sometimes be conflicting. Similarly the standards that were available are tailored to suit the climate and availability of materials to the geographical region the designs are meant to be used. Therefore it is very difficult to compare and evaluate the results according to local scenarios. To ensure a reliable mix is obtained, a separate design of optimum rubber content is therefore required for each crumb rubber content, size and bitumen grade to ensure a properly designed CRMB that will function well and have adequate durability.

1.3 Research Objectives

This research attempts to provide a spectrum of options of CRMB produced with varying percentage and nominal crumb rubber size that will satisfy the requirement of the Road Engineering Association Malaysia (REAM) specifications to produce satisfactory porous pavements in terms of air void, abrasion loss and binder drainage with additional durability indicators such as tensile strength and resilience modulus.

The objectives of this study are:

1. To study the effect of crumb rubber to the rheological properties of CRMB.
2. To investigate the relationship between crumb rubber addition to the optimum binder content of CRM porous asphalt.
3. To study the effect of crumb rubber addition to the resistance of disintegration, tensile strength and resilient modulus of CRM porous asphalt.
4. To study the effect of water to the resistance of disintegration, tensile strength and resilient modulus of CRM porous asphalt.

1.4 Research Questions

This thesis aims to answer the following research questions:

1. What is the effect of the crumb rubber (CR) particle size and crumb rubber content on the physical and rheological behaviour of crumb rubber modified bitumen (CRMB)?
2. How significant are the crumb rubber particle size, crumb rubber content and binder content in terms of the resistance of disintegration, tensile strength and resilient modulus of CRM porous asphalt?
3. What is the relationship of the crumb rubber particle size and crumb rubber content to the optimum binder content (OBC) of crumb rubber modified (CRM) porous asphalt?
4. What is the effect of water to the resistance of disintegration, tensile strength and resilient modulus of CRM porous asphalt?

1.5 Scope of Work

The scope of work adopted to meet the objectives of this study involves a review of the literature and a laboratory investigation. The literature review is conducted to identify important factors that influence the behaviour of CRMB and consequently to the properties of the CRM porous asphalt. The available testing methods that are used to characterize CRM porous asphalt and suitable statistical analysis are also reviewed. Moreover, effects of water to the behaviour of CRM porous asphalt are studied extensively.

Laboratory investigations were carried out to develop the relationship between the physical and rheology of the binders with the properties of the porous mixtures. In this study, the properties of the binders modified with different sizes and percentages of crumb rubber were performed using conventional test methods (penetration test, ring and ball softening point test and Brookfield viscosity test) and dynamic shear rheometer (DSR). The CRM porous asphalt was then prepared using the CRMB at various percentages (4%-7%) to ensure a wider coverage of binder content. Next, the binder properties obtained were verified by the mix performance. The density test, indirect tensile modulus (ITS) test for conditioned (wet) and unconditioned sample, Cantabro test for conditioned (wet) and unconditioned sample were performed for this purpose. The scope of the laboratory works will be discussed further in Chapter 3.

Moreover, multiple linear regression analysis (Stepwise method) was used to determine the factors (crumb rubber particle size, rubber content and binder content) that significantly affect the properties of CRM porous asphalt as well as to develop a model that correlates with the engaged factors.

1.6 Significance of the Study

As country that experiences a significant amount of rainfall throughout the year, porous asphalt offers Malaysian roads a safer alternative which, if constructed properly, will have zero ponding problems, reduced splash and spray and provides better friction in wet conditions. Rubber is a popular choice of bitumen modification used to increase the durability of porous asphalt throughout the world. However, the results of studies available are mainly carried out with specifications and material (i.e. base bitumen and crumb rubber type) different than what is normally available in Malaysia and the results can sometimes be conflicting. This study attempts to study the rheological properties of crumb rubber modified asphalt and establish the relationship between some durability properties and water effect to crumb rubber modified porous asphalt, with local specifications and materials. This would assist the designers to achieve a design that conforms to Road Engineers' Association of Malaysia (REAM) specifications while utilising the available type crumb rubber, amount and size.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The use of OGFC which is also known as porous asphalt started in the 1930s when Oregon's Department of Transportation applied the open graded design in an attempt to improve the skid resistance of its' road. In the 1940s, California Department of Transportation (CALTRANS) utilized this type of surface course as drainage interlayer and as an alternative to chip seals and slurry seals (Caltrans, 2006). The first guide in designing porous asphalt mixes was published in 1974 by the Federal Highway Administration agency (Putman and Kline, 2012) and in 1978; The Franklin Institute in Philadelphia published a guideline in designing porous pavements which includes considerations in-soil conditions, load bearing capability and hydrological concerns of the design (Thelen and Howe, 1978). The popularity of his type of pavement is due to a number of advantages it have such as reduction in splash and spray, reduction of the risk of wet skidding and hydroplaning with lower noise generated from the traffic friction. It is also more resistant to freezing due to the higher water content in the soil underneath (Bäckström, 2000). This could also reduce the risk of skidding of vehicle due to a thin layer of ice on the surface of the road. These benefits make it gains popularity with time and more authorities had started using the system until the present day. In tropical countries such as Malaysia where the average monthly precipitation can be as high as 314mm (Wong et al., 2009) the use of open graded pavement system can be extremely beneficial. However, the advantages also come with a list of disadvantages such as reduced structural and functional durability and higher construction and maintenance costs. This calls for continuous research (Younger et al., 1994; Alvarez et al., 2011) in this field in order to improve the shortcomings of the design.

Open graded friction course or porous asphalt system consists of a layer of porous asphalt, a layer of granular sub-base and a layer of crushed stone base course that acts as a reservoir (Thelen and Howe, 1978). This allows water to infiltrate the surface course and stored at the base before the water discharged into the drainage system. Due to its high porosity, porous asphalt can face problems such as faster oxidation rate of binder and loss of adhesion due to contact with water. This accelerates the disintegration process which contributes to raveling problem (Alvarez et al., 2006; Putman and Kline, 2012). This call for modified binder to be used as modified binder can improve the durability characteristics of the pavement. Currently, most authorities that use open graded asphalt in their roads opted for either rubber or polymer modification to increase the durability of the pavement (Alvarez et al., 2011).

2.2 Advantages of Porous Asphalt

2.2.1 Reduction of Splash and Spray

One of the main features of porous asphalt is its capability to reduce splash and spray from surface runoff during rainstorm doe to its porous nature. Water from the precipitation seeps into the pavement and then discharged into the drainage system. Lesser amount of water on the surface of the road increase the safety of drivers where the risk of skidding is being reduced and the level of visibility are increased. Rungruangvirojn and Kanitpong (2010) mentioned that porous asphalt reduces visibility from splash and spray by 28% while visibility reduction of SMA and dense-grade asphalt are 30% and 55% respectively and visibility reduction from splash and spray due to trucks travelling on the adjacent lane are also 2.7 to 3.0 times more for dense-grade asphalt when compared to porous asphalt. British Pendulum Test shows that porous asphalt has a significantly higher skid resistance value than conventional asphalt mix giving porous asphalt an added factor of safety (Keymanesh et al., 2013).

Expressways in Japan have used porous asphalt since 1998 and according to a 15 years long-term survey on site, had helped in reducing the number of road accidents due to wet surface conditions (Takahashi, 2013). Ragnoy (1989) estimated that porous asphalt can reduce daytime accidents due to bad weather by 9.5% and night time accidents by 13.6% assuming that there are no negative impacts of porous asphalt such as drivers speeding up.

It is natural that one may wonder that the ability of porous pavement to increase visibility and reduce splash and spray during a rainstorm on the other hand can give an effect where drivers speed up due to the better driving conditions even during a downpour. Elvik and Greibe (2005) and Edwards (2002) found that although splash and spray were reduced, drivers do tend to not speed up and speed reduction during precipitation period is statistically significant. This is important as a speed increase of 5% can offset the favourable effect of porous asphalt.

2.2.2 Noise reduction

Freitas et al., (2009) studied traffic noise changes due to the presence of water on pavement surfaces. It is found that water will increase noise level up to 4dB (A) on all types of pavement. Porous pavement has lower noise propagation when compared to dense asphalt. Watts et al., (1999) found that porous asphalt an advantage of 8.9 dB(A) for car sources and 6.9 dB(A) for lories when compared with dense asphalt. Fujiwara et al., (2005) however, stated that porous asphalt have a reduction of between 7 to 9 dB(A). Although for heavy vehicles, the effect of porous asphalt is rather limited, due to the structure of porous asphalt horn effect is lower where the sound is partly absorbed by the pavement Anfosso-Lédée and Dangla (2006). Single layer porous pavement gives better noise reduction compared to double layer pavement according to Shen et al., (2009). on the other hand found that porous asphalt using basic oxygen furnace slag have the ability to further reduce the noise propagation further from the range of 800–1200 Hz to 1000– 1600 Hz due to the nature of the material that can absorb high-frequency noise that is produced from tire to road contact.

2.2.3 Heavy metal filtration

The quality of water filtered through porous pavement has been found to be significantly improved. This shows that porous pavement has good filtration capacity of heavy metals in the rainwater. Legret and Colandini (1999) and Legret et al., (2007) compares the chemical properties of water collected in storm water outlets between porous pavement with a reservoir structure and a nearby catchment drain and at a highway site before and after the replacement of conventional asphalt to porous asphalt. The study found that the quality of water from porous asphalt have less pollutants such as lead, cuprum and cadmium. This is due to the filtration capacity of porous asphalt where the pollutants are retained in the porous asphalt and the soil beneath the asphalt does not show any pollutants. Examinations of sludge that were removed in porous asphalt cleaning process also reveal that the clogging sludge contains heavy metals such as lead, cuprum, cadmium and zinc where the concentrations are related with traffic (Colandini et al., 1995). The materials from the pores of the pavement also contains organic materials, however organic degradation is not a source of other contaminants (Welker, 2012).

Porous asphalt without a reservoir structure, can increase flow, however the filtration of heavy metals can be less effective (Wada et al., 1997.) Legret, and Colandini (1999) found that in porous pavement without a reservoir structure, metal contaminants are normally retained in the top layer of the soil. However, the filtration of porous asphalt has its limitation. In a study by Roseen et al., (2011) it is found that there are no removal of dissolved anionic contaminants such as nitrate and chloride; and only 42% of phosphorous are removed.

2.3 Durability of Porous Asphalt

The Transport Research Laboratory (TRL) in their publication "Best practice guide for durability of asphalt pavements" defined durability as "the retention over the structure's expected service-life of a satisfactory level of performance without major maintenance for all properties that are required for the particular road situation in addition to asphalt durability" (Scaffer et al., 2008). In terms of asphaltic mixture, durability can be defined as its ability to resist weather conditions such as water and temperature variations and traffic loading over its design period (Putri and Suparma, 2009).

Durability is one of the most important characteristics of any type of pavement. Factors that influence durability of a particular pavement are age, temperature, traffic loading (Takahashi, 2013). Failure of a porous pavement can be caused by failure of the bituminous mortar or adhesion failure between aggregate and the bitumen (Mo, 2009) and this will cause durability issues such as ravelling and cracking. Due to its structural configuration, porous pavement have less tolerance to fracture and with bituminous mortar that have a lower tensile strain the pavement are prone to cracking due to the movement of aggregates (Moriyoshi et al., 2013).

2.3.1 Effect of moisture

Porous pavement has a higher surface area that is in contact with water during precipitation period. This can affect the durability of the pavement and limits its life period. Significant differences were found between the durability of samples that were water conditioned and the ones that were tested in dry condition. This is due to the reduction of the modulus of the tested samples (Poulikakos and Partl, 2009).

Poulikakos and Partl (2012) also found that water reduces the viscosity and increases the phase angle of bitumen, therefore they concluded that it is important that water conditioning should be a part of mechanical analysis of porous asphalt. Also, it is important to note that in porous asphalt pavement, water sensitivity of the binder course also plays a role since as water seeps through the pavement and become in contact with the binder course, the binder course will also experience stripping of aggregate (Takahashi, 2013). An analysis of the sensitivity of porous asphalt to water and thermal conditions reveals that rubber modified porous asphalt has a higher resistance to the two elements compared to SBS modified samples. This was not only due to the properties of rubberised binders, but also due to the higher binder quantity that was used (Partl et al., 2010). Hossain et. al. (2015) also reported that rubber modification increases adhesion properties of bitumen and hence increased its moisture resistance.

2.3.2 Effect of aggregate gradation and additives

One of the parameter that determines the durability of porous asphalt is aggregate grading. Mansour and Putman (2012) mentioned that aggregate gradation does affect the performance of porous asphalt and aggregate gradation for porous asphalt can be optimized based on the void ratio of the gradation. Strength of a mix is determined by the value of the indirect tensile strength where the strength decreased when the porosity of a mix increased. In Japan, Takahashi (2013) found that the binder course underneath porous asphalt pavement should be tighter than conventional dense asphalt. Suresha et al., (2009) and Wu et al., (2006) carried a CT scan test on several porous asphalt samples and found that stone-on-stone contact within the porous asphalt skeleton are in the form of contact point between course aggregates. Therefore, the strength that governs the cohesion of the mix is the binding strength between the contact points. Hasan et al., (2013) concluded that the best performance for porous asphalt in terms of abrasion loss are achieved with a mix that utilises 14mm nominal sized aggregate in with 5.0 mm break point compared to other mixes. When larger aggregates were used the abrasion resistance decreases while the permeability and resilient modulus value improved.

The dominant aggregate size range, according to Kim et al., (2009) on the other hand, must be less than 50% to ensure aggregate interlock and the proportion of the adjoining size particles within the dominant aggregate size range should not be greater than 70/30 for proper interlock of the aggregate skeleton. Poulikakos and Partl (2012) mentioned that although a lab sample sometimes does not reflect field compaction, it is found that the performance of porous asphalt can be predicted using micro-structure of the samples and it is suggested that more research in the area of micro-structure of porous asphalt to optimise the performance of the pavement.

Apart from aggregate gradations and binder properties, aggregate type, fiber and hydrated lime addition can also influence pavement's moisture susceptibility. Khan et al., (2013) concluded that dense asphaltic mixes that uses basic aggregates (limestone) have a higher water resistance when compared with the ones that use acidic aggregates (granite). Similarly, Xu and Wang (2016) concludes that the adhesion strength between bitumen and aggregate is highly dependent on the type of aggregate used (silicate or calcite). Hydrated lime fillers assist in improving ravelling and increase resistance to oxidation. Ameri and Esfahani (2008) and Chen et al., (2012) Fibres addition on the other hand, thickens the binder film coating the aggregate and subsequently increasing the water resistance of the mix (Wu et. al., 2006).

2.3.3 Effect of binder type

The durability of asphaltic mixes such as porous asphalt can be increased using polymer modified bitumen as binder (Chen et al., 2012). While increasing the mixture resistance to moisture damage, ravelling and rutting. Chen et al., (2012) found that polymer modified asphalt increases the fatigue resistance in porous asphalt and can reduce the ravelling up to half of that of a conventional binder. Polymer modified binder also can reduce the effect of rutting where the rutting parameter G*/sin δ is higher for polymer modified asphalt. Jeong et al. (2011), Partl et al., (2010) and Suresha et al. (2009) summarises that aggregate gradations and binder type are the main parameters that governs the properties of porous asphalt mixes. In other words, a design that balances aggregate gradation and binder type is required in designing durable open graded asphalt. Modified asphalt lowers the air void and permeability of porous asphalt while aggregate gradations that have higher amount of coarse aggregates gives a mix that have a higher air void and permeability. Partl et al., (2010) recommended the use of rubber crumbs as bitumen modifier as it is proved to reduce moisture susceptibility of porous mixes and have a better performance compared to SBS modified mixes. The effect of using modified bitumen as binder in asphalt mixes are explained further in Section 2.4.4 and Section 2.4.5.

2.4 Porous Asphalt Mix Design

Interest in porous asphalt has been increasing since it was introduced due to the unique properties and the advantages that it offers. More research is being carried out to improve the durability and functionality of this pavement which is determined by the mix design process. Putman and Kline (2012) states that currently there are more than 20 types of mix design method for porous asphalt mixes in the United States. These methods generally determine the optimum binder content of the mixes by either evaluating the properties of trial compacted specimens (Type 1), using the absorption capacity of the aggregate (Type 2) or by visual inspection of the mix (Type 3). Table 2.1 summarizes the main governing parameters that were specified in some the design guides to determine optimum asphalt content.

Table 2.1: Parameter used in determining optimum binder content for open graded friction courses (Putman and Kline, 2012; Alvarez et al., 2006)

Authority	Air Voids (%)	Abrasion Loss (%)	Binder Draindown (%)
ASTM (USA)	≥ 18	≤ 20	≤ 0.3
NCAT (USA)	≥ 18	≤ 20	≤ 0.3
Virginia Department of Transport (USA)	≥ 16	≤ 20	≤ 0.3
REAM (Malaysia)	18% - 25%	≤ 15	≤ 0.3
Austroads (Australia)	20% - 25%	≤ 20	≤ 0.3

Although type 2 and 3 of the methods requires visual experience of the designer to accurately choose the optimum binder content, the method give a single value of optimum binder content for the mix and when tested as compacted specimen, the samples show adequate durability and permeability characteristics as well. Type 1 design method; which is also used by The Road Engineers Association of Malaysia (REAM); on the other hand; tend to give a range of optimum binder content that is determined to be suitable and this does not give the designer an accurate guide in determining the optimum value. However since Type 1 methods evaluates the performance properties such as the durability and permeability of the mix, it gives a designer a good idea on the performance of the mix with different binder contents. Alvarez et al., (2011; 2012) argues that field performance is still an important characteristic to design porous asphalt mixes and additional research is required to accurately determine and validate the specifications used for the mix design; also, apart from durability characteristics, functional characteristics such as noise reduction capability and drainability are suggested to be included in the design procedure. Mansour and Putman (2012) highlighted that the vital characteristics that needed to be considered are infiltration rate of the pavement and the predicted traffic loading on the pavement while Sungho Kim et al., (2009) suggested a sensitivity analysis to evaluate the effect of dominant size aggregate gradation to permeability of porous asphalt. High traffic loading can cause over compaction during the pavement's early life. This problem can be solved using a mix design method that are based on aggregate gradation optimisation to reduce post-compaction effect by traffic load are proposed by Takahashi and Partl (2001) where a tighter aggregate skeleton can be achieved and therefore prolonging the life of the pavement.

2.5 Crumb Rubber from Scrap Tyres

Rapid urban growth in many countries in the world increases the requirement of increasing the capacity of road network in a modern city. This resulted in huge demand for raw materials such as aggregates and asphalt. However, it is important that environmental sustainability is taken into account when considering a new construction project. When raw materials availability and sustainability are under the threat of depletion, it is vital that an alternative source of raw material substitute is established. The most direct source of recyclable material comes from waste materials that had been filling landfills in the modern era.

Waste materials such as glass, steel slag, plastics and rubber are some of the waste materials that have the potential to be used in road or construction projects. Yu Huang reviewed that steel slag, have adequate angularity, hardness and rough surface texture to replace coarse aggregates in asphaltic mixes while glass of higher content and larger size on the other hand is reported to have led to a number of problems such as insufficient friction and bonding strength. Recycled plastics can be used as a replacement of aggregates or as a binder modifier while asphaltic mixes with recycled plastics, as aggregate replacement, can reduce the density of the mix and shows a significant increase in Marshall Stability (Huang et al., 2007). Pavements that incorporated waste materials such as coconut and sisal fibres had been shown to have a high modulus of resilience and tensile strength while prohibiting binder drain down (Oda et al., 2012).

Scrap tires are another source of recycling material. The accumulation of scrap tires has become a worldwide problem, as this particular waste material is quite difficult to dispose and/or recycle. For instance, the amount of waste tires generated, in the United States of America, 281 million scrap tires were disposed in 2001 (Sunthonpagasit and Duffey , 2004) and by 2009 the number had increased to 291.8 million. 40.3% of tires were used as tire-derived fuel, 26.2% were tuner as crumb rubber, 12.6% were disposed in landfills and the remaining were put into other uses (Rubber Manufacturers Association, 2011). Tire rubber is very difficult to be recycled compared to other materials such as thermoplastics as the chemical structure of rubber from scrap tires has a complex three dimensional structure present due to the vulcanizing process. A number of methods had been introduced in order to assist the degradation process of vulcanized rubber. These methods include, rubber reclamation using (Dubkov et al.,2012) Nitrous Oxide, microbial techniques of degradation (Stevenson et al., 2008) of tire rubber using the activity of aerobic and anaerobic microbes and (Miranda et al., 2013) pyrolysis technique where pieces of rubber are subjected to high temperature and low pressure in order to degenerate the rubber particle into a solid and volatile fraction (Martínez et al., 2013).

Recycled rubber from waste tires are normally supplied in crumb form. When used as an addition to natural rubber, crumb rubber can be activated by special processes such as mechanochemical reaction, polymer treating and anhydrous maleic acid treatment (Fang et al., 2001) in order to improve its properties. However, in most civil engineering uses, crumb rubbers are normally used as an untreated material.

Other uses of crumb rubber spans from being used as ground cover in playgrounds, surface material for running tracks, soil conditioner in turfgrass soil and as an additive to improve thermal and acoustic properties in concrete. It can also be an effective sound absorbing material that can be used in absorbent screens in road barriers to reduce traffic noise and as a mechanical additive in coarse and fine grain soil (Pfretzschner et., 1999; Palit et al., 2004; Sukontasukkul, 2009; Zhao et al., 2011). There are also attempts to use crumb rubber as an addition with concrete, however the attempt are not quite successful due to chemical incompatibility issues (Shu and Huang, 2014).

In pavement construction, apart from being cost effective, the use of crumb rubber in asphaltic mixes had been proven to increase the rutting and fatigue resistance of the pavement. Rubber crumbs can be mixed with aggregates within the asphaltic mix or blended in asphalt at a specific temperature where rubber crumbs serves as a binder modifier.

2.5.1 Rubber Crumb Production

Tires can be recycled in two ways. It can be shredded or shaved and it can also be recycled as tyre crumbs. Tyre shreds have applications in road foundation while, tyre crumbs are mainly used as a modifier in asphalt in pavement constructions. There are two methods of producing tyre crumbs namely the ambient method and the cryogenic method. Rubber crumbs produced by ambient grinding has a large surface area while cryogenically ground rubber crumbs on the other hand, have a flatter surface (Navarro, et al., 2002). In the ambient method, tires were grinded at ambient temperature. The type of grinding process experienced produced rubber crumbs of different sizes. Tires are shredded into chips about 3 to 5mm in size. The chips are passed through a coarse cutter and a finer grinding mills and screens. Commercial roll mills have also been used to produce such crumbs. Steel belting present in tires are separated and removed using magnetic force. Rubber crumbs obtained from this process tend to have a larger specific area where the rubber particles tend to have an irregular shape and are rather porous.

When extra-fine crumbs are required, the wet grind process is used. In this process rubber particles are fed through rigorous cutting paths where a fairly precise particle size distribution is obtained. The medium for cutting in this process is water with a temperature not exceeding 83˚C. Particle sizes up to 325 mesh size can be obtained from this process.

In the cryogenic technique rubber are dipped in liquid nitrogen with a temperature of (-75˚C). Due to the extremely low temperature, rubber becomes brittle and can then be fragmented into the desired size using hammer mill or fragmentor. Steel beltings and fabric are then separated using magnetic force. Rubber particles obtained from this process is much more regularly shaped and thus has lower specific gravity than the ones produced with the ambient process.

Crumb rubber sizing can be a problem to be generalized since different product uses different mesh size. According to manufactures, finer meshes are more expensive to produce and therefore rather are expensive and quite difficult to be acquired. However, Sunthonpagasit and Duffey (2004) stated that some producers affirmed that the fine rubber particle size has a very good price competitiveness with virgin rubber products and therefore have a high potential especially in molded rubber and composite products. Sunthonpagasit estimates that recent demand has been about 14% for coarse sizes (larger than 2.00mm), 52% for mid-range sizes (2.00mm to 600μm), 22% for fine sizes (425μm to 180μm), and 12% for superfine sizes (150μm to 75μm).

2.5.2 Crumb Rubber in Pavement Construction

In pavement construction, crumb rubber is being used to produce rubberized asphalt. Earlier rubber modification to asphalt used natural rubber (latex). The United States' Federal Highway FHWA-SA-92-022 stated that there is evidence that the attempt of modifying asphalt with natural rubber is recorded since the 1840s' while in 1898 de Caundenberg patented a process for manufacturing rubberized asphalt in France (Heitzman,1992; Report Cairo University, 1983). In 1937, coarse grading rubber particles (solid blocks) from ground rubber tire tread started to be used in Great Britain as aggregate replacement (dry mix) to construct rolled asphalt carpets.

The Road Research Laboratory in the United Kingdom also conducted a research program from 1953 to 1966 to study the effect of various types of rubber forms to asphaltic mixes with the help of the Natural Rubber Producers' Research Association (Thompson, 1960). The types of rubber form that were investigated are latex, sheet rubber and powdered rubber. Examples of powdered rubber used in the research are Pulvatex, an unvulcanised rubber powder containing 40% inert filler; Mealorub, a lightly vulcanized powder containing 96% rubber, Rodorub, a lightly vulcanized rubber powder containing 75% rubber and 25% inert filler and rubber powder from grinded waste tires.

A trial mix was laid down in Huntingdonshire in 1955 using rubberized asphalt with 7% Pulvatex and this mix is reported to have lasted to up to eight years which is 16%

longer than the average of 6 years life span with the normal macadam mix at that time. In an experiment carried out in 1963 on a road stretch in Leicestershire, asphaltic mixes modified with 4% natural rubber from evaporated latex and with a slightly increased binder content of 1% had shown to have a higher resistance to reflection cracking than standard mixes (Thomson, 1964).

In the United States, crumb rubber modified asphalt is first being used in the late 1960's by Charles McDonald in Phoenix, Arizona (Mundt et al., 2009). The Intermodal Surface Transportation Efficiency Act (ISTEA) passed by the United States Congress in 1991, authorized the use of 5% of crumb rubber to be used in in federally funded roadway construction projects in 1992 and by 1997, the amount should be increased to 20% (Xiao et al., 2006). This initiative is taken as one of the way out of the scrap tire problem in the USA. However, the mandate was lifted in 1995 due to a number of reports from several of the projects that were utilizing rubberized asphalt do not meet the performance expectations. As result, funds were allocated for more research to be carried out to study the test methods and specifications and performance properties of crumb rubber modified asphalt (CRMA) (Report Cairo University, 1983).

A study carried out by the Department of Transportation had concluded that CRMA can have reduced permanent deformation and improved thermal cracking properties due to the higher dissipation of energy at low temperature (Shatnawi, 2001; Garcia et al., 2006). It absorbs UV rays from the sun and can help in reducing the formation of ice on the roadways in cold region and can help reducing stress due temperature gradient in overlays (Karacasua and Okur, 2012; Hsu et al., 2010). Although higher energy is required in mixing of rubber crumb and compaction of pavement, CRMA had been proven to be cost effective compared to conventional mixes (Celik and Atiş, 2008; Lee at el., 2008). Warm asphalt additives (Akisetty et al., 2011) can be used to lower the mixing and compaction temperature and also help in extending the long term performance of the pavement (Xiao et al., 2009; Akisettyet al., 2009). States like California, Florida and Arizona has found that CRMA is cost effective and has continued to use CRMA in their roads (Wong, 2007).

Although there are some concerns regarding dangerous gas emissions in the process of producing CRMA, Zaneti et. al., (2016) have found that the carcinogenic effect of the released gas is low. Presently, CRMA is experiencing an increased usage in the USA in recent years when several roads that utilize CRMA stood the test of traffic and time and still performing well compared to conventional design and due to this fact researches are still being carried out in order to improve the understanding of the properties and limitations of crumb rubber modified asphalt.

2.5.3 Interaction between bitumen and rubber

Bitumen is a unique material of petroleum origin that is viscoelastic and also has a self-healing property that can help it recovers its strength after damage (Qiu et al., 2011). These properties make it a very desirable material for pavement construction. Bitumen primarily consists of several chemical types namely asphaltenes, resins, and aromatics and saturates. Asphaltenes are highly polar, insoluble brown or black solid which are amorphous and forms 5% to 25% of the bitumen. The amount of asphaltenes governs the rheological properties of bitumen. Bitumen with a higher amount asphaltenes will have a lower penetration, higher softening point and a higher viscosity.

Resins acts as peptising agent of asphaltenes where the amount of resin in the bitumen influence the fluidity of the bitumen. It is black or brown solid or semi-solid and is very polar in nature. They form 5% to 30% of the content of bitumen.

The majority (40% to 65%) of bitumen consists of aromatics. They have a low molecular weight and are dark brown in nature. With a high dissolving ability for other high molecular hydrocarbon, it acts as a dispersion medium for peptised asphaltines. The last component of bitumen is the low molecular weight saturates. It forms 5% to 20% of the volume in bitumen as non-polar viscous oil. Resins, aromatics and saturates form the maltenes part of the bitumen.

The two main components (asphaltenes and maltenes) in bitumen play an important role in determining the properties of bitumen when mixed with rubber. Percentage and type of rubber, mixing duration and type of mixing method determines the property of the rubber modified binder and subsequently its performance (Read and Whiteoak, 2003).

Modifying bitumen with crumb rubbers can be done in either the wet process or the dry process. In the dry process rubber is not blended with asphalt but used as a replacement to a small portion of aggregate in the asphaltic mix. Rubber crumbs are mixed with aggregates and react as filler within the asphaltic mix. In the wet process, rubber crumbs are blended with bitumen at a certain temperature that is high enough to achieve adequate interaction between rubber and bitumen. There are two variants of wet process; the high-viscosity process and the no-agitation (terminal blend) process (Presti et al., 2012). In the high-viscosity process, the minimum percentage of crumb rubber is 15% to the weight of the bitumen and the rubberised bitumen blend must be continuously agitated at elevated temperature at certain duration to maintain good dispersal of the rubber crumbs. However, due to settlement problems in long term storage, rubberised bitumen produced in this process must be use immediately after being produced. In the no-agitation process, rubber crumbs are being mixed at high speed (8000 rpm) and high processing temperature (200^{o}C -260^{o}C) up to the point of rubber depolymerisation and are dissolved into the bitumen (Wang et al., 2015). This type of rubber modified bitumen does not require continuous agitation after the mixing process and can be transferred to the site like conventional bitumen. Although the performance of bitumen that was produced with this method is rather uncertain. Zhang and Hu (2013). claims that the addition of SBS polymer and moderate vulcanisation of CRMA can improve the storage stability and flexibility of the mix. Similar findings are also reported by Dong et al., (2016). In the dry process, on the other hand, coarser rubber crumbs are directly being added to the aggregates before the asphalt is added to the mixture.

When rubber crumbs are mixed with bitumen, maltenes component in the bitumen were absorbed by the rubber particle and this causes the rubber particles to swell 3 to 5 times its original size (Peralta et al., 2010). The change of the morphology of crumb rubber can be observed with an optical microscope (Miknis and Michon,1998) and some researcher had even proposed the use of nuclear magnetic resonance imaging to examine the morphology and the interactions of rubber particles with bitumen (Peralta et al., 2012). The absorption process of lighter constituents (maltenes) of bitumen has been shown to be rapid in the beginning and slows down in time until equilibrium of maltenes in the mix is achieved (Dong et al., 2012). This process left a higher proportion of asphaltenes in the asphalt and thus making the binder more viscous, the softening point value is increased while ductility and penetration value for the bitumen are decreased. Higher percentage of rubber crumb, mixing temperature and longer mixing duration will also produce a binder that has a higher viscosity with a higher failure temperature due to the absorption of maltenes in the binder into the rubber crumb particles (Jeong et al., 2010). Increased viscosity of crumb rubber modified bitumen enables the use of higher bitumen content with less binder drain down problem.

The adsorption rate (Airey et al., 2004) of bitumen that has a higher content of light weight fraction i.e. bitumen with higher penetration value and lower viscosity; has been found to be independent of rubber-bitumen ratio and will have a higher initial rubber adsorption rate and possibly a higher rubber swelling (Airey et al., 2003) . For instance, the rate of adsorption of the softer 160/220 penetration grade bitumen is roughly four times higher when compared to a 35 penetration grade bitumen. Neat bitumen with a higher content of light weight fraction will also give a better performance due to the higher swelling size of the crumb rubber particles (Cong, et al., 2013). Examinations through a florescent microscope reveals that higher swelling rate of crumb rubbers helped to improve the dispersal in asphalt to form a continuous and interlocked phase. This will cause the viscosity of the bitumen to increase.

Further, lighter components of bitumen that were absorbed into the rubber particle consequently cause a relaxation effect in the links between rubber atoms and decreasing the bulk density of the rubber and saturated rubber particles become brittle gel and at higher temperatures will split from the action of stirring and heating (Peralta et al., 2010). This will cause the rubber crumbs to depolymerise and lose its viscosity. Examinations of extracted rubber crumbs from the mix show that rubber particle size will decrease due the breakdown effect of rubber particles (Xiao et al., 2006). The breakdown process causes crumb rubber to release short fibres and filler materials which previously are included in the rubber compounds. Fatty acids, on the other hand move from rubber to bitumen and it is probable that it is contained naphthene-aromatic fraction of the bitumen (Holbert et al., 1997). Thermogravimetric (TGA) method analysis shows that crumb rubber starts to release polymeric components at mixing temperature of 200^{o}C (Navarro et al., 2007; Ghavibazoo and Abdelrahman, 2012). However, at lower interaction temperature where the rubber crumbs only swell, the type of crumb rubber composition may not be as vital.

The interaction that was described above occurs during the mixing process between bitumen and rubber. The outcome properties of crumb rubber modified bitumen is very sensitive and are highly governed by the mixing process which is dependent on external factors such as the mixing temperature, mixing duration and type; and internal factors such as type of bitumen, crumb rubber quantity, particle size, and type.

2.5.4 Performance of Dry Mix CRMA

In the dry mix process, crumb rubbers are added in to the mix along with the aggregates and binder at high temperature (150°C to 160°C) (Moreno et al., 2011). There is a higher potential of energy and natural resources savings in this process as the amount of crumb rubber used can be of a higher proportion and the amount of bitumen also can be increased (0.4% higher) (Hernández et al., 2009). As with wet process CRMA, the addition of rubber crumbs by the dry process also can increase the dynamic stability (Cao, 2007), creep modulus (Moreno et al., 2013) and the stiffness of asphaltic mixes (Navarro and Gámez, 2011; Cao, 2007; Moreno et al., 2013). Dry process CRMA also had been shown to have better performance than the wet mix in terms of stiffness modulus (Moreno et al., 2011; Moreno et al., 2013) .Cao (2007) reported that dry process CRMA have a good ability to resist permanent deformation at high temperature (60°C) and cracking at low temperature (-10°C). Moreno et al., (2013) on the other hand indicated that at a 20°C, CRMA had a higher stiffness modulus compared to unmodified mixes. However at elevated temperatures (60°C), CRMA mixes were found to have similar stiffness values with unmodified mixes which shows that CRMA mixes may have a higher thermal susceptibility at higher temperatures.

Cao (2007) highlighted that 3% (from the total weight of the mix) crumb rubber addition shows the best performance of dry process CRMA at both high and low temperature. Moreno et al., (2012,2013) however reported that 1.5% of crumb rubber addition gives the best results in terms of permanent deformation. An increase in the percentage of crumb rubber will increase the void contend and subsequently reduces the density of the mix due to the resilient properties of the rubber (Moreno et al., 2011). This means a higher amount of binder need to be incorporated into the mix to ensure good cohesion of the mix.

2.5.5 Performance of Wet Mix CRMA

Although CRMA mixes have a higher void content and would require higher energy to adequately compact the mix (Lee et al., 2008), a number of studies carried out to ascertain the durability of crumb rubber modified asphalt (CRMA) confirms that the rutting and ageing resistance (Tsu et al., 2010; Palit et al., 2004; Moriyoshi et al., 2013; Khalid and Artamendi, 2003; Xiao, 2007; Lee, 2009) and also the dynamic modulus (Hsu et al., 2010) of asphalt can be increased with the addition of rubber. Factors such as rubber type, rubber percentage and rubber mixing type have been identified to contribute to a higher rutting resistance. Moriyoshi et al., (2013) studied the effect of different sizes (0.85mm and 0.6mm) and proportion (20% and 30%) of rubber crumbs to the rutting resistance of stone matrix asphalt (SMA). Comparing mixes that contain different combinations of the selected crumb rubber percentage and size, the study found that while crumb rubber modified (CRM) mixes showed a higher rutting resistance when compared to control mixes, larger crumb rubber size (0.85mm) causes a higher void content in the mix. Satisfactory SMA mixes in terms of air void only can be achieved with mixes that contain 20% crumb rubber sizing 0.6mm. According to Khalid and Artamendi (2003) the improvement in rutting resistance in CRMA was marginal when the amount of crumb rubber is between 5 to 10%. Imaninasab et al., (2016) shows that the rutting depth of CRMA were reduced up to 61% with 20% crumb rubber modification. In terms of moisture susceptibility, Palit et al., (2004) reported that the higher retained Marshal stability, higher tensile strength ratio and improved stripping characteristic proved that CRMA is less susceptible to moisture damage.

The complex modulus, G*/sin δ and the storage modulus value, G', can be used to correlate the rutting resistance of pavements. A higher G*/sin δ and G' value reflects a higher elasticity and energy storage capability and therefore can be associated to rut resistance. Hamzah et al., (2006) found that the addition of rubber can increase the G*'sin δ value of CRMA mixes at temperatures between 20°C to 40°C by 30 to 55% while the storage modulus, G' value is increased up to 51%. Xiao et al., (2007) demonstrated that ambient processed crumb rubber increases the rutting resistance of CRMA. However, studies carried out by Fontes et. al. (2006) show that the mixture prepared with cryogenically processed crumb rubber displays a better complex modulus and fatigue resistance. The increase of crumb rubber content also can help in reducing the fatigue cracking factor, G*sinδ value of CRMA (Xiao and Amirkhanian, 2008). This helps the pavement in terms of fatigue resistance and extending the pavement life.

Apart for the G*/sin δ value, other parameters such as the penetration, the softening point value and the zero-shear viscosity, η_o can also be used to predict the rutting resistance of CRMA (Fontes et al., 2006, 2010; Khalid and Artamendi, 2003). Ghafarpour and Khodaii (2008) on the other hand, introduces the usage of rubber coefficient of rutting parameter (R_{cg}) in modelling the rutting parameter in CRMA mixes, which is a quantitative representation of the increase in rutting parameter values with the addition of crumb rubber. This allows them to conclude that finer rubber particle and crumb rubber from truck tyres yielded higher R_{cg} value. Higher R_{cg} value is also obtained for rubber crumbs that were produced in the ambient process.

Researchers are reporting different results for the tensile strength of CRMA. Palit et al (2004) and Xiao et al., (2008) showed that CRMA can have lower resilient modulus and indirect tensile strength (Shen et al., 2009) while Hossain et. al reported that the addition of crumb rubber does not show significant differences in the increasing the indirect tensile strength and fracture energy of CRMA. Pasquini et al., (2011) and Moreno et al., (2013) however indicated that crumb rubber does help to increase the tensile strength of asphaltic mixes. Apart from increasing the indirect tensile strength, Palit et al., (2004) added the CRMA is found to have higher flexibility at low temperatures and high stiffness and tensile strength at high temperatures while the increment in fatigue life is almost double.

Navarro et al., (2011) on the other hand, concluded that while the addition of rubber crumb does increase the stiffness and stability of the mix, the tensile strength of CRMA is decreased. Although the tensile strength however, is still within acceptable range, it is important to note that a lower tensile strength can cause lack of cohesion in the mix resulting in peeling and loss of aggregates while a stiffness modulus that is too high can cause crack reflection problems in a fatigued pavement. Lower tensile strength is also reported by Xiao et al., (2007) while adding that there is no significant difference between ambient and cryogenic rubber when the same percentage of rubber is used to the tensile strength.

2.6 Crumb rubber modification by wet process

Crumb rubber modification by the wet process has been shown to have the ability to help improve the rutting resistance, resilience modulus and fatigue cracking resistance of asphaltic mixes. This is due to the alteration to the property of the bituminous binder in terms of the viscosity, softening point, loss modulus (Lougheed and Papagiannakis, 1996) and storage modulus (Ali et al., 2013). The improvement however, is governed by the swelling process of rubber particles that were interacted with bitumen. Rubber crumbs can swell up to 3 to 5 times its original size due to the absorption of maltenes component of the bitumen (Peralta et al., 2010). This left a higher proportion of asphaltenes in the binder therefore increasing its viscosity. The outcome properties of crumb rubber modified bitumen (CRMB) is very sensitive and are highly governed by the mixing process which is dependent on external factors such as the mixing temperature, mixing duration and type; and internal factors such as type of bitumen, crumb rubber quantity, particle size, and type. Accurate selection of the processing variables such as bitumen type, rubber particle size and content, mixing temperature and duration are the keys to successful CRMB production. Table 1.1 lists the key parameters in for preparing CRMB that are suggested by American Society of Testing Material (ASTM), California Department of Transportation (Caltrans), South African Bitumen Association (Sabita) Association of Australian and New Zealand Road Transport and Traffic Authorities (Austroads) (Presti et al., 2012).

In recent developments, terminal blend CRMB has gain popularity due to a higher quality CRMB (Billiter, 1997; Attia and Abdelrahman, 2009). Unlike conventional wet mix that create a gel-like rubber particles through swelling, terminal blend process uses high shear mechanism to completely depolymerise rubber particles therefore achieving total digestion of crumb rubber into bitumen. Although the viscosity of such mix is reduced, total digestion of crumb rubber resolves the problem of crumb rubber settlement in CRMB. However, some researches argue that too much digestion can cause CRMB to lose its stiffening and elastic effect on the mix (Report by the University of Wisconsin-Madison, 2011).

Table 2.2: Important parameters in manufacturing CRMB according to several specifications around the world (Presti et al., 2012)

Properties	ASTM 2002	Caltrans 2006	SABITA 2007	Ausroads 2007
Bitumen Penetration (dmm)	Type 1: 85-100 Type 2: 120-150 Type 3: 200-300	120-150	60-100	85-100
Rubber sieve size (mm)	2.36	2.36	1.18	2.36
Rubber content (%)	≥15	18-22	18-24	15-18
Extender oil (%)	-	2.5-6	0-4	-
Calcium carbonate/talc (%)	0-4	-	0-4	-
Mixing Temperature (^oC)	177	190-220	180-220	195
Mixing speed (RPM)	-	-	3000	-
Mixing time (min)	45 + reaction	45-60	-	30-45

2.6.1 External Factors – Mixing Temperature and Duration

Factors such as mixing temperature and duration of crumb rubber modified bitumen are very crucial and will affect the performance of the binder. Due to the unique and delicate interaction process and the number of parameters involved, it is important that the mixing process of bitumen with rubber to be handled with extra precautions and care. For instance, coarser rubber particles and higher rubber concentrations would require a higher mixing temperature where a more stable binder against rubber segregation and settling can be achieved (Navarro et al., 2007; Attia and Abdelrahman, 2009). However, rubber will be depolymerised and dispersed into the mix if the temperature is too high and the duration too long (Chehovits ,1989).Crumb rubber mesh size, curing time, temperature and mixing rate are the factors that affect the rubber depolymerisation rate (Leite et al., 2001). Table 2.2 summarises the mixing parameters by some of Transportation Agencies in the United States and Canada.

The rate of swelling and the extent of swelling were highly dependent on the temperature of the interaction process. The rate of swelling increases when the temperature is increased for example from 160°C to 200°C and at the same time as the temperature increase the extent of swelling decreases (Green and Tolonen, 1977). Lalwani et. al. (1982) however, reported that there is no significant effect to the properties of bitumen when the temperature is increased from 150°C to 200°C, and when the temperature is increased from 200°C to 300°C, depolymerisation occurs and causes the binder to lose its elasticity. Depolymerisation process occurs slowly when the temperature is between 150°C to 200°C and proceeds rapidly (within several hours) when the temperature is above 200°C (FHWA , 1993). Viscosity increases continually at 150°C while at 175°C or 200°C, the viscosity initially increases rapidly, then reduced its pace, and decreases subsequently. At higher temperatures, (225°C) the viscosity reaches a maximum value within 5 min and decreases rapidly thereafter (Sun and Li, 2010).

Shen and Amirkhanian (2005) concluded that a mixing process for 15 minutes at 177°C is adequate for 15% of rubber crumb addition sizing between 30 to 40 mesh sizes to fully interact with the binder. Jeong et al., (2010) on the other hand, concluded that for a 10% crumb rubber mixture, a longer blending time up to 60 minutes and higher mixing temperature up to 177°C can contribute higher failure temperature and viscosity of binder at 135°C.

Table 2.3: Mixing parameters used by several Transportation Agencies (Cheng and Hicks, 2012)

Agency	Mixing temperature	Mixing time (min)	Crumb Rubber Size	Crumb Rubber (%)
Ontario, Canada	180^{o}C	45	0.5mm to 1.0mm. Gradation should be suitable to Type III of ASTM.	18-20%
California	190 -226^{o}C (adding CR)	45 (minimum)	2.36mm - 75µm. Length of particle should not exceed 4.75mm.	20 ± 2%; (75% scrap tire CR and 25% high natural CR)
	190-218^{o}C (blending)			
Arizona	180-205^{o}C (adding CR)	60 (minimum)	Type A (for chip seals): 2.36mm - 1.18mm. Type B: 2.0mm - 75µm.	Minimum 20%
	165-190^{o}C (blending)			
Florida	168-190^{o}C	30 (minimum)	Type A: 150um-300µm. Type B: 300µm-600um. Type C: 1.18mm-300µm	Minimum 20%

However, while the releasing of harmful gases into the environment, longer mixing duration and higher mixing and storage temperature have been shown to cause a higher rubber particles size reduction which leads to depolymerisation and this will lead to loss in viscosity. In an attempt to balance performance and storage compatibility of crumb rubber modified bitumen, Attia and Abdelrahman (2009) suggested the use of fine rubber crumb to produce terminal blends of CRMB. This approach saves energy as only 8% of the total interaction time requires high temperature of 200^{o}C and lower temperature can be used for the storage period. Billiter et. al (1997) also suggested that by increasing the mixing temperature, the mixing time and shear rate can be reduced and this can in fact produce a homogenous and truly elastic terminal blend that have enhanced performance.

At higher mixing temperatures, the viscosity of CRMB was found to increase quite dramatically. According to Jeong et al., (2010) compared to PG64-22 binder that was mixed at 177^{o}C, at 200^{o}C mixing temperature, the viscosity is 5% higher and at 223^{o}C, the viscosity increased 41%. With regards of the blending time, it was found the viscosity of binder that was mixed for 5 minutes increases 11% while at 480 minutes the viscosity increased to 46%. On the other hand, the failure temperature, between binder mixed at 177^{o}C and 200^{o}C, however was found to be insignificant. However, the failure temperature increased with blending time up to 60 minutes. Beyond the 60 minute period, the fail temperature was found not to be affected by blending time.

Mixing type too, can affect the properties of crumb rubber modified bitumen. Low temperature properties for instance, were improved with high shear mixing while low shear mixing improves medium and high temperature properties and its resistance to fatigue cracking (Aflaki and Memarzadeh, 2011). Dynamic viscosity, however are not affected by the blending type (Li et al., 2009). For high shear mixing technique, to produce optimal results for softening point and penetration values for modified binder with less than 25% crumb rubber, H. Li et al had suggested a shearing time of 40 min, a shearing temperature of 180^{o}C with a shearing rotational speed of 7000 rpm. High shear mixing will reduce the size of coarser rubber thus speeding the interaction process. Storage stability and rubber particle dispersal can also be improved with high speed shear mixing. Attia and Abdelrahman (2009) had proven that 88% (0.6% remaining from 5% rubber by the weight of bitumen) of the rubber particle can digested by the end of the interaction process. The shape of the impeller, on the other hand, does not contribute to any changes to the rheology of binders (Navarro et al., 2007). Celauro et al., (2012) however, mentioned that a low shear mixing can also produce the best performing CRMB provided that the base bitumen and crumb rubber are appropriately selected.

2.6.2 Internal Factor – Crumb rubber quantity & type of bitumen

The addition of crumb rubber has been proven to increase the properties of the bitumen such as the softening point, penetration and the viscosity in proportion of the amount of the rubber (Jeong et al., 2010; Wang et al., 2012; Nejad et al., 2012; FHWA, 1993). Table 3.1 shows the properties of an AC-20 asphalt blended with up to 21% of 1.18mm whole tire crumb rubber size with mixing time is 90 minutes at 176°C. Bitumen with higher viscosity will generally have a higher failure temperature and therefore have a longer service life due to higher temperature stability. Comparing crumb rubber addition of 10% and 20%, Jeong et al., (2010) shows that the 20% crumb rubber addition increased the viscosity by 550% and G*/sinδ (stiffness) value by 225%. However, when subjected to Rolling Thin Film Oven test (RTFOT) which simulated short term aging, it is found that the viscosity decreases with increasing rubber concentration (Wang et al., 2012). This is probably due to higher rubber dissolution as demonstrated by Billiter et al., (1997).

Table 2.4: Properties of crumb rubber modified bitumen (FHWA, 1993)

Binder property	Percent rubber (by weight of binder)						
	0	6	9	12	15	18	21
Viscosity at 176°C (cp)	60	550	800	900	1500	2500	6000
Cone penetration at 25°C	48	40	43	44	40	30	27
Resilience at 25°C	-1	-1	12	19	23	40	47
Softening point, °C	50	52	58	60	61	63	72

Apart from increasing the viscosity at high temperature, crumb rubber also contributes to a lower creep stiffness of the asphaltic mix which increases the low temperature cracking resistance of asphaltic pavement and lowering the aging index (Wang et al., 2012, Nejad et al., 2012, Billiter et al., 1997, Sebaaly et al., 2003). Wang et al., (2012) recommended 15% to 20% crumb rubber addition for a significant improvement in aging effects, creep stiffness and economic factors. Shen et al., (2005) on the other hand showed that 10% of CR addition increased the performance grade of bitumen from 64 to 70°C and 15% CR addition increased at least two high temperature performance grades from 64 to 76°C. However, Khalid and Artamendi (2003) highlights that an addition of crumb rubber of more than 10% would a binder that is too viscous for field mixing operations.

Crumb rubber modified bitumen however, can have storage problems due the settling of the rubber crumbs. Shearing the mix in high temperature until the rubber particles depolymerize is one of the option that can eliminate sedimentation problems and subsequently improve the properties of the bitumen if been properly manufactured (Attia and Abdelrahman, 2009). Very fine rubber particles (100 to 500 mesh) on the other hand, have been proven to have a non-settling properties when processed with high shear mixing. This can reduce the mixing time and temperature and therefore reduce depolymerisation and enhance aging resistance (Billiter et al., 1997). Cong et al. (2013) showed that a high amount of rubber (e.g 25%), with a high swelling rate and a high light weight fraction bitumen can improve the storage stability of CRMB. This is due to the reduction of the non-dissolved rubber particle thus reducing the sedimentation trend of the rubber particles. Navarro et al., (2004) on the other hand reported that crumb rubber modified bitumen is stable for particles that are sized 0.29mm or less.

Crumb rubber from waste tyres typically contain several types of compound such as synthetic rubber content, natural rubber content, total rubber hydrocarbon content and acetone extractables (FHWA, 1993). This is due to the different proportion of natural rubber, synthetic rubber and other components between truck tyres and passenger car tyres. For instance, tuck tyres contain more natural rubber when compared to passenger cars (which is higher in synthetic rubber) and this can affect the interaction between bitumen and rubber particles. Higher dissolution of crumb rubber that contains a mixture of truck and passenger car tyres can improve the viscoelastic properties of bitumen while higher dissolution of crumb rubber solely sourced from truck tyres does not enhance the properties of the modified binder (Ghavibazoo and Abdelrahman, 2012) . Table 3.2 shows the chemical composition of passenger car tire and truck tires (FHWA, 1993). Thodesen et al., (2009) showed that CRMB produced using truck tires crumb poses the highest viscosity and Cao and Bai (2007) reported that crumb rubber that come from truck tires gives a better performance in terms of a better fatigue resistance and high temperature performance.

Table 2.5: Chemical Composition of Various Types of Tires (FHWA, 1993)

Chemical Composition	Passenger/ Light Truck tread rubber (%)	Heavy truck treads rubber (%)	Whole tire rubber (%)	Range (%)
Acetone extract	17.2	11.4	15.1	5.8
Ash	4.8	5.1	5.0	0.29
Carbon black	32.7	33.2	32.0	1.2
Rubber hydrocarbon	42.9	50.2	47.9	7.3

The properties of lean bitumen used to produce CRMB also are very important to the quality of the modified binder. Softer bitumen with higher light weight fraction gives a higher swelling rate to the rubber particles and thus displays a better high and low temperature properties compared to harder bitumen with the same amount of rubber modification (Chehovits, 1989, Cong et al., 2013). Stiffer bitumen will typically show better high temperature stiffness compared to CRMB produced with softer bitumen that have improved low temperature stiffness. Bitumen with a lower light weight fraction will also produce CRMB that have lower viscosities and lesser degree of modification properties (FHWA, 1993).

2.6.3 Internal Factor - Crumb Rubber Type and Particle Size

Crumb rubber sizes can be classified into four groups, which are; coarse (9.5mm and 6.3mm), medium size (10–30 mesh or 2mm to 600µm); fine (40–80 mesh or 425µm to 180µm); and superfine (100–200 mesh or 150µm to 75µm) (Sunthonpagasit and Duffey, 2004). Similar to mixing time and temperature, crumb rubber mesh size is one of the important factors that govern the rubber depolymerization rate (Leite and Soares, 1999). Finer crumb rubber will swell faster due to a larger specific area and therefore give higher viscosities compared to coarser size. CRMB produced from fine rubber particles will also have a quicker viscosity reduction in the heating process due to its faster swelling rate and thus a faster depolymerisation. Sun and Li (2010) mentioned that the factors that influences the viscosity of CRMB according to their order of significance are crumb rubber content, curing temperature, rubber particle size and mixing time (Sun and Li, 2010; Liu et al., 2009). However, if the mixing time is increased, the viscosity of finer rubber crumbs tend to be lower (Presti et al., 2014) . This is, again, probably due to the depolymerisation of crumb rubber in the mix.

Apart from its sizing, crumb rubber properties can also, differ in terms of its microstructure. Many methods have been used to improve the microstructure of crumb rubber surface. Microwave irradiation of crumb rubber surface method cleft the surface of the vulcanization network, giving crumb rubber higher surface activity and therefore improves its viscoelastic nature and storage stability (Yu et al., 2011). Shatanawi et al., (2009) explores the possibility of using hot water to activate the surfaces of crumb rubber. This process removes light oil fractions in the crumb rubber particles, where it reduces segregation between rubber particles and binder thus improving its compatibility. Although the process does improve the settling properties of CRMB, it does not improve the rheology of the binder.

The difference in the crumb rubber surface microstructure can also differ due to the method the crumb rubber are manufactured. Crumb rubber that are produced using the cryogenic method will has angular smooth and cracked appearance while crumbs that were produced using ambient grinding has a rather porous surface (Shen and Amirkhanian, 2005) . This gives the crumb rubber that was produced using the ambient grinding twice the amount of surface area when compared with its cryogenic counterpart (Shen and Amirkhanian, 2009).

Due to its larger surface area and subsequent swelling rate, ambient processed crumb rubber will generally give a better performance than its cryogenic counterpart (Cong et al., 2013). CRMB produced from ambient crumb rubber gives a higher viscosity, complex modulus and phase angle thus gives better rutting resistance and higher elasticity (Shen et al., 2009; Thodesen et al., 2009; Lee et al., 2008; Shatanawi et al., 2008). Porous surface of ambient crumb rubber assisted the absorption of higher light constituents from the asphalt thus increasing its failure temperature regardless of the mixing time. Shen and Amirkhanian (2005) showed that CRMB produced with ambient CR also showed a better resistance on low temperature cracking than those with cryogenic CR (Lee et al., 2008).

Crumb rubber particle size also plays an important role in determining the outcome performance of CRMB. Smaller particle size produces modified bitumen that have higher viscosity, softening point and resilience due to a higher surface area (Neto et al., 2006; Putman and Amirkhanian, 2006; Billiter et al., 1997; Sun and Li, 2010) and aspect ratio (Navarro, 2002). Wang et al., (2012) reported that finer crumb rubber attains higher viscosity at high temperature and lower creep stiffness at low temperature. Higher viscosity also leads to a better rutting resistance as shown by Wong et al., (2007).

Cao and Bai (2007) on the other hand, showed that larger crumb rubber size gives a better high temperature performance and similar low temperature cracking resistance between CRMB manufactured with smaller crumb rubber particle size.

Similar results are demonstrated by Sebaaly et al., (2003) where he mentioned that while crumb rubber size does not have a significant effect on the low temperature properties of bitumen, different combinations of crumb rubber size and content can either improve or jeopardize the low temperature performance grade of the CRMB. A separate design of optimum rubber content is therefore required for each crumb rubber size and bitumen grade to ensure a properly designed CRMB.

Attia and Abdelrahman (2009) and Navarro et al., (2002) uses a wide variety of crumb rubber sizes in their attempt to study the effect of crumb rubber particle size to the rheology of bitumen. Their study concluded that the incorporation of coarser rubber into bitumen, increases the G* value (Attia and Abdelrahman, 2009) and subsequently increases the value of storage (G*/sinδ) and loss moduli (G*sinδ) especially at low frequencies (Navarro et al., 2002). However, according to Tayebali et al., (1997) , the coefficient of variance for the G*/sinδ values obtained from samples modified with 40 mesh crumb rubber size is statistically in close approximate with the one modified with an 80 mesh crumb rubber. Liu et al., (2009) also mentioned that there is no significant difference between basic performances of bitumen modified with different crumb rubber size. However, it is important to note that in this particular research, the crumb rubber sizes used are 60 mesh and 80 mesh size which is rather closely spaced.

2.6.4 Aging properties of CRMB

Binder aging is a process of oxidation and loss of light weight constituent in bitumen that leads to hardening of the material. There are two types of aging, namely short term aging and long term aging. Short term aging occurs during the mixing period of aggregate and bitumen while long term aging occurs in a longer time period after the construction process. In the oxidation process, polar aromatics component of the bitumen are converted into asphaltenes and this can be indicated by carbonyl formation (Chipps et al., 2001) and this resulted in a binder that a have higher viscosity. For this reason, it is important that the selection of lean bitumen to produce CRMB are done correctly since short term aging of CRMB manufactured using harder bitumen on the can create a binder that is too hard and cannot be used for pavement applications (Ali and Sadek , 2013).

Rubber addition on the other hand can help reduce the hardening rate and susceptibility of bitumen (Ruan et al., 2003; Ali and Sadek , 2013; Fanga et al., 2013) where rubber absorbs lighter constituent in the binder thus making the residual bitumen with a higher proportion of asphaltenes. Rubber also helps in lowering viscosity build-up with aging at low temperatures (Huang, 2006). Gel permeation chromatography analysis shows that a higher proportion of crumb rubber (15% to 20%) in the bitumen contributes to the reduction of large molecular size value of the binder. This is due to the ejection of lighter constituents that were earlier absorber by the rubber into the bitumen (Lee et al., 2011) thus helps in reducing the rate of asphaltenes formation and therefore slowing the aging process (Fanga et al.,2013). In order to further improve the aging characteristics of CRMB, Chipps et. al recommends the use of low-asphaltene bitumen processed with high-cure (terminal blend) CRMB with minimum rubber content of 10% (Chipps et al., 2001). Although hardening of asphalt cannot be avoided there are ways that aged bitumen can be rejuvenated to its original properties with the help of rejuvenating agent (Shen et al., 2005) or other substance such as recycled waste cooking oil (Asli et al., 2013). This technology have the potentially to be an excellent solution in using recycled asphaltic pavement.

2.6.5 Chemical modification of CRMB

Chemical modification of CRMB aims to alter the typical chemical bonding between bitumen and rubber particles. This is typically achieved with terminal blending process enhanced with certain chemicals or activators. Kocevski et. al uses grafting process to improve the properties of CRMB. In this process, the surface of crumb rubber is modified by bulk polymerization of acrylic acid. This process also can increase the viscosity and failure temperature of the CRMB (Kocevski et al., 2012). Chemical modifications that generates free radicals on the surface of crumb rubber is used by the US Federal Highway Administration where better interactions with bitumen is achieved resulting in a homogenous CRMB mix and therefore improving storage stability of the mix. (Mull et al., 2002).

Yadollahi and Mollahosseini (2011) on the other hand, uses polyphosphoric acid and trans-polyocternamer additive to achieve crosslinking between the sulphur elements in the asphaltenes and maltenes in the bitumen to produce macro-polymer network. This produces a CRMB that have better elastic properties at high temperatures and lower creep stiffness at low temperatures. Xie and Shen (2014) mentioned that adding trans-polyocternamer additive can improve the G*/sin(Δ) values between 14% to 20% and the phase angle up to 1.8%. Shatanawi et. al.(2012) on the other hand, showed that storage stability of CRMB can be highly improved with the addition of furfural as an activation agent in the mix. Better storage stability is also achieved by Cheng et al., (2011) that polymeric compatibaliser containing conjugated diene that reacts as a crosslinking agent. An addition to that the CRMB produced also has an improved permanent deformation and thermal cracking resistance. Puga and Williams (2016) however, noted that the use of polyoctonamer does not significant impact to the low temperature CRMA mixes.

2.7 Research Gap

From the literature survey that has been conducted, it can be seen that the studies that had been done are largely conducted in varying parameters from each other. The differing parameters that were used such as the mixing time, temperature and crumb rubber particle size for instance, can vary from one research to another and can be confusing at times. The high degree of variance of results shows that the properties of crumb rubber modified asphalt (CRMA) is very sensitive to changes in the method of preparation.

On the industrial side, crumb rubber is produced in a range of different nominal sizes. Due to the high demand of other sectors of the industry towards recycled crumb rubber, one of the problems faced by the authorities is the availability of certain size of crumb rubber size to be used in producing CRMB. This is due to the fact that the design for CRMB has been standardised and amount and the type of crumb rubber used normally have been limited to a certain range. This requires redesigning of the mix and this process can be time consuming and due to the urgency nature of some of the projects, and this can be counterproductive. The availability of a design system that could predict the properties of CRMB produced with different percentage and crumb rubber nominal size would provide flexibility to authorities to utilise the presently available crumb rubber size and quantity that would produce similar outcomes as the original design recommended in construction specifications.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter explains the methodology, materials, preparation of samples, experimental procedure, test apparatus, statistical method and model used in the study. The main objective of this research is to study the effect of crumb rubber modified asphalt (CRMA) to the durability of porous asphalt pavement. In order to achieve this objective, several tests had been carried out. For each test, three duplicate samples were prepared and tested. Figure 3.1 and Figure 3.2 show the methodology flow chart for the whole process utilised in the preparation and testing of the binder and mixture, respectively.

The tests that are conducted in this research can be divided into three stages. The first stage consists tests that evaluate the rheology properties of crumb rubber modified binder (CRMB) such as the penetration test, softening point test, the viscosity test (by Brookfield viscometer) and the oscillation temperature sweep test (by dynamic shear rheometer)t. The amount of crumb rubber modification used are 4%, 8% and 12% [m/m] to the weight of bitumen with each percentage group having four different crumb rubber size namely 150μm, 180μm, 425μm and 850μm. Apart from studying the properties of the modified bitumen, these tests are carried out to ensure that the resulting modified bitumen has suitable properties to be used in asphaltic mixes.

In the study, the laboratory produced binders were given identification names (ID) to differentiate them. In the identification nomenclature, the ID is as follows: number in front of the sample name is the rubber size and R for rubber content. For example, 850μm 4R the rubberised binder prepared with 850μm rubber size contains 4% crumb rubber, whereas the control sample is designated as 0R, which was prepared with bitumen 80/100 penetration.

In the second stage, using a series of different percentages of bitumen content ranging from 4% to 7% at 1% increment in each mix, three duplicates of Marshal mix samples are prepared for each rubber percentage and particle size and the properties of asphaltic mixes are assessed using the density- test (ASTM D3023), binder drain-down test (BS EN 12697) and Cantabro test for unconditioned sample (REAM-SP 5/2008) in order to obtain the optimum bitumen content for the mixes.

Using the optimum bitumen contents obtained above in consequent mixes, the durability of these CRMA mixes are then evaluated in the third stage using Cantabro test (ASTM D7064), Indirect Tensile test (ASTMD6931-12) and Indirect Tensile Stiffness Modulus (ASTM D4123) in both conditioned and unconditioned state. All tests were conducted in compliance with the Road Engineering Association of Malaysia (REAM-SP 5/2008), American Society of Testing and Materials (ASTM) and the British Standard (BS).

The results of the third stage of this research are the analysed using statistical software package to analyse the pattern of the results and look for correlations between the results and model any relationship between the parameters found.

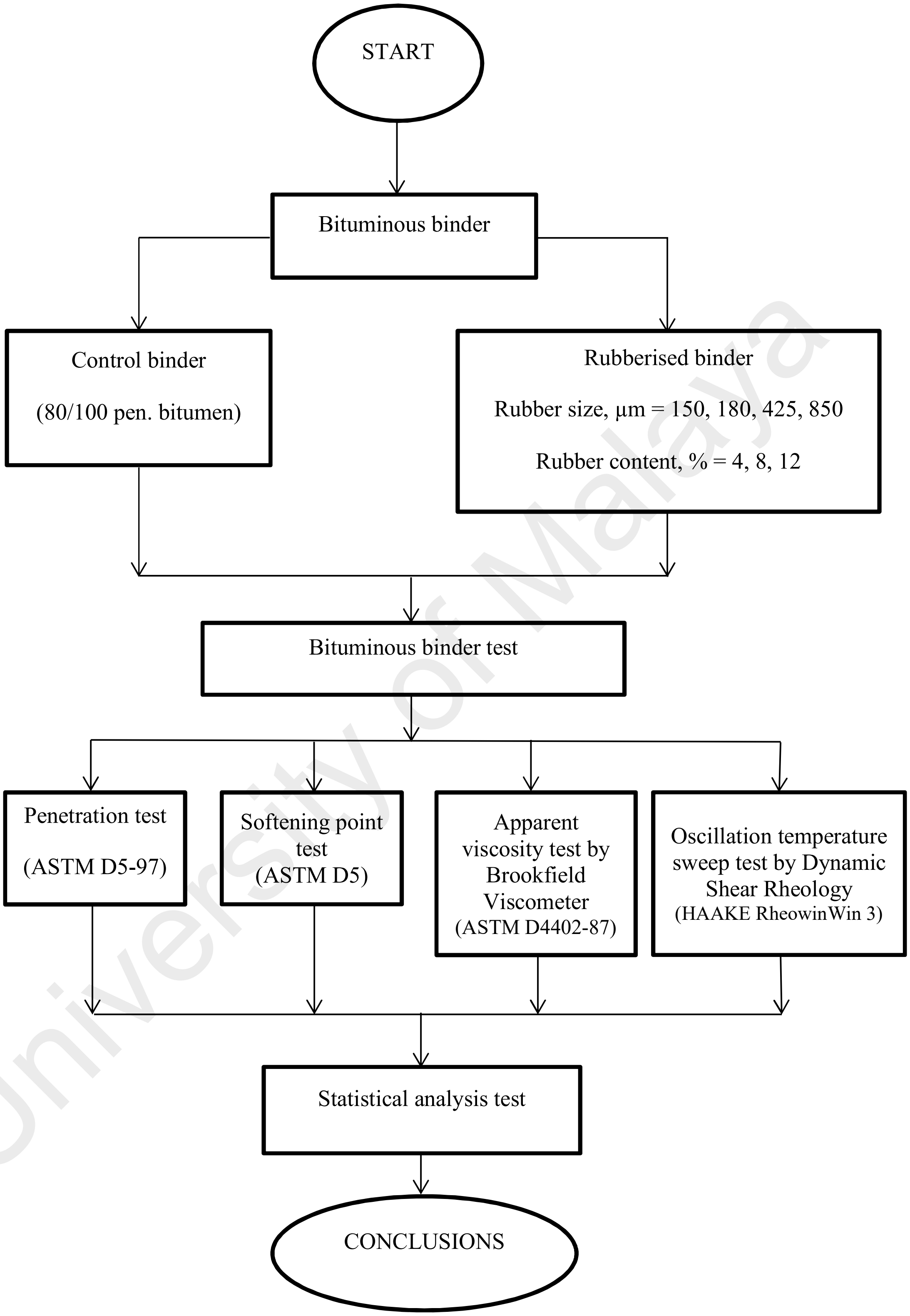

Figure 3.1: Methodology Flow Chart for Binder

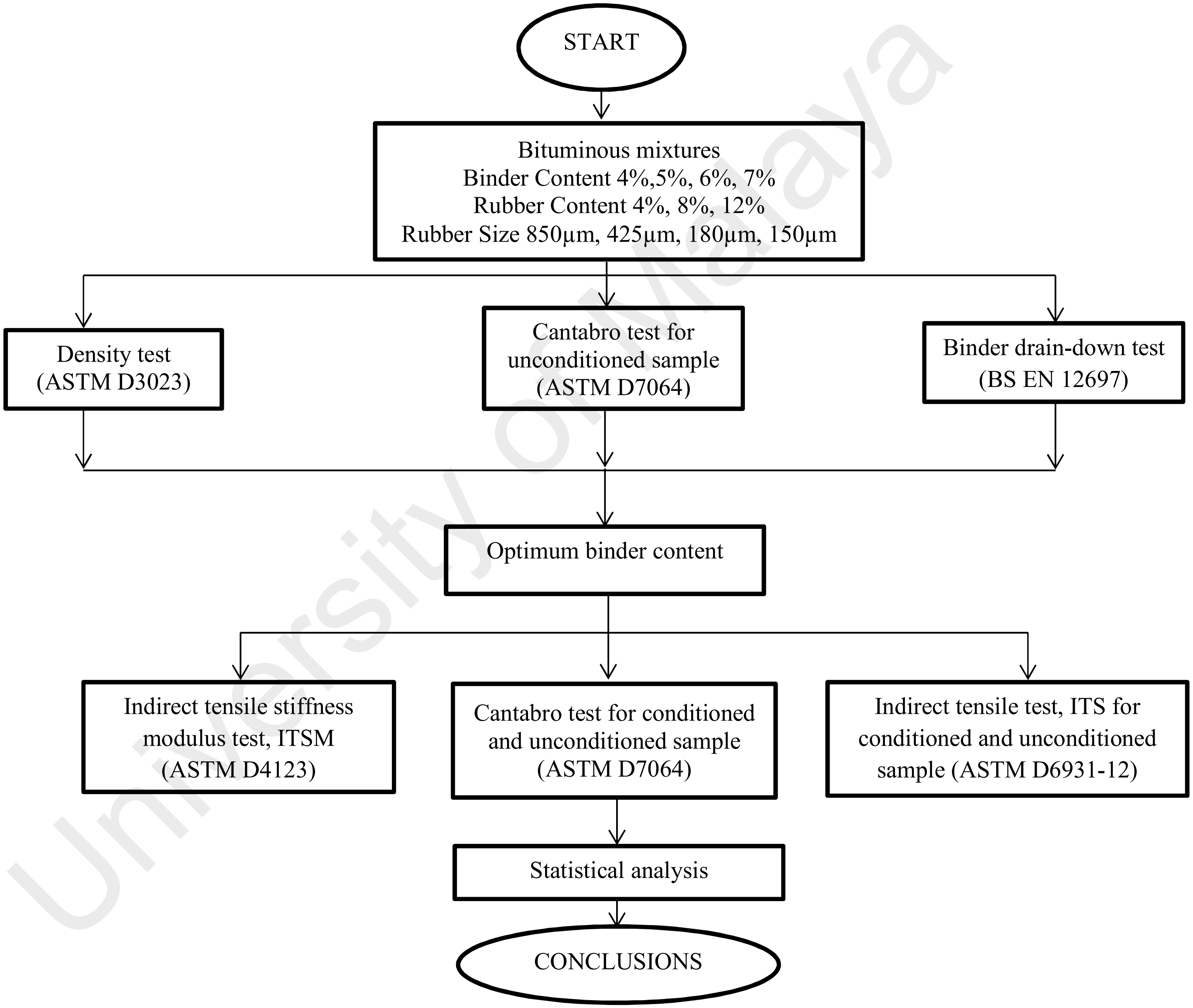

Figure 3.2: Methodology Flow Chart for Bituminous Mixture

3.2 Materials

The porous mixtures tested in this study were prepared with a bitumen 80/100 penetration, crumb rubber (150µm, 180µm, 425µm, 850µm in size) and mineral aggregate. All materials are determined locally in Malaysia and the sources remained constant for this study.

3.2.1 Aggregates

A mixture of coarse aggregate, fine aggregate and Portland cement as mineral filler was used to produce the test mix samples. Mineral filler (Portland cement) is incorporated as part of the combined aggregate gradation and the amount is 2% by weight of the combined aggregates (REAM-SP 5/2008). Aggregates were acquired from Kajang Rock Quarry in Kajang, Selangor. The test results in Table 3.1 shows that the physical qualities of the aggregates conform to the requirement of Road Engineers Association of Malaysia (REAM).

The gradation for porous asphalt is obtained from Road Engineers Association of Malaysia standard REAM-SP 5/2008 as shown in Figure 3.3 and Table 3.2. 1100 g of aggregates and 2% of the mineral filler (Portland cement) were used in each sample.

Table 3.1: Physical Quality of the Aggregates

Properties	Specification	Results / REAM Requirement
Aggregate crushing value	BS812:Part3	20 % (<25%)
Polished stone value	BS812:Part3	51.7 (>40%)
Flakiness index (coarse aggregate)	BS182:Part3	4% (<25%)
Flakiness index (fine aggregate)	BS182:Part3	13% (<25%)
Water absorption (coarse aggregate)	ASTM C 127-88	0.586% (<2%)
Water absorption (fine aggregate)	ASTM C 127-88	0.723% (<2%)

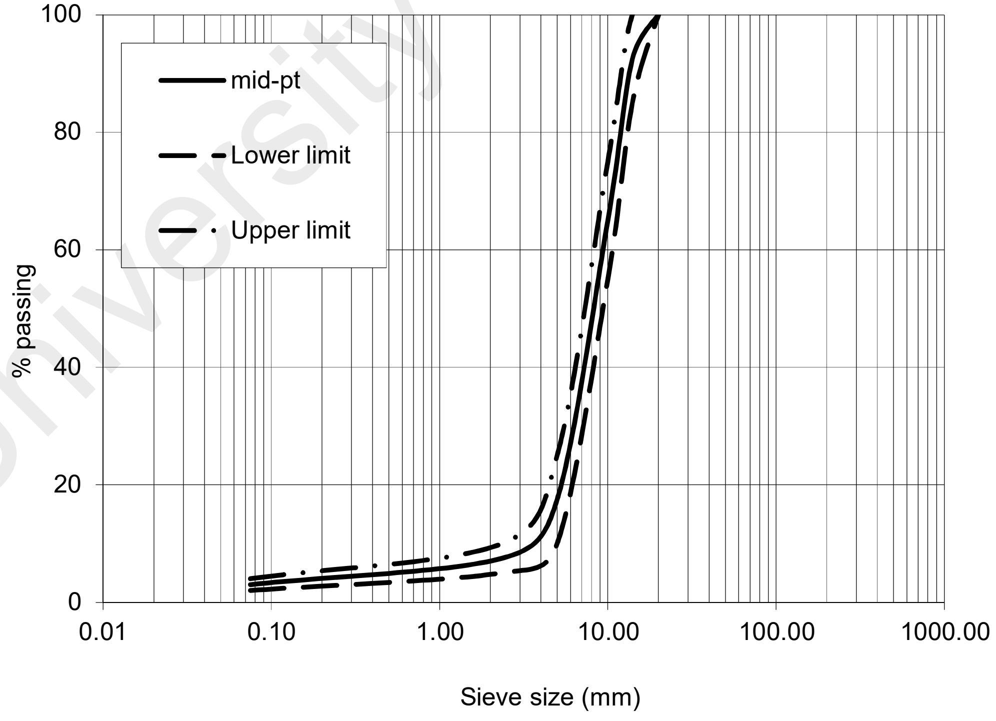

Figure 3.3: Aggregate Grading for Porous Asphalt Specimen

Table 3.2: Porous Grading for Porous Asphalt Specimen

BS Sieve size, mm	Percentage Passing, by weight
20.0	100
14.0	85-100
10.0	55-75
5.0	10-25
2.36	5-10
0.075	2-4

3.2.2 Bitumen

As penetration grade bitumen 80/100 is the most common type of bitumen used in Malaysia, this study uses 80/100 penetration grade bitumen acquired from Asphalt Technology Pte. Ltd with an average of 89 penetrations at 25°C (BS 2000-49:2007) was used in this study. The average softening point value (ASTM D36-95) for the bitumen is 48°C. Table 3.3 shows the specifications of the bitumen 80/100 penetration used in this study.

Table 3.3 Specification of Bitumen 80/100 Penetration used in this Study

Property	Unit	Test Method	Value	
			Min	Max
Penetration at 25°C	0.1 mm	ASTM D5	80	100
Softening Point (Ring & Ball)	ºC	ASTM D36	45	52
Flash Point (Cleveland Open Cup)	ºC	ASTM D92	225	-
Relative Density at 25ºC	g/cm³	ASTM D71	1.00	1.05
Ductility at 25°C	cm	ASTM D113	100	-
Loss on heating, wt.	%.	ASTM D6	-	0.5
Solubility in trichloroethylene, wt., min.	%	ASTM D2042	99	-
Drop in penetration after heating, max.	%	ASTM D5	-	20
Application temperatures, mixing at	ºC	-	140	165

3.2.3 Crumb Rubber

Four sizes of crumb rubber obtained from Rubplast Pte. Ltd. is used in the preparation of rubberised bitumen. The crumbs are ambient grinded and sizes are 850µm (20 mesh), 425µm (40 mesh), 180µm (80 mesh) and 150µm (100 mesh). These size are the the common sizes available in the market and are therefore selected to be used in this study. Table 3.4 shows the chemical composition and physical properties of rubber crumb.

Table 3.4: Chemical composition and physical properties of rubber crumb

Test	Value (%)	Method
Acetone Extract	10 ± 3	ISO 1407
Ash Content	8 ± 3	ISO 3451
Carbon Black	30 ± 5	ISO 1408
Rubber Hydrocarbon	52 ± 5	ASTM D297
Passing	>90	ASTM D5644
Heat Loss	<1	ASTM D1509
Metal Content	<1	ASTM D5603
Fiber Content	<3	ASTM D5603

3.3 Sample Preparation

3.3.1 Rubberised Bitumen

Each sizes of crumb rubber as mentioned in section 3.2.3 are used to prepare rubberised bitumen with three percentages of rubber content of 4%, 8% and 12% respectively by the weight of bitumen. The blend was produced using a propeller mixer at a speed of 200 RPM with the temperature at 160°C. In total there are 12 variants of rubberised blend with different rubber content and size that was used in this study and 3 duplicates were prepared for each sample.

3.3.2 Rubberised Porous Mixes

Rubberised porous asphalt mixes are prepared according to the methods suggested by ASTM D6926: Practice for Preparation of Bituminous Specimens Using Marshall Apparatus. Rubberised binder with different percentages of crumb rubber and crumb particle size described in the previous section are used to prepare the porous asphalt mixes in this study using the wet process. Mixes are identified with the size of crumb rubber modifier used, amount of crumb rubber and amount of binder used in each mix. For instance, a mix designated as “850μm 4R 5B” is a mix modified with 4% rubber sizing 850μm and the binder content for the mix is 5%.

Aggregates were heated in the oven at 160°C for an hour to ensure there is no moisture within the batch before being mixed by hand with the modified binder at temperature 180°C. After an even coating has been achieved, the mix was transferred into the Marshall mould and the samples were compacted at a temperature 165°C by a Marshall compactor with 50 blows at each face and the samples were then stored at room temperature for at least 24 hours. The temperatures chosen to mix and compact are consistent with field practice when rubberized bitumen is being produced (Puga, 2013). Moreover, Lee et al. (2008) mentioned that a suitable compaction temperature for rubberized bitumen is between 154°C and 173°C. The control specimens were prepared using similar procedures; however, the mixing temperature was fixed at 160°C and the compaction temperature at 145°C.Each specimen was 100±5mm in diameter and 65±5mm in height. Specimens were then tested for air voids (ASTM D3023), indirect tensile stiffness modulus test (ASTM D4123), Indirect tensile test (ASTM D6931-12) and Cantabro test (ASTM D7064).

The optimum binder content (OBC) was then determined in accordance with the Malaysian Standard (REAM-SP 5/2008). For the determination of OBC, three graphs, namely, loss of mass determined from Cantabro test, voids in mix (VIM) and binder drain-down were plotted versus the percentage of binder for each bituminous mixture. The OBC was determined in accordance with the criteria: average loss of mass obtained from Cantabro test (<15%), average air voids (18%-25%), average binder drain-down (<0.3%).

3.4 Experimental Works

3.4.1 Stage 1 – Physical and Rheological Tests

Four laboratory tests were selected to evaluate the physical and rheological characteristics of rubber modified bitumen. The tests are; the penetration test for bituminous materials (ASTM D5-97), the softening point test of bitumen – (Ring and Ball test) (ASTM D5), Viscosity Determinations of Unfilled Bitumen Using the Brookfield Thermosel Apparatus (ASTM: D4402-87) and the Oscillation temperature sweep test by Dynamic Shear Rheology (HAAKE RheoWin 3). These tests were conducted for both unmodified bitumen and the rubber modified bitumen.

3.4.1.1 Penetration of Bituminous Materials

The penetration test (ASTM D5-97) measures the consistency of bitumen using the penetration of a standard sized needle with a loading of 100g as the penetrating force. The sample was placed in a small containing water to maintain the temperature at 25°C. The penetration needle with the load was released and penetration value was measured in 1/100th of a centimetre during a 5 seconds loading time. Softer bitumen will indicate a higher penetration value while stiffer bitumen is identified with a higher penetration value. Three readings are taken for each sample and then averaged.

3.4.1.2 Softening Point of Bitumen - Ring and Ball Test

The softening point of bitumen test (ASTM D5) determines the susceptibility of bitumen to temperature changes. In this test, a small amount of bitumen was poured in a pair of brass rings. After the bitumen solidifies, a steel ball was placed on top of each ring and the setup was positioned in jar containing water with a temperature of 5°C. After 15 minutes, the water was then heated at a rate of 5°C per minute. As the heating continue, the bitumen become softer and the steel ball will sink to the bottom of the jar. The temperature where the steel ball touched the bottom of the jar is taken as the softening point of the bitumen. Stiffer bitumen would normally have a higher softening point while softer samples would have lower softening point temperature.

3.4.1.3 Viscosity Determinations of Unfilled Bitumen Using the Brookfield Thermosel Apparatus

The viscosity of bitumen at different temperatures was determined using the Brookfield Thermosel Viscometer (ASTM: D4402-87). In this particular test, molten bitumen was poured in a cylinder and then placed inside a thermosel where the temperature of the bitumen was controlled. A spindle was then lowered into the cylinder. The spindle spins and the resistance to rotation of the spindle at different temperatures were then translated by the apparatus as the viscosity of the bitumen. The temperature was increased to the desired temperature and the necessary readings were taken when the torque reading stable. Results were recorded at test temperature 110°C, 130°C, 135°C, 150°C, 170°C and 175°C.

3.4.1.4 Oscillation Temperature Sweep by Dynamic Shear Rheometer

The Oscillation Temperature Sweep is the ideal tool to observe how material changes over temperature. The test was performed using a dynamic shear rheometer under controlled strain conditions of 4%. The plate used was 25 mm in diameter and in order to improve the repeatability of testing the gap between the parallel plates was selected at 2 mm (Attia and Abdelrahman, 2009). In this study, the test was performed at temperature 30°C to 80°C with a frequency from 1 rad/s to 100 rad/s.

3.4.2 Stage 2 –Optimum Binder Content for Rubberised Porous Mixes

The optimum binder content for asphaltic mixes are the amount of bitumen that is adequate to give coat the aggregates in the mix in order for it to have good cohesion within the mixture and at the same time is not too much that it drains down to the bottom of the mix. There are many method of obtaining the optimum binder content for porous asphalt mix. This research uses the characteristics of compacted specimens to determine the optimum binder content as suggested by the Road Engineers Association of Malaysia porous asphalt specification REAM SP5/2008. This method requires the design to balance between the abrasion loss of the mix and binder draindown values while retaining adequate amount of air void in the mix to provide good permeability. The optimum mix should have a dry abrasion loss value not more than 15%, binder drain-down value not more than 0.3% by weight of the total mix and the amount of void in mix of around 18% to 25%. The bitumen content that produces samples that fits all the required criteria is taken as the optimum bitumen content.

Laboratory tests that were carried out to determine the characteristics of rubberised porous mixes are the Percent of Air Voids in Compacted Dense and Open Bituminous Paving Mixtures Test (ASTM D3203), Binder Drainage Test (BS EN 12697-18:2004) and Cantabro Abrasion Test (ASTM D7064). In order to obtain the density and specific gravity of the mix as per required by ASTM D3203 above, Theoretical Maximum

Specific Gravity and Density of Bituminous Paving Mixtures Test (ASTM D2041) are also carried out.

3.4.2.1 Percent of Air Voids in Compacted Dense and Open Bituminous Paving Mixtures Test (D3023)

The air voids (P_{av}) in a compacted mixture defined as the ratio between the volume of the small air voids between the coated particles and the total volume of the mixture. It is related to the maximum specific gravity, G_{bcm} and bulk specific gravity G_{mp} of the mix. The P_{av} value was calculated using the following equation:

$$\mathrm{P_{av}} = 100\,\frac{\mathrm{G_{mp}} - \mathrm{G_{bcm}}}{\mathrm{G_{mp}}} \qquad (3.1)$$

where;

G_{mp} = maximum specific gravity of the compacted mixture;

G_{bcm} = bulk specific gravity of the compacted paving mixture

The theoretical maximum specific gravity value of a mix is the ratio of the weight of the mix to the weight of water with the same volume of the mix. In order to obtain the theoretical specific gravity of the mix, the dry weight of loose asphalt mix were compared to the weight of water reduced from the mix which was submerged in a vacuumed sealed pycnometer. The temperature of the water is kept at constant at 25°C ± 4°C while the pressure of the vacuum is at 30mmHg for 5 to 15 minutes.

The theoretical maximum specific gravity, G_{mp} was calculated from the following equation:

$$\text{Theoretical maximum specific gravity, } G_{mp} = \frac{A}{A+D-E} \qquad (3.2)$$

where:

A = mass of oven dry sample in air, g

D = mass of pycnometer filled with water at 25°C, g

E = mass of pycnometer filled with sample and water at 25°C, g

The bulk specific gravity of the sample, on the other hand, is determined by obtaining the ratio of the weight of the sample in air to the difference between the weight of the saturated sample in air and the weight of the sample in water. Both the theoretical maximum specific gravity and the bulk specific density test are conducted according to ASTM D2041.

The bulk specific gravity of each sample was then calculated from the equation 3.3:

$$\text{Bulk specific gravity, } G_{bcm} = \frac{A}{B-C} \qquad (3.3)$$

where:

A = mass of the dry specimen in air, g

B = mass of the saturated surface-dry specimen in air, g

C = mass of the specimen in water, g

3.4.2.2 Binder Drainage Test

The binder drainage (BS EN 12697-18:2004) was conducted to determine the amount of binder that will drain from the mix during construction process. This is to ensure that the mix will have adequate bitumen coating before compaction. The acceptable value of drainage shall be not more than 0.3%. In this test, a loose mix of asphalt were placed in a wire basket and hung above a tray covered with aluminium sheet in the oven for three hours. The temperature of the oven is set to 15°C higher than the mixing temperature for the particular mix. The amount of bitumen drained from the mix into the tray was than weighed and the amount of binder percentage was then calculated with the following formula:

$$\text{Drained material, D} = 100\ x\ \frac{(W_2 - W_1)}{(1100 + A + B)} \qquad (3.4)$$

where:

W_1 = the initial mass of the tray and foil (gm)

W_2 = the mass of the tray and foil with the drained material (gm)

A = the mass of Portland cement in the mix (gm)

B = the initial mass of binder in the mixture (gm)

3.4.2.3 Non-Conditioned (Dry) Cantabro Test

The Cantabro Test analyses the resistance of compacted porous mixture to abrasion and was performed according to ASTM D7064. The test and was carried out in the abrasion machine. In the air conditioned Cantabro test, the samples were allowed to cure at room temperature (25°C) for 24 hours before the test. The samples were weighed and placed in the Los Angles Machine with no steel balls. The drum was then rotated at 300 revolutions per minute at room temperature (25°C). When the rotation had completed the samples were weighed one again and the loss of the samples due to the abrasion in the machine was calculated. Three duplicated samples for each mixes were used for the evaluation of the abrasion loss. The percentage of Air Abrasion Loss, P was calculated according to equation below:

$$\text{Abrasion loss, P} = \frac{P_1 - P_2}{P_1}\ x\ 100 \qquad (3.5)$$

where:

P_1 = initial mass of sample

P_2 = mass of sample after 300 revolutions

3.4.3 Stage 3 – Durability of Rubberised Porous Mixes

In order to assess the durability of the rubberised porous asphalt mixes the Indirect Tensile Test (ASTM D6931-12), the Indirect Tensile Stiffness Modulus test (ASTM D4123), and the Cantabro Test (ASTM D7064) which had been explained in section 3.4.2.3; were conducted. All tests were done with the samples both conditioned and non-conditioned.

Samples that were subjected to the Indirect Tensile Test and the Indirect Tensile Modulus test on the other hand were conditioned according to the AASHTO T283 method where the samples were water saturated at 25°C in a vacuum container with 13 – 67kPa pressure to obtain 70% to 80% saturation and then placed in water bath at 60°C for 24 hours. The samples were then transferred in another water bath where the temperature is 25°C for 2 hours before being subjected to the respective tests.

3.4.3.1 Conditioned (Wet) Cantabro Test

Similar procedure with unconditioned Cantabro test was performed in the conditioned Cantabro test. However in the conditioned Cantabro test, the samples were placed in a water bath at 49±1^{o}C for four days. The samples were then taken out of the bath and allowed to drain for 18 hours before being tested as described in section 3.4.2.3 on air cured samples.

3.4.3.2 The Indirect Tensile Stiffness Modulus Test

The Indirect Tensile Stiffness Modulus Test is a material stiffness test that conforms to the ASTM D-4123-82 (1987). The test was performed to determine resilient modulus values using the repeated-load indirect tensile test. This repeated-load indirect tensile test method was conducted by applying compressive loads with a prescribed sinusoidal waveform and can be used to study effects of temperature, loading rate, and rest periods. The resilient modulus of the sample was calculated using the horizontal deformation and the Poisson's ratio. Consequently, the values of resilient modulus can be used to evaluate the relative performance of bituminous mixtures as well as to generate performance input for pavement design or pavement evaluation and analysis.

The diameter and thickness of the samples was measured using a venire clipper and recorded to the nearest 0.1mm. The sample was then placed in a UMATTA Machine cabinet and set the temperature of UMATTA Machine to the specified test temperature. The sample was mounted in the indirect tensile jig and the loading frame height was adjusted. The level display was used to mechanically adjust the LVDT transducer to operate within the electrical range. The "Edit" function was enables to alter the parameters used in the test. The test was begun by entering the "Run" command. All samples were tested with selected parameters i.e. 24 hours preconditioning time at 25^{o}C, test temperature at 25^{o}C, 0.40 Poisson ratio, 1000 ms testing pulse period and 5 conditioning pulse count. The resilient modulus was automatically calculated as a part of the operation of the UMATTA machine using computer software supplied by UMATTA.

3.4.3.3 The Indirect Tensile Strength (ITS) Test

The indirect tensile strength (ITS) test was conducted in accordance with ASTM D6931. The values of ITS can be used to evaluate the quality of the mixes including the potential for rutting and cracking. This study performed two conditions of samples namely unconditioned and moisture-conditioned samples to analyze the potential of moisture damage to the mixes. Under unconditioned, samples were placed in an air bath for a minimum of 4 hours, whilst for moisture-conditioned samples were conditioned by immersed in a water bath at 25^{o}C for 24 hour prior to testing. The conditioned samples are treated the same was as explained in 3.4.3.1.

Diameter and thickness were recorded and designated as D and t respectively prior to conditioning the samples. Sample was placed onto the lower loading strip and the top loading strip was slowly lowered until in light contact with the specimen. Loading strips are checked to ensure it is parallel and centered on the vertical diametral plane. A vertical compressive ramp load was applied until the maximum load is reached. The maximum load was recorded and designated as P.

The ITS was calculated using the following equation 3.7:

$$\text{ITS} = \frac{2000\ x\ P}{\pi\ x\ t\ x\ D} \qquad (3.7)$$

3.5 Statistical Analysis

In this study, four different size of crumb rubber (150µm, 180µm, 425µm, 850µm), four percentages of rubber content (0%, 4%, 8% and 12%) and four percentages of binder content (4%, 5%, 6% and 7%) were investigated. After studying the individual effects of the independent variables (rubber size, rubber content and binder content) on the properties of the binder and mixture, it is necessary to statistically compare and evaluate the significant effect of each variable involved. In addition, the collective effects due to any combination of the independent variables need to be identified. Multiple linear regression was considered for such purpose assuming that the sample population follows a normal distribution.

There is more than one factor (rubber size, rubber content and binder content) that affects the properties of the binders and mixtures investigated in this study. Therefore, multiple linear regression analysis was employed to compare the significant effects as well as to predict and explain the properties of the binders and mixtures based on different factors. The output of regression analysis is an equation that represents the best prediction for the properties of the binders and mixtures based on the value of a few factors and the coefficient of determination (R^2) was used to investigate the contribution of the factors on the variance of the measured properties.

Multiple linear regression with stepwise method was conducted with the assumption that the linearity, normality and homoscedasticity were not violated. It is a method of regressing multiple factors while simultaneously removing those that are unimportant and the regression was executed at the significance level, $\alpha = .05$ (5%) or confidence level 95%.

3.6 Summary

This chapter consists of several sections: the first section of this chapter discusses the physical properties of the materials used. The second section explains the preparation of the samples and the related test. The third section describes the experimental works, performance predicted model and statistical analysis used in this study.

The materials used in this study are aggregate, mineral filler, bitumen and crumb rubber the properties of which are tabulated in Tables 3.1 – 3.4, respectively. In this study, rubberized bitumen was first prepared for use as a binder in preparation of the bituminous mixtures.

Different sizes of crumb rubber (150μm, 180 μm, 425 μm and 850 μm) were used in the preparation of rubberized binder. Different percentages of rubber content (4%, 8% and 12%) were incorporated into the bitumen 80/100 penetration in preparation of the rubberized binder produced with continuous blend. The amount of rubber content was limited to 12% since a further increase in the rubber content could decrease the performance of the rubberized mixtures (Nuha et al., 2013a; 2013b; 2014). Properties of the rubberised bitumen and bitumen 80/100 penetration were evaluated by penetration test (ASTM D5-97), softening point test (ASTM D5), apparent viscosity test (ASTM D4402-87) by Brookfield Viscometer and oscillation temperature sweep test (HAAKE RheoWin 3) by Dynamic Shear Rheology. For each test, three duplicate specimens were prepared and tested.

Aggregate gradation, porous was utilised in preparation of the bituminous mixtures as suggested by the Road Engineering Association of Malaysia (REAM). In this study, rubberized bitumen was used in the preparation of the bituminous mixtures with different percentages of binder content (4%-7%).

The effects of rubber size, rubber content and binder content in properties of porous mixtures were evaluated using density test (ASTM D3023), indirect tensile stiffness modulus test (ASTM D4123), indirect tensile test (ASTM D6931-12), Cantabro test (ASTM D7064) and binder drain-down test (BS EN 12697). Based on the results obtained from above experiments, optimum binder content (OBC) was determined and used in the preparation of next sample for further performance evaluation. Mixes prepared with OBC were then tested for indirect tensile stiffness modulus test, Cantabro test for conditioned and unconditioned sample and indirect tensile test for conditioned and unconditioned sample.

Moreover, statistical analysis was conducted using multiple linear regression (stepwise method) at a confidence level of 95% in order to develop the empirical relationship models as well to determine the significant factors. In this research, the factors that might influence the research objectives are crumb rubber size, crumb rubber content and binder content.

CHAPTER 4: RESULTS AND ANALYSIS

4.1 Introduction

This chapter presents and discusses the results obtained from the testing that was carried out according to the experimental plans presented in Chapter 3. In addition, this chapter deals with the results of the statistical analysis (multiple linear regression) performed using statistical package for the social sciences (SPSS) software. Multiple linear regression was performed using the stepwise method at the significance level, $\alpha = .05$ (5%) or confidence level of 95%. In this study, all results were plotted and discussed using the average results of the three replicates.

4.2 Penetration Test

Table 4.1 shows the average penetration value for samples with different rubber content (RC) and varying nominal crumb rubber size (RS) while Figure 4.1 and 4.2 show the trend of penetration reduction with respect to RC and RS. Penetration test carried out to the rubberized bitumen samples showed that the addition of crumb rubber (CR) and reducing the RS decreases the penetration value.

Table 4.1: Average penetration value (0.1 mm) of crumb rubber modified bitumen and control sample

Rubber Content, %	**Crumb Rubber Nominal Size, µm**				**Average**
	850	**425**	**180**	**150**	
0% (control)	87.5				-
4%	80.5	75.8	76.3	71	75.9
8%	79.3	67.5	55.8	52.8	63.9
12%	58.3	57.5	57	55.3	57.0
Average	72.7	66.9	63.0	59.7	

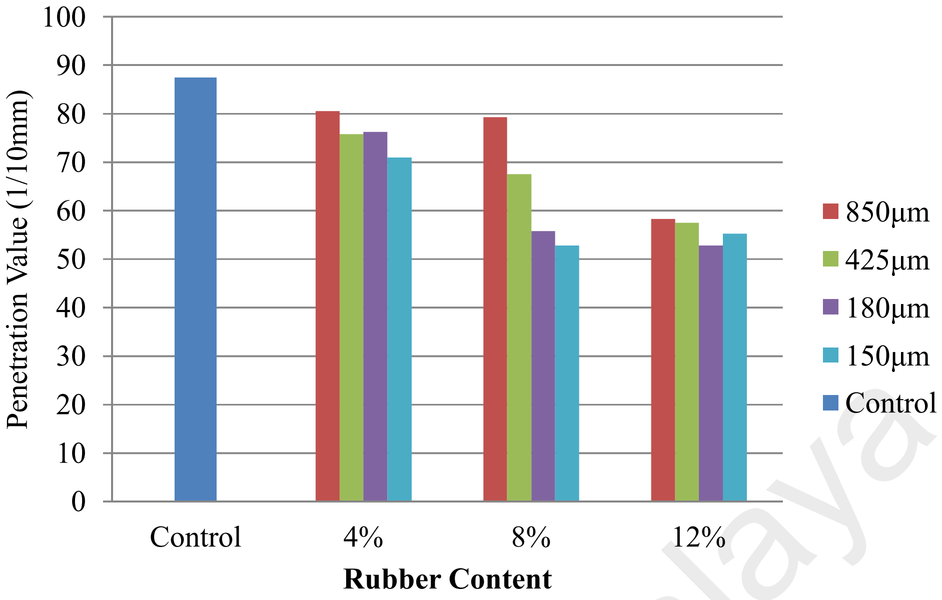

Figure 4.1: Average penetration value of crumb rubber modified bitumen according to rubber content

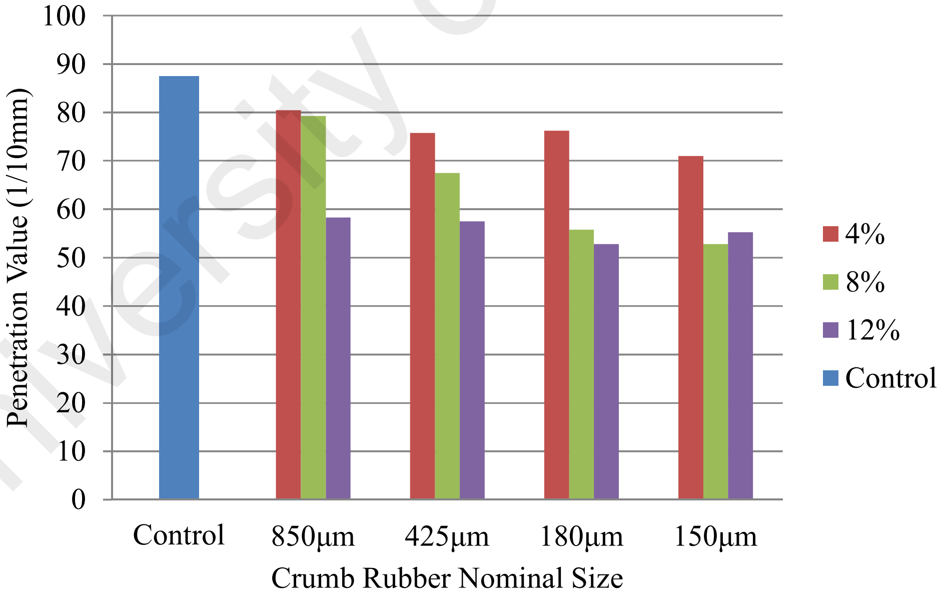

Figure 4.2: Average penetration value of crumb rubber modified bitumen according to crumb rubber nominal size

The results show that at 4% rubber addition, the penetration value for different CR sizes ranges within 8.05mm to 7.1mm with an average penetration of 7.59mm; while 8% rubber addition recorded an average of 6.39mm with penetration values ranging from 7.93mm to 5.28mm. Samples with 12% rubber modification shows a lower penetration value from 5.83mm to 5.53mm with an average of 5.7mm.

In general, the results reveal that higher amount of rubber content clearly contributes to a lower penetration value. For instance, in the case for 850µm rubber size, the increase from 0% to 4% rubber content shows a decrease of about 8% penetration value; a further increase in rubber content from 4% to 8% and 8% to 12% show a decrease of about 1.49% and 26.48% penetration value, respectively.

From the results it can be seen that apart from crumb rubber content, crumb rubber size also contributes to the reduction of penetration value (see Figure 4.2). Samples with finer CR shows lower penetration value compared to samples with coarser CR. Average penetration value for control samples (0% rubber addition) are recorded at 8.75mm. At 4% to 12% RC, the penetration values for samples with RS of 850µm range from 8.05mm to 5.83mm with the average of 7.27mm while samples with RS of 425µm recorded penetration value from 7.58mm to 5.75mm with the average penetration value of 6.69. Lower range of penetration values (7.63 to 5.7mm) are shown by samples with 180µm RS with an average of 6.30 and samples with 150µm RS recorded an even lower penetration value which is between 7.1mm to 5.53mm where the average penetration is 5.97. Stated another way, for instance at 8% RC, the decrease of rubber size from 850µm to 425µm shows a decrease of about 14.88%; a further decrease in rubber size from 425 µm to 180 µm and 180 µm to 150 µm show a decrease of about 17.3% and 5.38%, respectively.

From the obtained results, it is clearly reveals that the decrease in penetration value of crumb rubber modified bitumen is due to the addition of crumb rubber to the binder, which makes the binder stiffer, thus increasing the difficulty of the penetration needle to penetrate the crumb rubber modified bitumen. The reduction of penetration value of crumb rubber modified bitumen are mainly attributed to the absorbtion of asphaltenes from the bitumen to crumb rubber particles. Therefore, the higher amount of crumb rubber used in modifying bitumen, the lower the penetration would be. Larger surface area of finer crumb rubber on the other hand contributes to a higher absorption ratio of asphaltenes with respect to its volume by the rubber crumbs thus further reducing it's viscosity and subsequently it's penetration. The results are consistent with the findings of previous studies (Mansob et al., 2014; Singh et al., 2017).

Figure 4.3 and 4.4 show that the relationships between the amount of crumb rubber and its nominal size to the penetration of bitumen are linear. It can be seen that the slope showing the relationship between penetration value and rubber content (RC) is higher (-228.13,-240.63,-278.12) than the slope between penetration value and crumb rubber nominal size (0.0102, 0.0141, 0.0032). This shows that RC has a higher impact to penetration value than crumb rubber size. The relationship between crumb rubber nominal size and penetration value on the other hand, shows a slightly flatter curve. This demonstrates that the relationship between penetration value and nominal crumb rubber size have a lower correlation compared with that of rubber content. This is confirmed with statistical analysis (multiple linear regression with stepwise method) where the beta value (β) of rubber content (0.75) is higher compared to rubber size (0.393). Details on the statistical analysis can be referred in Section 4.1.1.

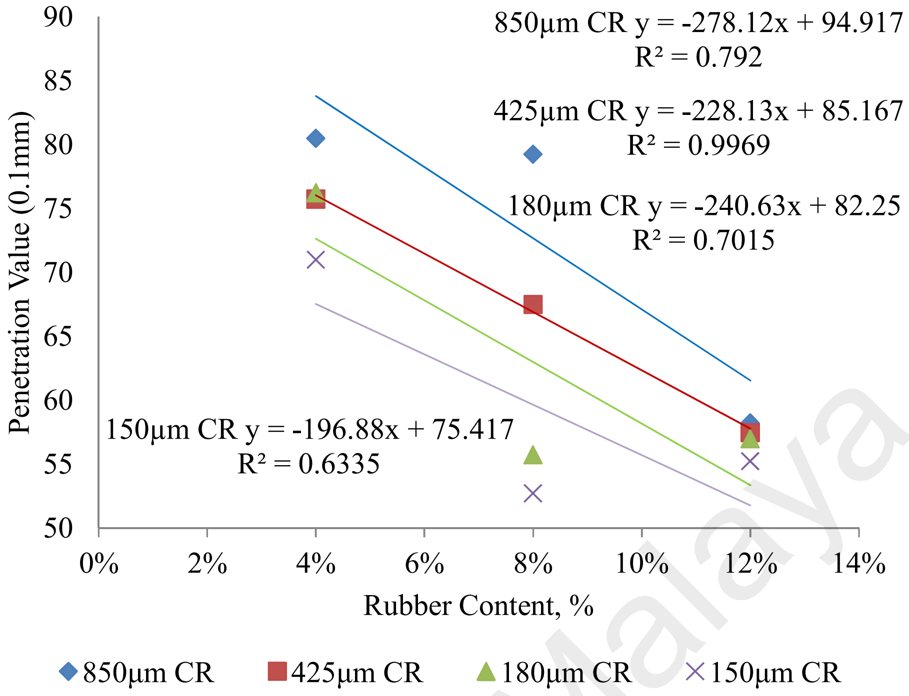

Figure 4.3: Relationship between penetration values to rubber content for different crumb rubber nominal size

Using the regression equations in Figure 4.3, the amount of rubber content required to obtain a specific penetration value with the crumb rubber nominal size can be estimated. The same relationship can also be obtained from Figure 4.4; however regression equations from Figure 4.3 are selected as the statistical analysis shows that the β value for the rubber content (0.75) is higher compared to the rubber size (0.393).

Table 4.2 lists the rubber content required to obtain a range of expected penetration value using several crumb rubber size while Figure 4.5 shows the generalized relationship between penetration values to crumb rubber nominal size for different rubber content achieved from equations in Figure 4.3. This relationship is useful in manufacturing CRMB particularly when the supply of a certain size of crumb rubber is not available at the time of manufacture. However, solely selection based on the penetration values are not recommended as it is show only the physical characteristic of the CRMB. Therefore further justifications on the behavior of the CRMB should be examined to ensure adequate selection of the crumb rubber nominal size in the manufacturing process.

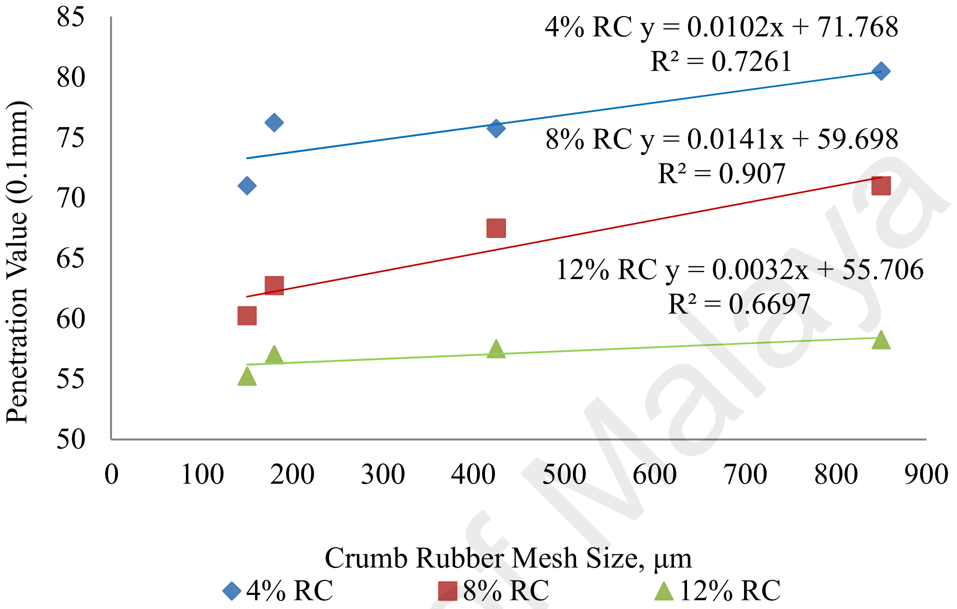

Figure 4.4: Relationship between Penetration Values to Crumb Rubber Nominal Size for Different Rubber Content

Table 4.2: The amount of rubber content (%) to be used to achieve an expected penetration value using different nominal crumb rubber size

Crumb Rubber Nominal size, μm	**Expected Penetration**			
	45	**55**	**65**	**75**
850	17.9	14.4	10.8	7.2
425	17.6	13.2	8.8	4.5
180	15.5	11.3	7.2	3.0
150	15.4	10.4	5.3	0.2

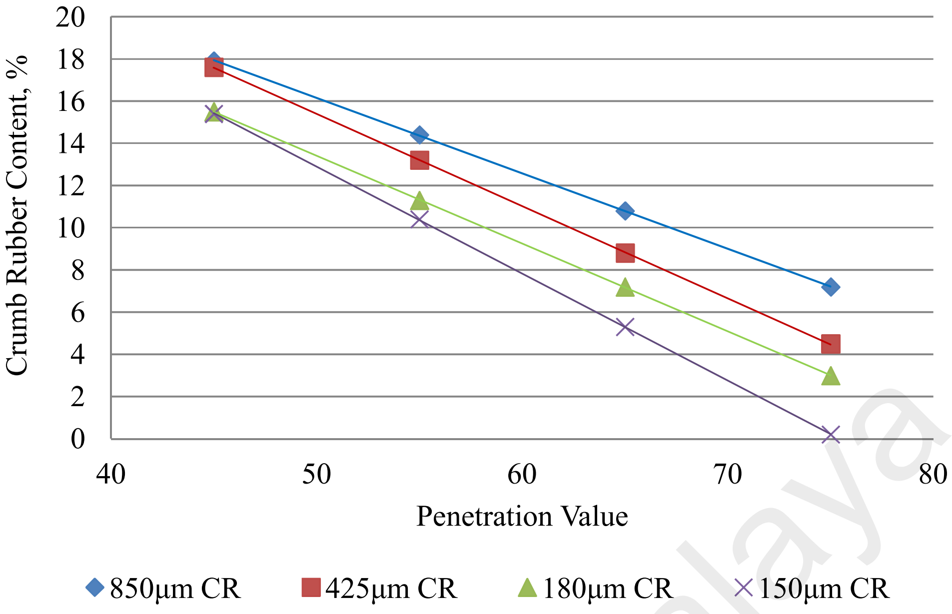

Figure 4.5: Generalised relationship between crumb rubber content and penetration value for different nominal crumb rubber size

4.2.1 Multiple Linear Regression Analysis on Penetration Value

Stepwise regression was conducted to determine which factors (rubber size and rubber content) were the predictors of the penetration values (Appendix A, Tables A.1a – A.1d). The regression results indicate an overall model of two factors (rubber content and rubber size) that significantly predict penetration values, $R^2 = 0.718$, $R^2_{\text{adj}} = 0.705$, $F(2, 45) = 57.157$, $p<0.05$. This model accounted for 71.8% of variance in the penetration values. The rubber content recorded a higher beta value (beta = -0.750, $p = 0.000 < 0.05$), followed by rubber size (beta = 0.393, $p = 0.000 < 0.05$). The regression model, which can be used to estimate the penetration value based on significant factors, is as follows (Equation 4.1):

$$\textit{Penetration value} = -0.750\ (\textit{Rubber content}) + 0.393\ (\textit{Rubber size}) \quad \ldots\ldots \quad (4.1)$$

A summary of the regression model is presented in Table 4.3. In addition, the bivariate and partial correlation coefficients between each factor and the penetration value are presented in Table 4.4.

Table 4.3: Model Summary: Penetration Value

Step	R	R^2	R^2_{adj}	ΔR^2	F_{chg}	p	df_1	df_2
Rubber content, %	.750	.563	.553	.563	59.225	<.05	1	46
Rubber size, µm	.847	.718	.705	.155	24.646	<.05	1	45

Table 4.4: Coefficients for Final Model: Penetration Value

Step	*B*	*β*	*t*	*Bivariate r*	*Partial r*
Rubber content, %	-2.359	-.750	-9.469	-0.750	-.816
Rubber size, µm	.014	.393	4.964	0.393	.595

4.3 Softening Point

The average softening point (SP) temperature of CRMB with different RC and RS is shown in Table 4.5, Figure 4.6 and 4.7. The results of the softening point tests show an increase in the softening point with the increase in rubber content. The higher softening point indicates that the binder is less susceptible to temperature changes, thus enhancing the ability of the binder to resist flow at higher temperature. The main reason for the crumb rubber increasing the softening point is the ability of crumb rubber to swell and absorb the aromatic oils from the bitumen; this results in an increase in the asphaltenes to resins ratio, which enhances the stiffened property of CRMB.

From the table and figures, control sample (80/100 bitumen) recorded an average SP of 44.7°C while samples with 4% RC shows SP value from 46.4°C for 850µm RS to 50.8°C for 150 µm RS with an average SP of 49°C. Samples with 8% RC shows SP ranging from 47.6°C to 54.1°C with an average SP value of 51.2°; 4.3% higher from the previous reading. At 12% RC, the average SP ranges from 50.3°C to 55.5°C where the average for the different RS is 53.3°C a further 3.9% increment of SP temperature.

Table 4.5: Average softening point temperature of CRMB and control sample

Rubber Content, %	Crumb Rubber Nominal Size, µm				Average
	850	425	180	150	
0% (Control)	44.7				-
4%	46.4	49.3	49.5	50.8	49.0
8%	47.6	50.9	52.3	54.1	51.2
12%	50.3	52.6	54.8	55.5	53.3
Average	48.1	50.9	52.2	53.5	

In general, the SP for all samples increased with the addition of rubber (see Figure 4.6). Finer rubber crumbs also shows a higher SP compared with samples with coarser CR (see Figure 4.7). The pattern obtained is somewhat similar with penetration test where the correlation is linear and the slope of relationship between softening point and rubber content is higher than that of crumb rubber size (see Figure 4.8 and 4.9). However, the statistical analysis shows significant correlation between the variables with P value < 0.05. Moreover, the beta value (β) obtained through multiple linear regression using stepwise method determines a good relationship of CR and RS to the softening point value (see Section 4.2.1).

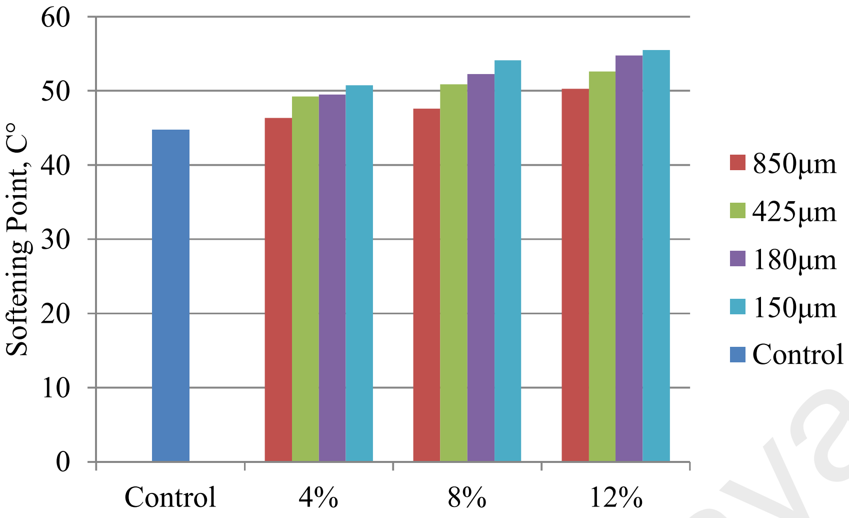

Figure 4.6: Softening Point Value versus Rubber Content

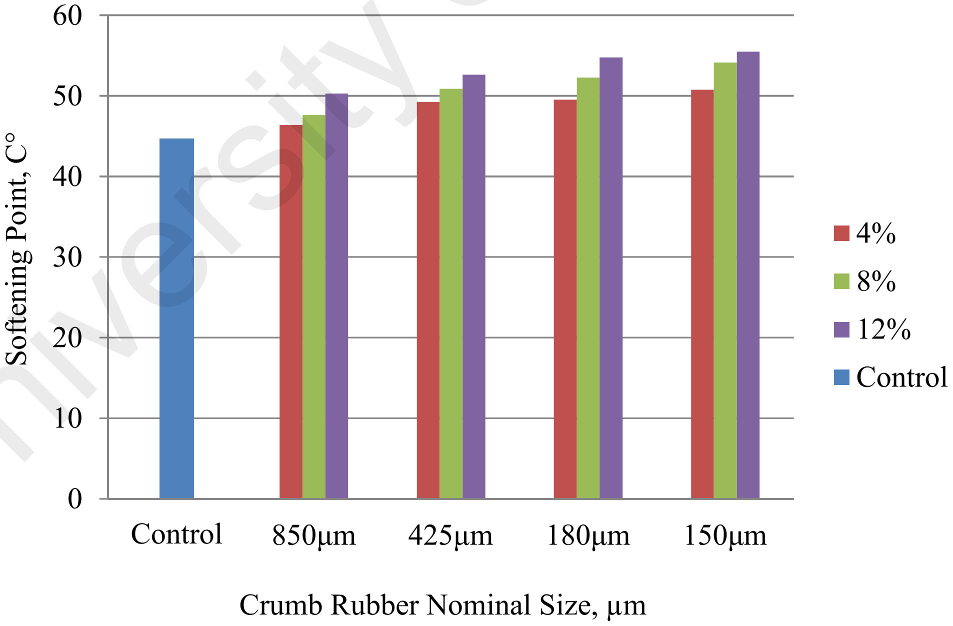

Figure 4.7: Softening Point Value versus Crumb Rubber Nominal Size

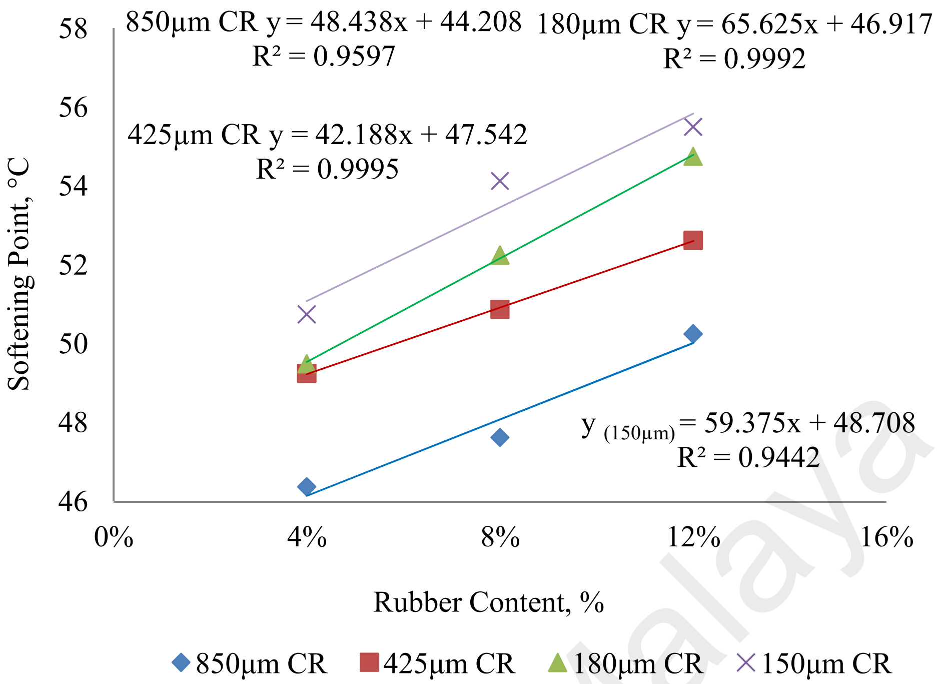

Figure 4.8: Relationship between Softening Point Values and Rubber Content for Different Crumb Rubber Nominal Size

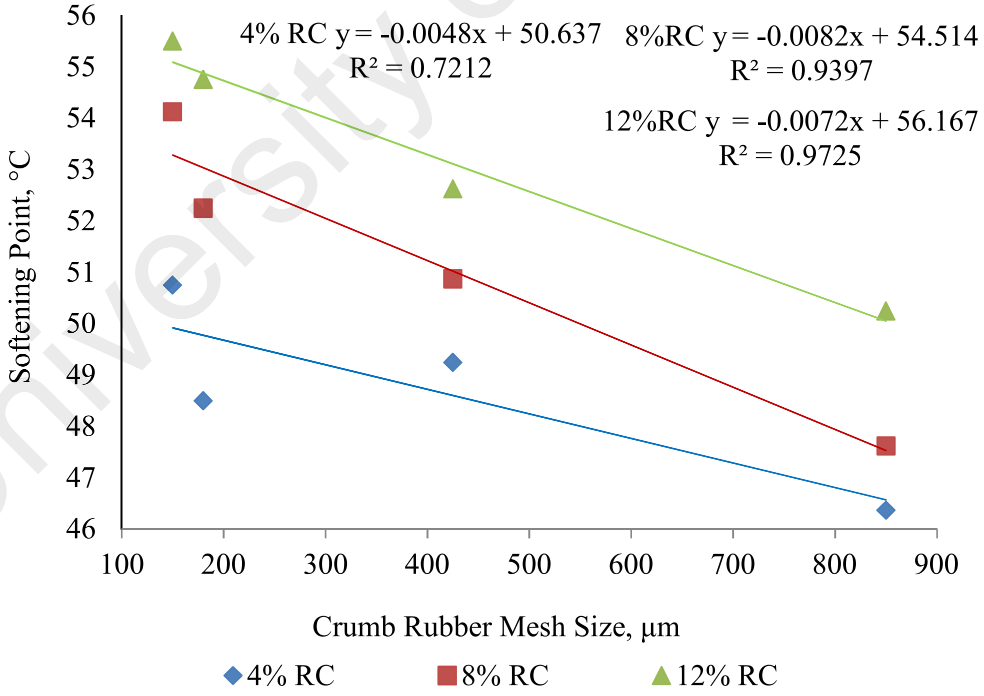

Figure 4.9: Relationship between Softening Point Values to Crumb Rubber Nominal Size for Different Rubber Content

4.3.1 Multiple Linear Regression Analysis on Softening Point Value

Statistical software SPSS 16.0 was performed to analyse the effects of factors (rubber content and rubber size) on the softening point value (Appendix A, Tables A.2a – A.2d). The analysis is performed at the significance level, $\alpha = .05$ (5%) or confidence level of 95%.

Multiple linear regression using the stepwise method was used to assess the ability of factors to predict the softening point value. Tables 4.6 and 4.7 show the summary of analysis. The factors explain 89.0% of the variance in the softening point value, R^2=0.890, R^2_{adj}=.0885, $F(2,45)$=181.176, $p<0.05$. Regression analysis shows that the rubber size and rubber content were statistically significant, with the rubber size recording a higher beta value (beta = -0.671, p =0.000 < 0.05), followed by rubber content (beta = 0.663, p =0.000 < 0.05). The regression equation, which can be used to estimate the softening point value based on the factors, is as follows (Equation 4.2):

$$\textit{Softening point value} = -0.671\ (\textit{Rubber size}) + 0.663\ (\textit{Rubber content}) \qquad (4.2)$$

Table 4.6: Model Summary: Softening Point Value

Step	R	R^2	R^2_{adj}	ΔR^2	F_{chg}	p	df_1	df_2
Rubber size, µm	0.671	0.450	0.438	0.450	37.656	<0.05	1	46
Rubber content, %	0.943	0.890	0.885	0.439	178.991	<0.05	1	45

Table 4.7: Coefficients for Final Model: Softening Point Value

Step	B	β	t	*Bivariate r*	*Partial r*
Rubber size, µm	-0.007	-0.671	-13.541	-0.671	-0.896
Rubber content, %	0.570	0.663	13.379	0.663	.0894

4.4 Viscosity Value

The effects of rubber size and rubber content on the viscous properties of modified bitumen at a wide range of temperatures (between 110°C and 175°C) are presented in Figures 4.10 – 4.12. The results indicate that the increase in temperature always leads to a decline in viscosity. This could be due to the bitumen becoming less viscous at high temperature; hence, the attractive forces among the bitumen molecules could overcome the resistance to flow more effectively.

From Figure 4.10, it seems that the reduction in the viscosity is greater at the initial stage of the temperature increment, and that subsequent increases in the temperature during the latter part had less influence on reducing the viscosity, as was observed for the control and crumb rubber modified bitumen. The available results show that the viscosity decreases rapidly between a temperature of 90°C and 150°C. At higher temperatures (above 150°C), the viscosity tends to level off (asymptote) as the temperature rises. This indicates that binders almost present Newtonian behaviour at temperatures above 150°C, as it exhibits near zero slopes. From the above results, it can be concluded that the viscosities of both the control and crumb rubber modified bitumen were decreased exponentially as a function of temperature due to the Newtonian property of the bitumen.

Table 4.8: Viscosity Values for CRMB at Different Temperatures

Rubber %	Temperature	Crumb Rubber Nominal Size, µm			
		850	425	180	150
4% Rubber	110	1809.50	2028.00	2056.50	2144.00
	130	625.25	644.00	744.00	819.00
	135	419.00	503.25	528.25	688.00
	150	219.25	263.00	266.00	315.00
	170	87.50	113.00	116.00	130.00
	175	62.31	90.63	102.22	112.50
8% Rubber	110	1997.25	3034.50	3241.00	4090.75
	130	566.00	1131.75	1228.50	1241.00
	135	441.00	937.75	766.00	966.00
	150	209.50	366.25	391.00	491.00
	170	87.50	153.25	166.00	216.00
	175	62.50	128.25	141.00	178.25
12% Rubber	110	2934.75	3654.33	4491.00	5153.25
	130	640.75	1122.25	1359.75	1722.00
	135	484.50	803.25	1109.50	1322.00
	150	266.00	444.00	662.75	766.00
	170	169.25	263.00	344.00	416.00
	175	150.00	228.25	263.00	388.00

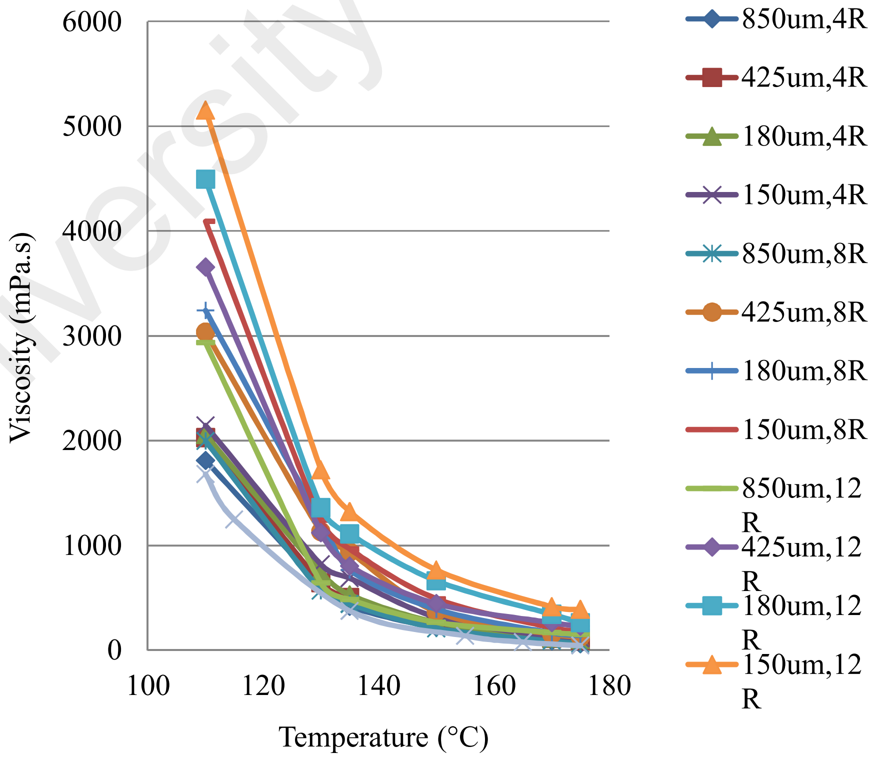

Figure 4.10: Viscous Properties of Binders at Different Test Temperatures

The effects of rubber content and rubber size to the viscosity value at test temperature 175°C are shown more clearly in Figures 4.11 – 4.12. Previous studies mentioned that the main effects of crumb rubber on the bitumen's viscosity can be seen at higher temperatures rather than at low temperature (Mashaan et al., 2013; Asim et al., 2013). The obtained results show that the increase in rubber concentration yielded a significant increase in viscosity, which may lead to better performance. The resulting viscosity increases due to the absorption of the bitumen's aromatic oil causes the swelling of the rubber particles. The swollen rubber increases the difficulty to flow since swollen rubber particles occupy more space than the rubber particles that are not swollen. Therefore, the higher the rubber content within the binder, the higher would be the density of the rubber particles within a unit volume of binder. Subsequently, this increases the viscosity of the binder.

As seen in Figure 4.11, the effects of rubber content are more significant with the decrease in rubber size. For instance, at 850µm rubber size shows similar viscosity values for rubberized bitumen prepared with 4% and 8% rubber content (62.31mPa.s and 62.5mPa.s for 4%R and 8%R, respectively). On the other hand, finest rubber size (150µm) shows an apparent increase in viscosity as the 4%R has a viscosity value of 112.5mPa.s while 8%R shows 178.25mPa.s, an increase of about 58%. These observations suggest that in order to achieve the desired viscosity of crumb rubber modified bitumen, a proper crumb rubber concentration should be properly selected especially when various sizes of crumb rubber were applied.

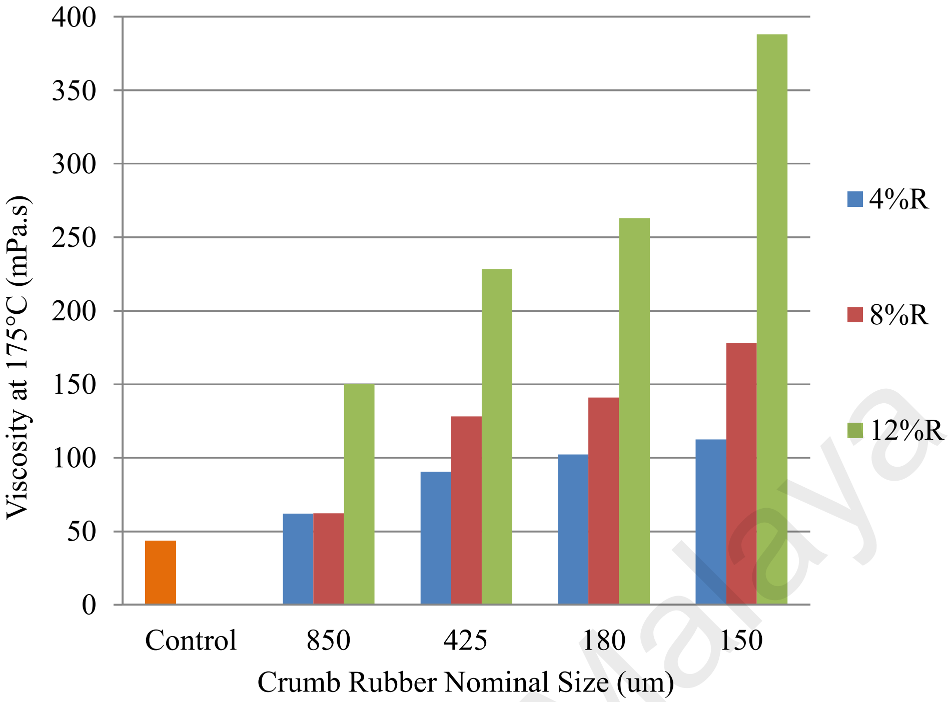

Figure 4.11: Viscosity versus Crumb Rubber Nominal Size

The effects of rubber size to the viscosity values presented in Figure 4.12 show an increase in the viscosity value with the decrease in rubber size. The main reason for the finer rubber size increasing the viscosity value is the swelling ability of large surface area associated with fine crumb rubber and the capability to absorb the aromatic oils from the bitumen; this results in an increase in the asphaltenes to resins ratio, which enhances the stiffened property of crumb rubber modified bitumen. From Figure 4.12, the effects of rubber size to viscosity values are more significant at high binder content (12%). At 12% rubber content, the viscosity of the crumb rubber modified bitumen prepared with 850µm, 425µm, 180µm and 150µm were 140%, 78%, 87% and 117% higher compared to the 8% rubber content.

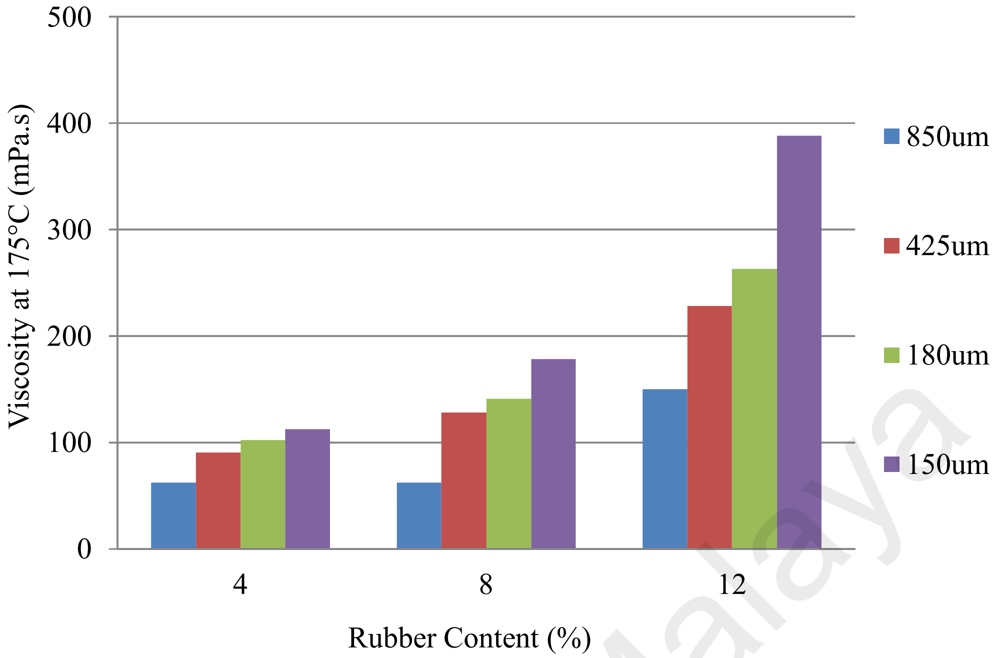

Figure 4.12: Viscosity versus Rubber Content

4.4.1 Multiple Linear Regression Analysis on the Apparent Viscosity Value

Table 4.9 and Table 4.10 show the multiple linear regression analysis using the stepwise method to assess the ability of factors (rubber size, rubber content and rubber size) to predict the viscosity value (Appendix A, Tables A. 3a – A.3d). The regression was conducted at the viscosity value obtained at 175°C. The regression analysis shows that the factors explain 68.9% of the variance in viscosity value, R^2=0.689, R^2_{adj}=0.676, F(2,45) =49.922, p<0.05, as shown in Table 4.9. In the final model, the rubber content and rubber size were statistically significant, with the rubber content recording a higher beta value (beta = 0.604, p =0.000 < 0.05), followed by rubber size (beta = -0.569, p =0.000 < 0.05) (see Table 4.10). The regression equation that can be used to estimate the viscosity value based on the factors, is shown in Equation 4.3:

Viscosity value = 0.604 (Rubber content) -0.569 (Rubber size)........... (4.3)

Table 4.9: Model Summary: Viscosity Value

Step	R	R^2	R^2_{adj}	ΔR^2	F_{chg}	p	df_1	df_2
Rubber content, %	0.604	0.365	0.352	0.365	26.479	0.000	1	46
Rubber Size, µm	0.830	0.689	0.676	0.324	46.927	0.000	1	45

Table 4.10: Coefficients for Final Model: Viscosity Value

Step	*B*	*β*	*t*	*Bivariate r*	*Partial r*
Rubber content, %	17.146	0.604	7.274	0.604	0.735
Rubber Size, µm	-0.188	-0.569	-6.850	-0.569	-0.714

4.5 Oscillation Temperature Sweep

4.5.1 Effect of Modification on Complex Modulus

Figure 4.13(a)-4.13(d) shows the results of oscillation temperature sweep test at temperatures ranges from 30°C to 80°C. The selected test temperature (30°C – 80°C) seems appropriate to activate the chemical reaction between binder and base bitumen to provide a significant elastic capacity (Mohamed et al., 2009). The complex modulus (G*) used to characterize the viscoelastic behavior of the binders seems to decreases rapidly as temperature increases. Certainly, it was shown by the regression analysis which found a good correlation ($R^2 > 0.9$) between complex modulus and temperature. This could be defines by the behaviour of bitumen becoming less viscous at high temperature; hence, the attractive forces among the bitumen molecules to overcome the strain imposed by the Dynamic Shear Rheometer is reduced.

Compared to the base bitumen 80/100 penetration, the rubberized bitumen show higher value of G* at any size of crumb rubber. The higher G* value indicates that the binder is better in deformation resistance. From the results, the rank of the binder from most resistant to deformation, to the worst is as follows: 12R, 8R, 4R and 0R. Above observation suggests that the amount of rubber affect the G* value; which G* increases with the increase in rubber content. This indicates that the crumb rubber affects the degree of change in the structure and compositions of bitumen by increasing the elasticity of binder thus influence the mechanical properties of the modified bitumen. Stated another way, higher the crumb rubber amount results in more elastic modified bitumen.

The achieved results also confirmed the findings from previous studies that the effects of crumb rubber are more significant at high temperature (Singh et al., 2017; Huang et al., 2017). As seen in Figure 4.13(a)-4.13(d), the behaviour of rubberised bitumen is almost similar with the base bitumen at low temperature (30°C) and more significant as the temperature increases especially at the highest temperature (80°C). For instance, in the case for 850µm at low temperature (30°C), the complex modulus value for 4%, 8% and 12% rubber content is 178800Pa, 203000Pa, 207400Pa, respectively, an increase about 9.76%, 24.6%, 27.3% compared to the base bitumen (162900Pa). On the other hand at high temperature (80°C), the difference in complex modulus is significant i.e. 173Pa, 293Pa, 427.30Pa for 4%, 8% and 12% rubber content respectively which the difference is 5.36%, 60.3%, 133.8% compared to the control bitumen (182.8Pa).

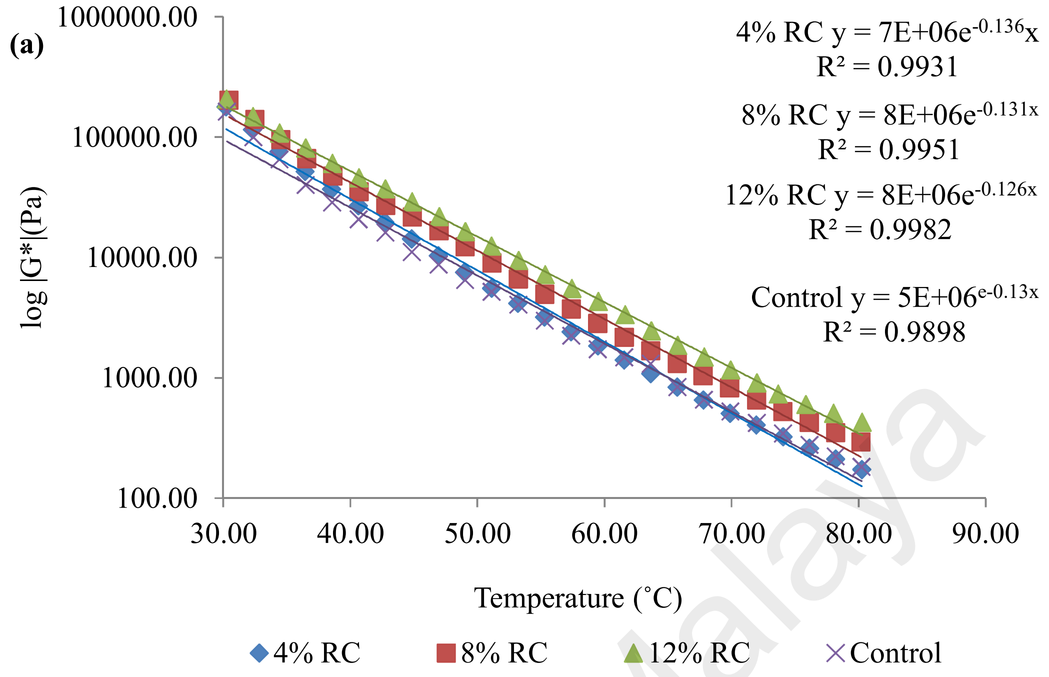

Figure 4.13 (a): Complex Modulus (G*) versus Temperature for 850µm rubber size

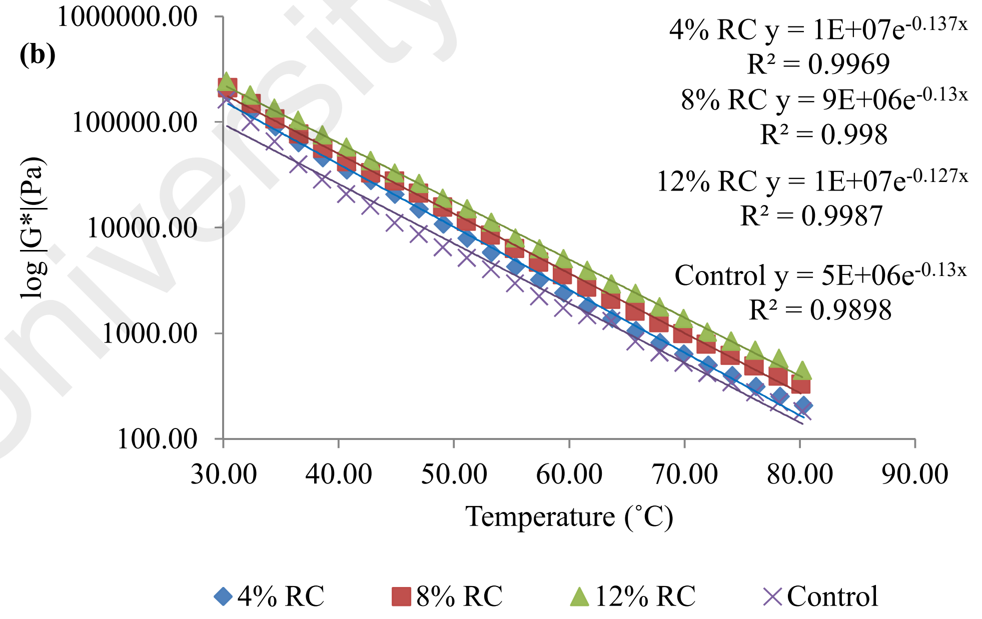

Figure 4.13 (b): Complex Modulus (G*) versus Temperature for 425µm rubber size

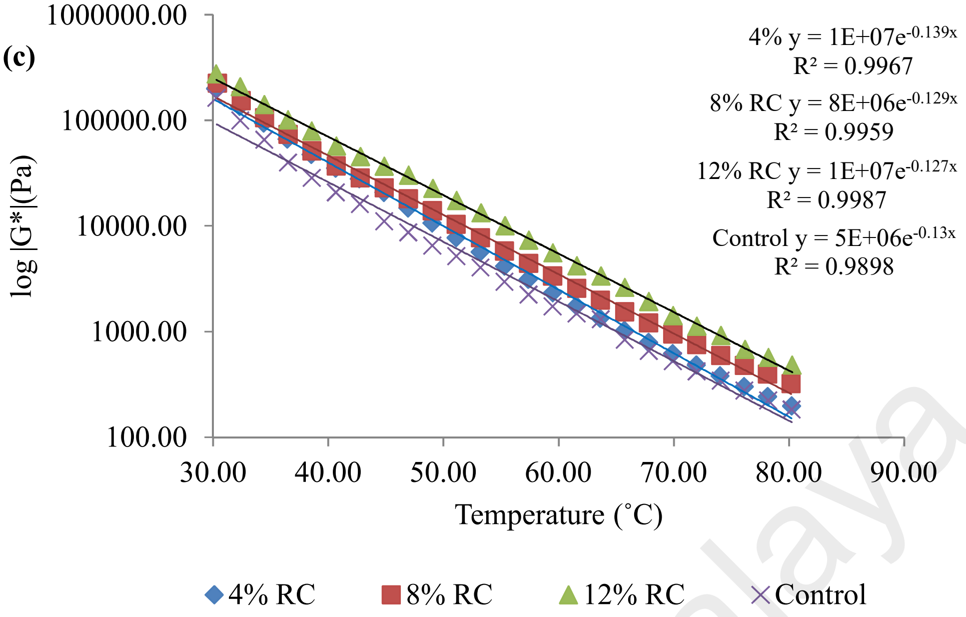

Figure 4.13 (c): Complex Modulus (G*) versus Temperature for 180µm rubber size

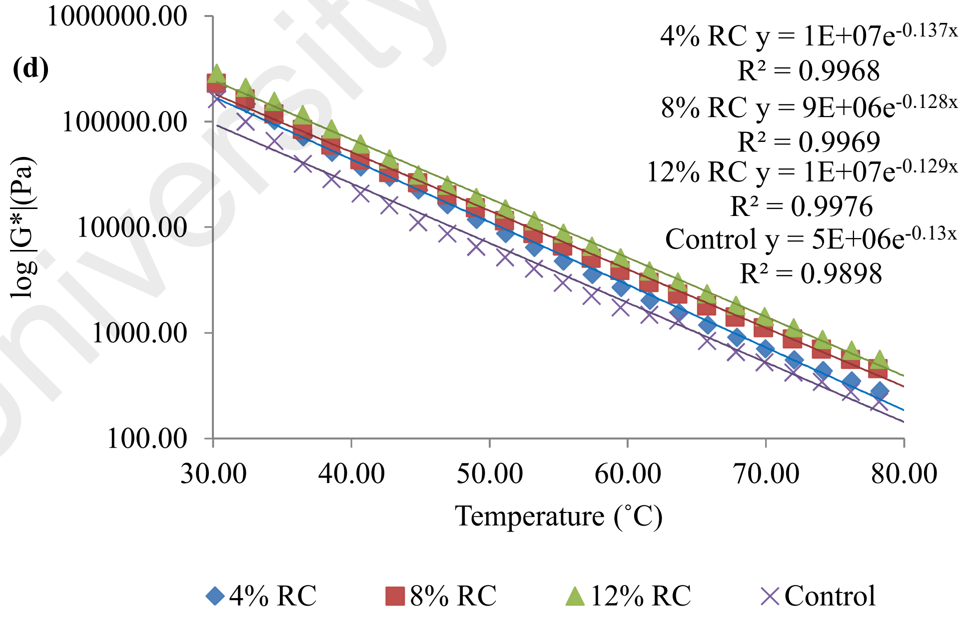

Figure 4.13 (d): Complex Modulus (G*) versus Temperature for 150µm rubber size

Effects of rubber size to the complex modulus can be referred in Figure 4.14. The graph was plotted using 12% rubber content at all rubber sizes since the findings show that 12% rubber content results in the highest complex modulus. In general, the highest complex modulus value at all temperatures shows by 150µm rubber size followed by 180µm, 425µm and 850µm. This finding reveals that the finest rubber results in the highest complex modulus. In other words, the complex modulus decreases with the increase in rubber size.

Previous studies mentioned that binder with high elasticity would recover a greater amount of deformation, which will result in less permanent deformation. Therefore, in this study, it was determined that the rubberised bitumen prepared with 150µm rubber size at 12% rubber content reveals as the best blend because a binder with high elasticity is more viscous-elastic, and, thus exhibits a more resistance to permanent deformation.

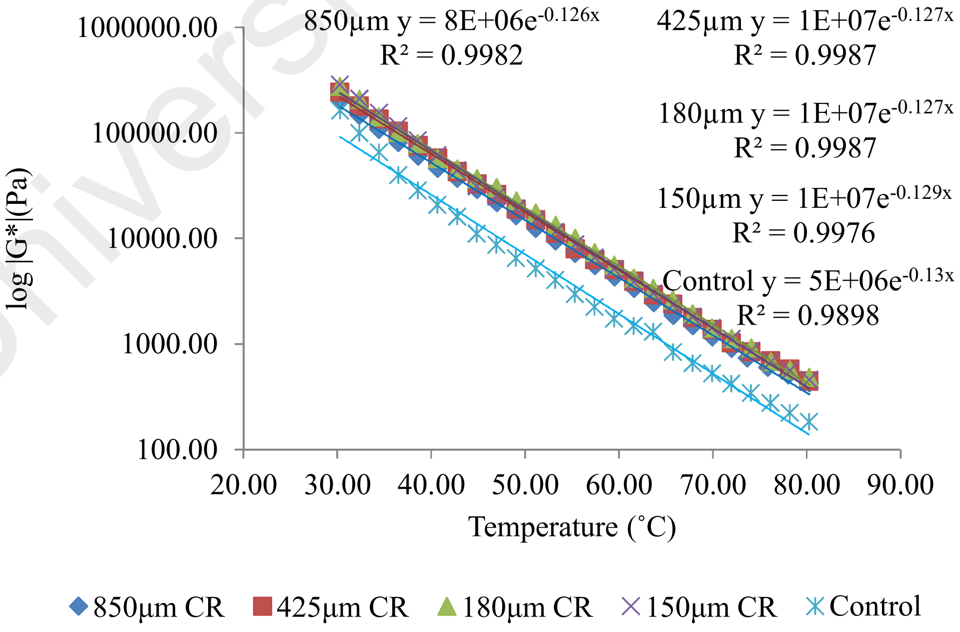

Figure 4.14: Complex Modulus (G*) versus Temperature for 12% Rubber Content

4.5.2 Multiple Linear Regression on Complex Modulus (G*)

Table 4.11 and Table 4.12 show the multiple linear regression analysis using the stepwise method to assess the ability of the factors (temperature, rubber size and rubber content) to predict complex modulus value for binders (Appendix A, Tables A.4a – A.4d). The factors can explain 54.5% of the variance in complex modulus value, *F* (2,322)= 192.837, *p*<0.05. In the final model, the temperature and rubber content were statistically significant, with the temperature recording a higher beta value (beta=-0.729, *p* =0.000 < 0.05) followed by rubber content (beta= 0.114, *p*= 0.000<0.05) (see Table 4.14). Equation 4.4 is the regression equation that can be used to estimate complex modulus value for binders:

Complex Modulus (G) = -0.729(Temperature) + 0.114 (Rubber content) ....* (4.4)

Table 4.11: Model Summary: Complex Modulus Value

Step	R	R^2	R^2_{adj}	ΔR^2	F_{chg}	p	df_1	df_2
Temperature (°C)	0.729	0.532	0.531	0.532	367.296	0.000	1	323
Rubber content (%)	0.738	0.545	0.542	0.013	9.132	0.000	1	322

Table 4.12: Coefficients for Final Model: Complex Modulus Value

Step	B	β	t	*Bivariate r*	*Partial r*
Temperature (°C)	-2650.719	-0.729	-19.404	-0.729	-0.734
Rubber content (%)	1635.548	0.114	3.022	0.114	0.166

4.5.3 Effect of Modification on G*/sin δ

The effects of rubber content and rubber size on the G*/sin δ of modified bitumen at a wide range of temperatures (between 30°C and 80°C) are presented in Figures 4.15(a) – 4.15(d) and 4.16. G*/sin δ was used to measure the binder systems to rutting resistance.

The plotted data in Figure 4.15(a)-4.15(d) indicates that by increasing the rubber content, the G*/sin δ is increased; hence, the resistance of the modified bitumen to rutting is increased.

Figure 4.15 shows the G*/sin δ versus temperature for rubberised binders prepared with different size of rubber. As expected, for all mixes, the 150µm rubber size results in the highest G*/sin δ while the control bitumen shows the lowest. In other words, the figure illustrates that the G*/sin δ increases following any decrease in the rubber size. These findings are consistent with the effect of modification on complex modulus as explained in section 4.4.1.

The result also indicates that the G*/sin δ for all modified binders deceases with an increase in temperature. This result is expected.

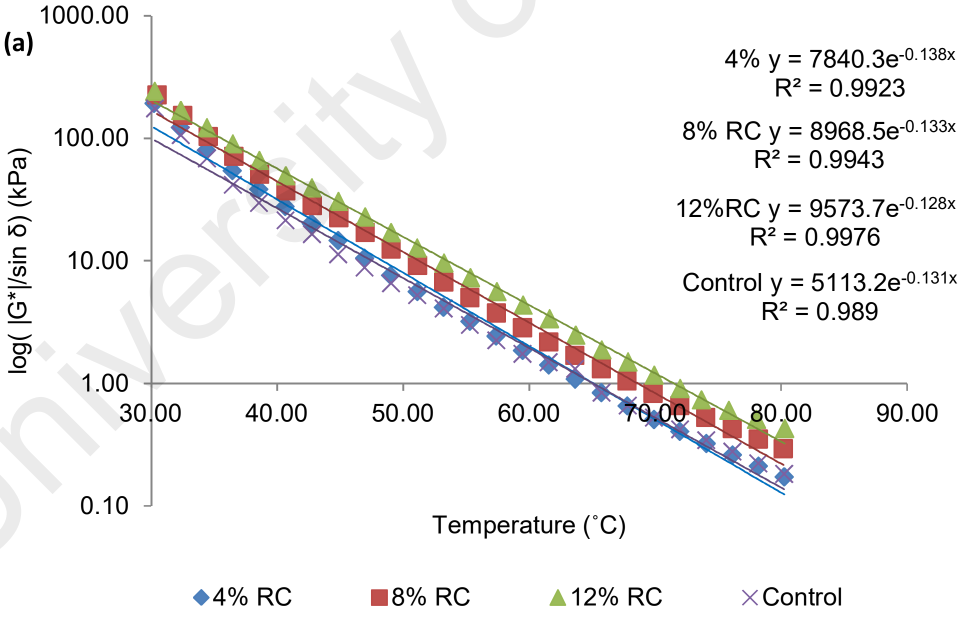

Figure 4.15 (a): G*/sin δ versus Temperature for 850µm rubber size

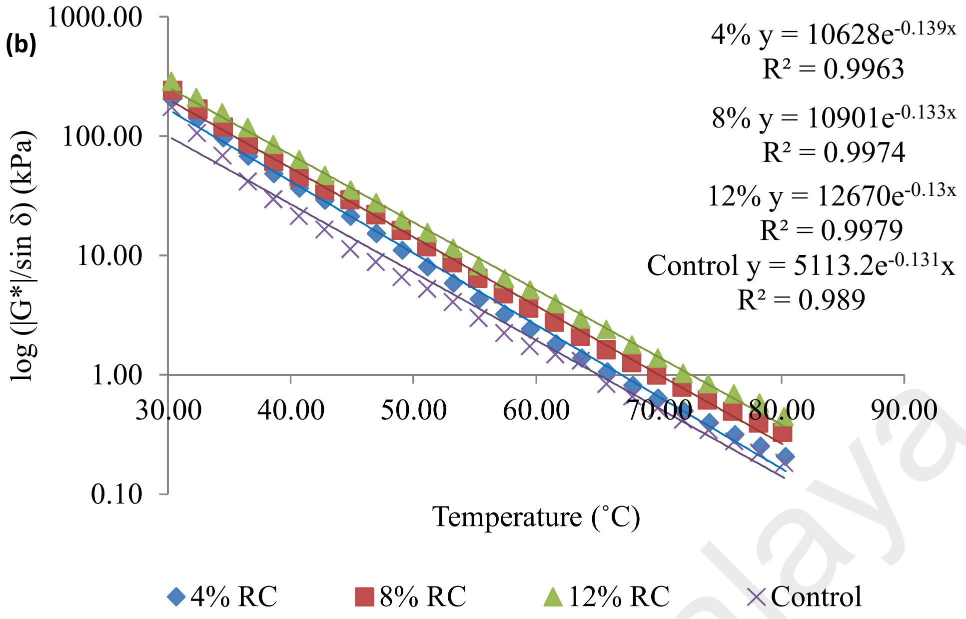

Figure 4.15 (b): G*/sin δ versus Temperature for 425µm rubber size

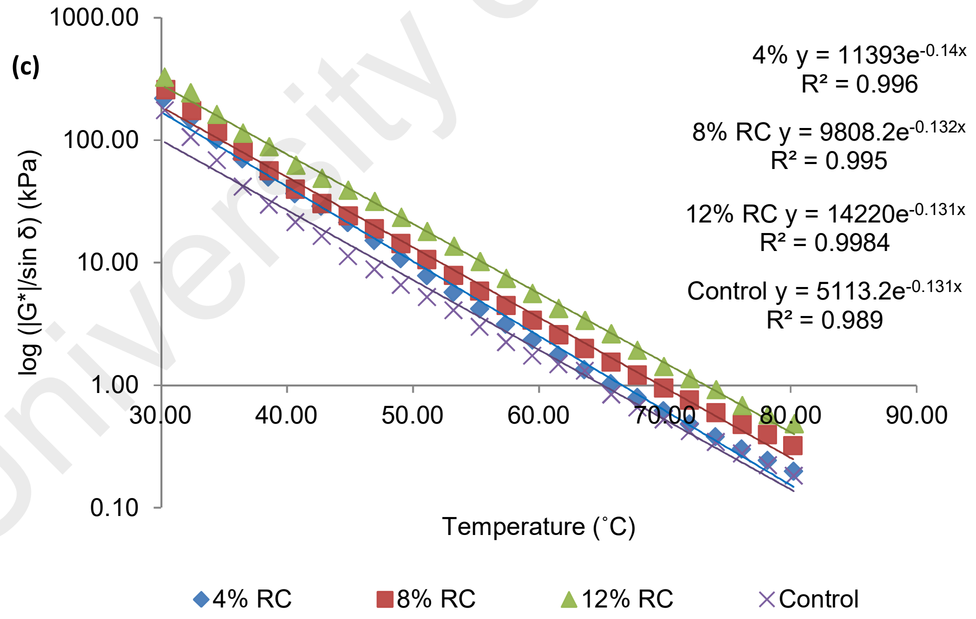

Figure 4.15 (c): G*/sin δ versus Temperature for 180µm rubber size

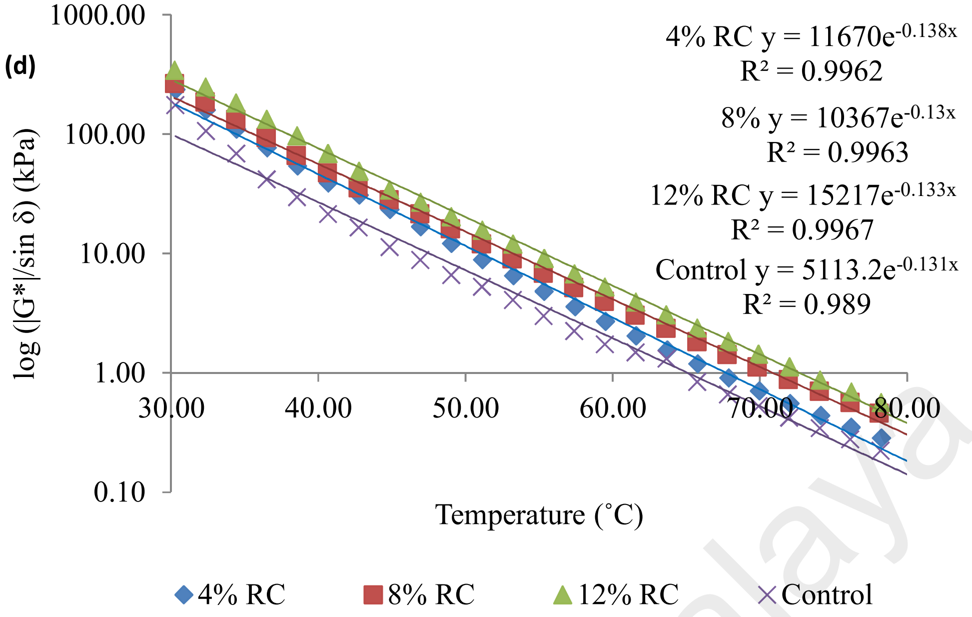

Figure 4.15 (d): G*/sin δ versus Temperature for 150µm rubber size

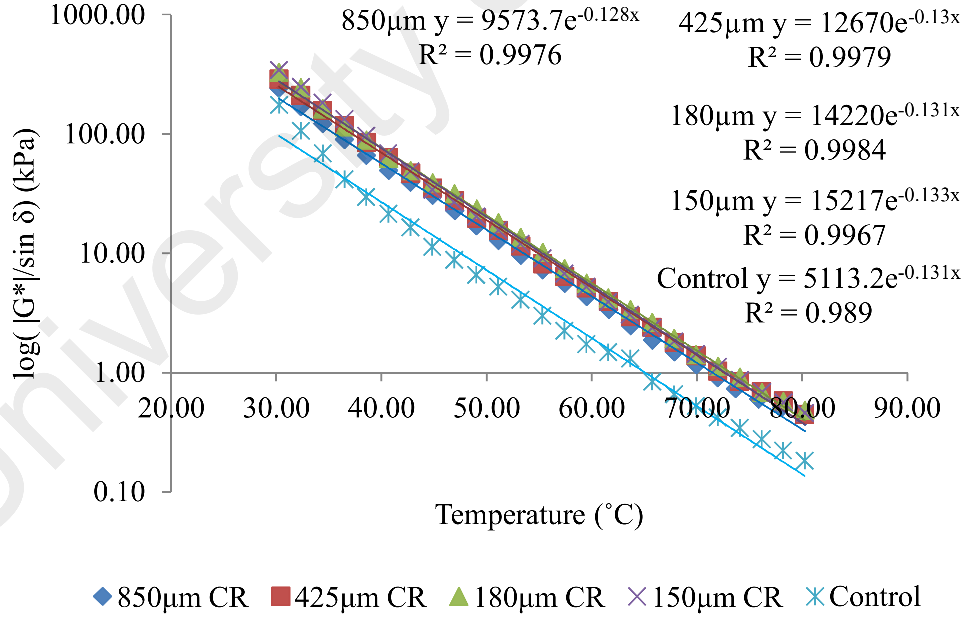

Figure 4.16: G*/sin δ versus Temperature for 12% Rubber Content

4.5.3.1 Regression Model for All Rubberised Binders

Table 4.13 shows the regression model to estimate the G*/sin δ value; hence, determine the rutting resistance of the binders. The temperature at which G*/sin δ equal to 1.0kPa is proportional to the occurrence of mechanical behaviour of binder to resist rutting. Table 4.14 indicates the temperature which proportional to the occurrence of rutting calculated using the regression model. It is clearly shows the relationship between the rubber content and the temperature at which G*/sin δ equal to 1.0kPa, as the rubber content increases, the temperature increases. From Figure 4.17, it is evident that the presence of the finest rubber (150µm) in the rubberised bitumen effectively improves the temperature at which the rutting will occurred. These observations suggest that the temperature at which rutting occurs can be improved by utilizing finer crumb rubber. Moreover, utilising higher rubber content also improves the temperature at which rutting occurs (Figure 4.18).

It was reported under ATJ 5/85 that the road pavement temperature in Malaysia ranges from 20°C in the early hours of the day to as high as 60°C at midday on a hot day. The important findings can be seen in Table 4.16, which all rubberised binders show the performance to resist rutting at temperature more than 60°C; obtained temperature is ranges between 66.72°C to 72.67°C.

Table 4.13: Regression Model for All Rubberised Binders

Rubber Content (%)	Crumb Rubber Nominal Size			
	150µm	180µm	425µm	850µm
4	$y = 11670e^{-0.138x}$	$y = 11393e^{-0.14x}$	$y = 10628e^{-0.139x}$	$y = 7840.3e^{-0.138x}$
8	$y = 10367e^{-0.13x}$	$y = 9808.2e^{-0.132x}$	$y = 10901e^{-0.133x}$	$y = 8968.5e^{-0.133x}$
12	$y = 15217e^{-0.133x}$	$y = 14220e^{-0.131x}$	$y = 12670e^{-0.13x}$	$y = 9573.7e^{-0.128x}$

Table 4.14: Temperatures at which the value of G*/sin δ is equal to 1.0kPa

Rubber Content (%)	**Crumb Rubber Nominal Size**			
	150µm	**180µm**	**425µm**	**850µm**
	T(°C), G*/sinδ			
4	67.86	66.72	67.20	64.98
8	71.13	69.63	69.90	68.43
12	71.81	71.34	72.67	71.62

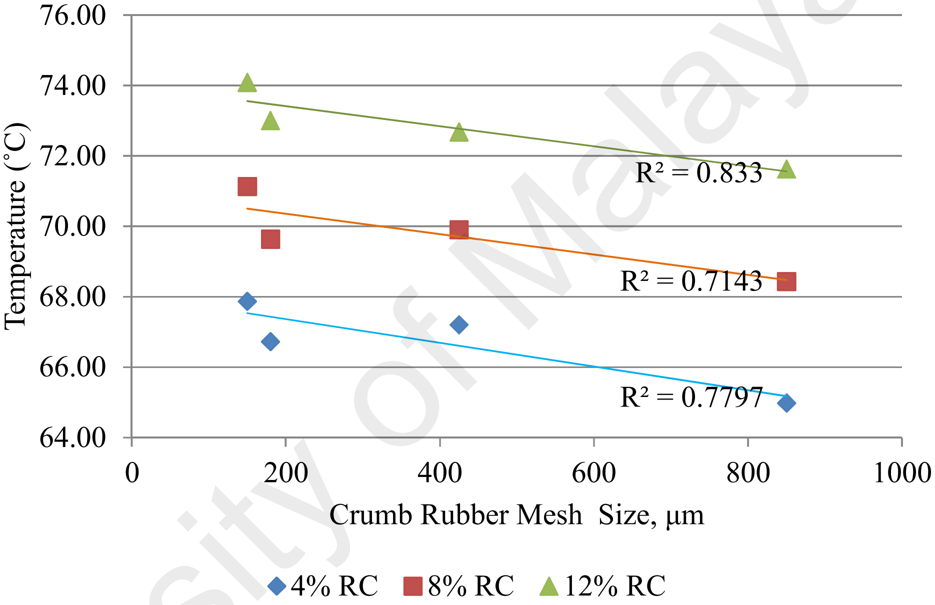

Figure 4.17: Temperatures at which the value of G*/sin δ is equal to 1.0kPa

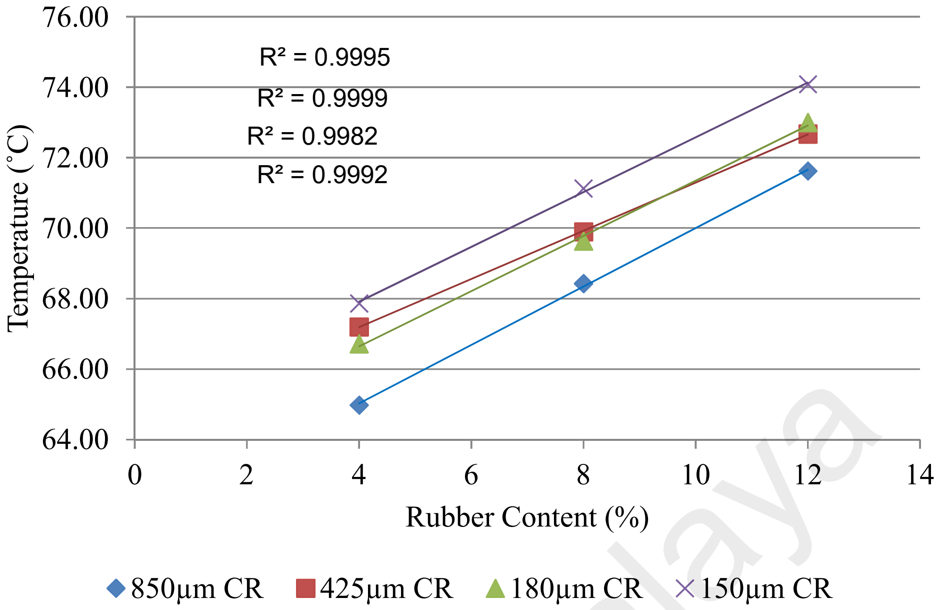

Figure 4.18: Temperatures at which the value of G*/sin δ is equal to 1.0kPa

4.5.3.2 Multiple Linear Regression on G*/sin δ

Table 4.15 and Table 4.16 show the multiple linear regression analysis using the stepwise method to assess the ability of the factors (temperature, rubber size and rubber content) to predict G*/sin δ value for binders (Appendix A, Tables A.5a – A.5d). The factors can explain 52.7% of the variance in G*/sin δ value, *F* (2,322)= 179.068, $p<0.05$. In the final model, the temperature and rubber content were statistically significant, with the temperature recording a higher beta value (beta= -0.715, $p = 0.000 < 0.05$) followed by rubber content (beta= 0.124, $p = .000 < .05$) (see Table 4.14). Equation 4.5 is the regression equation that can be used to estimate G*/sin δ value for binders:

G*/sin δ = *-0.715(Temperature) +0 .124 (Rubber content)* …… (4.5)

Table 4.15: Model Summary: G*/sin δ Value

Step	R	R^2	R^2_{adj}	ΔR^2	F_{chg}	p	df_1	df_2
Temperature (°C)	0.715	0.511	0.510	0.511	337.799	0.000	1	323
Rubber content (%)	0.726	0.527	0.524	0.015	10.452	0.000	1	322

Table 4.16: Coefficients for Final Model: G*/sin δ Value

Step	B	β	t	*Bivariate r*	*Partial r*
Temperature (°C)	-2.965	-0.715	-18.646	-0.715	-0.721
Rubber content (%)	2.037	0.124	3.233	0.124	0.177

4.6 Optimum Binder Content of Rubberised Porous Mixes

Crumb rubber modification increases the viscosity of the binder and this will alter the ability of the bitumen to coat the aggregates in the mix. Binders with higher viscosity typically will require higher amount of bitumen to effectively coat aggregate particles and this will affect the strength, binder draindown properties and the amount of void within the mix. For porous mixes, the amount of bitumen regarded as sufficient to give the mix adequate strength, reasonable amount of binder draindown and maintain satisfactory amount of void in the mix is defined as the optimum binder content.

In this study, the optimum binder content used meets the requirement criteria outlined by Road Engineers Society of Malaysia (REAM) specification for Porous Asphalt (REAM-SP5/2008). The criteria are summarised in Table 4.17.

Figures 4.19 to 4.30 show the abrasion loss, binder draindown and void in mix pattern for different crumb rubber nominal particle size (RS), rubber content (RC) and bitumen content (BC). The y-axis for binder draindown graphs is fitted with a log-scale axis to facilitate the interpretation of the values with exponential pattern. All samples show an exponential trend for abrasion loss and binder draindown results while air void and binder content seems to indicate a linear relationship.

Table 4.17: Optimum binder content criteria for porous asphalt mix

Criteria	Requirement	
Cantabro test abrasion loss	Loss of mass ≤ 15%	
Binder draindown	≤ 0.3%	
	Minimum	**Maximum**
Air void	≥ 18%	≤ 25%

4.6.1 Samples Modified with 850µm Nominal Size Rubber Crumb

The abrasion loss for samples prepared with 850µm rubber crumb shows an exponential trend for 4% to 7% BC. At 4% BC, abrasion loss is extremely high for all samples reaching 55.6% loss for 12% RC, 51% for 8% RC and 41.2% for 4% RC. This value drops significantly at 5% BC where the abrasion loss for samples with 12% RC is 23% and at 5% BC the average abrasion loss is 14.8%, a permissible value as specified by the REAM Porous Asphalt design guide. Acceptable abrasion loss values are recorded for all samples with 6% and 7% BC with all RC except for samples with 12% RC and 6% BC. This is probably due to inadequate binder in a mix that was modified with a high level of crumb rubber.

Binder draindown tests are carried out using bitumen content between 5-7% since at 4% bitumen the abrasion loss test has shown a very high abrasion loss. The test shows a very high draindown value for samples prepared with 8% and 9% binder content. At 7% BC, samples with 12% RC show an allowable draindown with a value of 0.27% while at 5% and 6% BC all samples show acceptable value of draindown except for samples modified with 4% RC. Adequate void in mix, are acquired for all binder and rubber content.

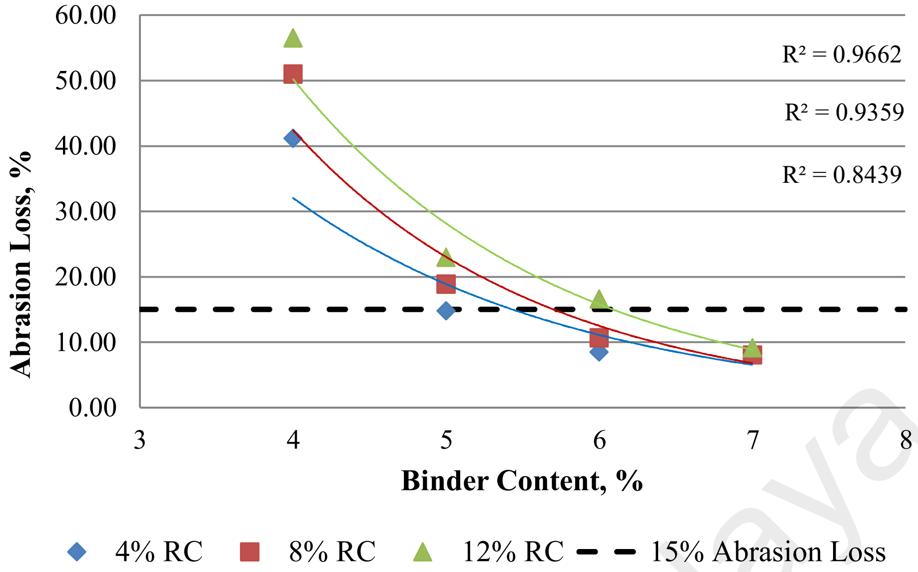

Figure 4.19: Abrasion loss at different rubber content (850µm rubber crumb)

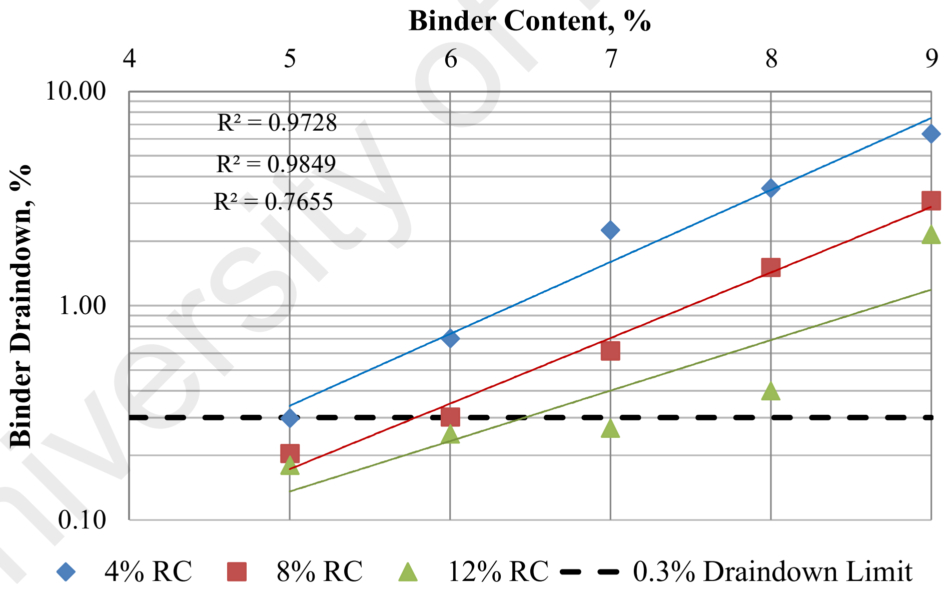

Figure 4.20: Binder draindown at different rubber content (850µm rubber crumb)

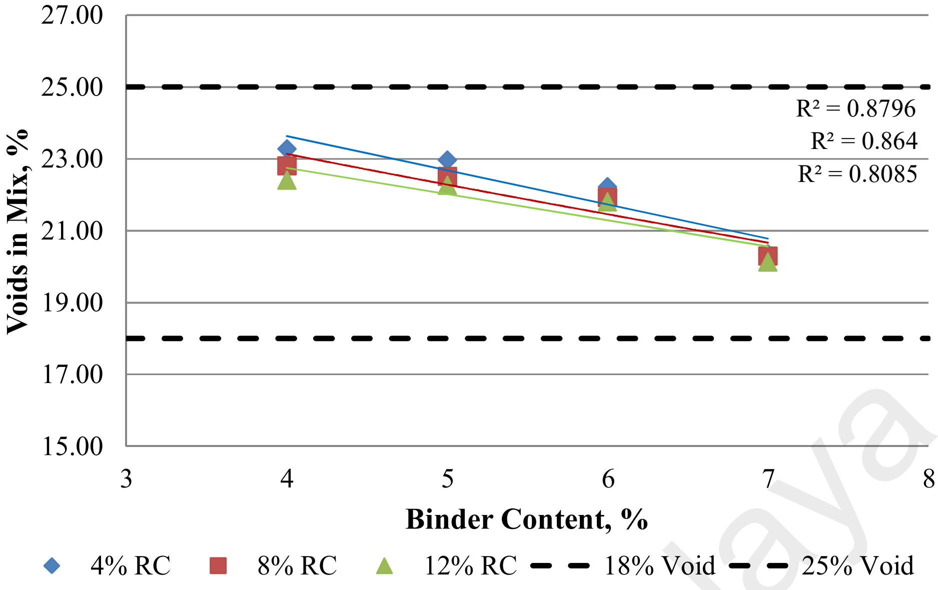

Figure 4.21: Void in Mix (VIM) at different rubber content (850µm rubber crumb)

4.6.2 Samples Modified with 425µm Nominal Size Rubber Crumb

All samples show satisfactory abrasion loss at 6% and 7% binder content for samples modified with 425µm rubber crumbs due to the extra strength provided by higher binder content. At 5% BC, only samples with 4% RC show adequate abrasion loss value of less than 15% while at 4% BC none of the samples show acceptable abrasion loss. Again, this is due to a high amount of rubber that is not compensated with higher binder content. This makes the mix brittle and shatters with impact.

Binder draindown at 8% and 9% are much higher from the acceptable limit as expected whereas at 6% and 7% BC, samples modified with 8% and 12% shows draindown value that is within the specified limit. At 5% BC, all samples gave acceptable draindown values. Contrary to the factors that govern abrasion loss, binder draindown value will increase as lower RC is used with samples that have a higher BC. This results with binders that has a low viscosity and tend to draindown easily. Void in mix, still shows satisfactory value for all binder and rubber content tested.

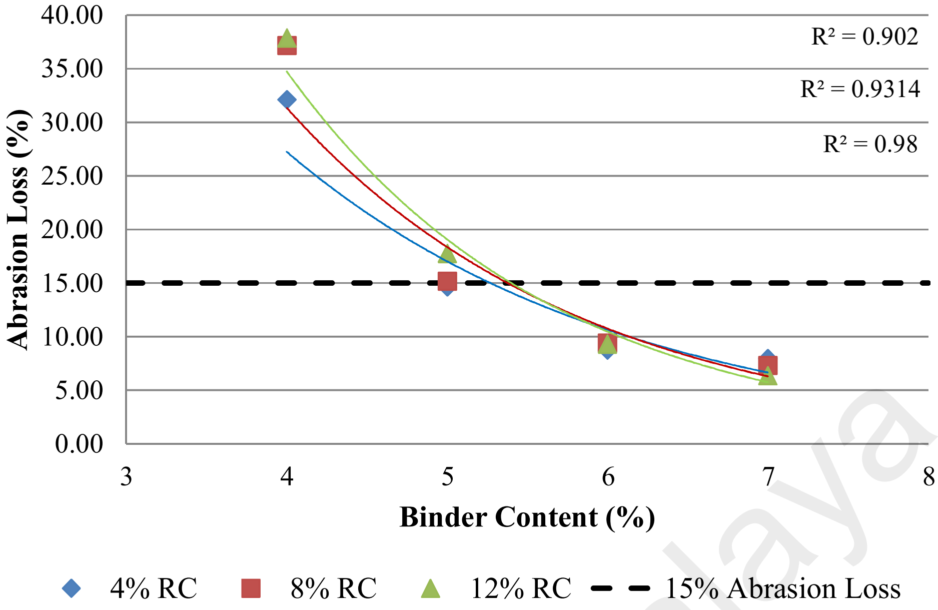

Figure 4.22: Abrasion loss at different rubber content (425µm rubber crumb)

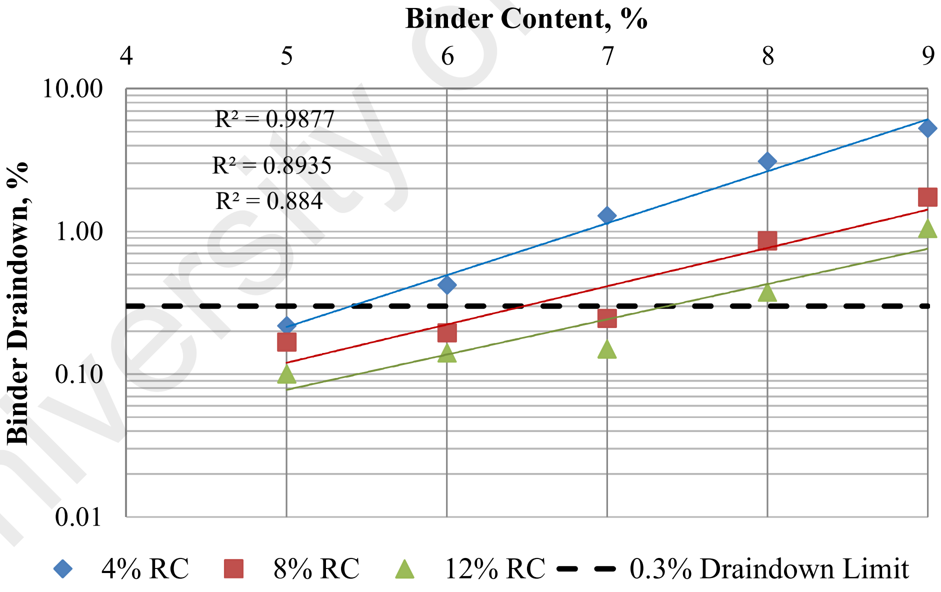

Figure 4.23: Binder draindown at different rubber content (425µm rubber crumb)

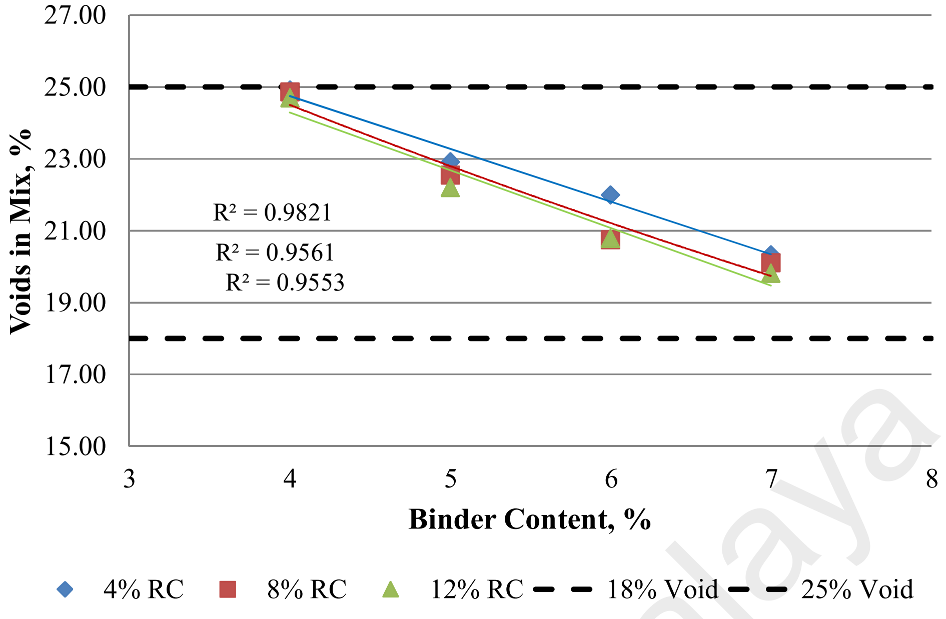

Figure 4.24: Void in Mix (VIM) at different rubber content (425µm rubber crumb)

4.6.3 Samples Modified with 180µm Nominal Size Rubber Crumb

Due to the finer nature of the rubber crumb, 180µm crumb rubber modification provides an acceptable abrasion loss for samples at all binder content except at 4% BC. Finer rubber crumb have larger surface area and hence absorbs higher amount of lighter oils in the bitumen. This increases the viscosity of the binder and subsequently increases the strength of the mix.

Draindown characteristics on the other hand, give sufficient results for 5%, 6% and 7% BC. At 8% and 9% BC, only samples with 12% RC provide adequate draindown value. As with coarser mesh size, this can be expected as 8% and 9% BC lower RC cannot provide the higher viscosity that is required to give acceptable draindown value.

Void in mix results show a slightly different pattern compared to previous results. At 4% binder content, the amount of void in the mix does not satisfy the requirement of the specification. This shows that finer rubber crumb would require a higher bitumen content to give the bitumen a viscosity that is low enough to be able to fully coat the aggregate but at the same time the viscosity is not too low that it drains down easily. Lower binder content combined with rubber crumb modification would produce a binder that is too thick and would not provide good coverage to the aggregates and hence creating higher void in the mix.

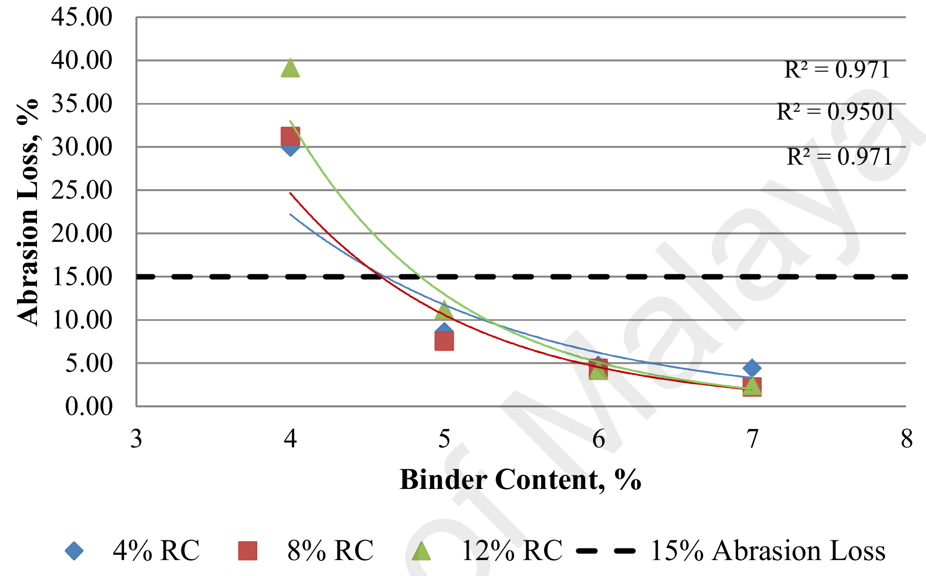

Figure 4.25: Abrasion loss at different rubber content (180µm rubber crumb)

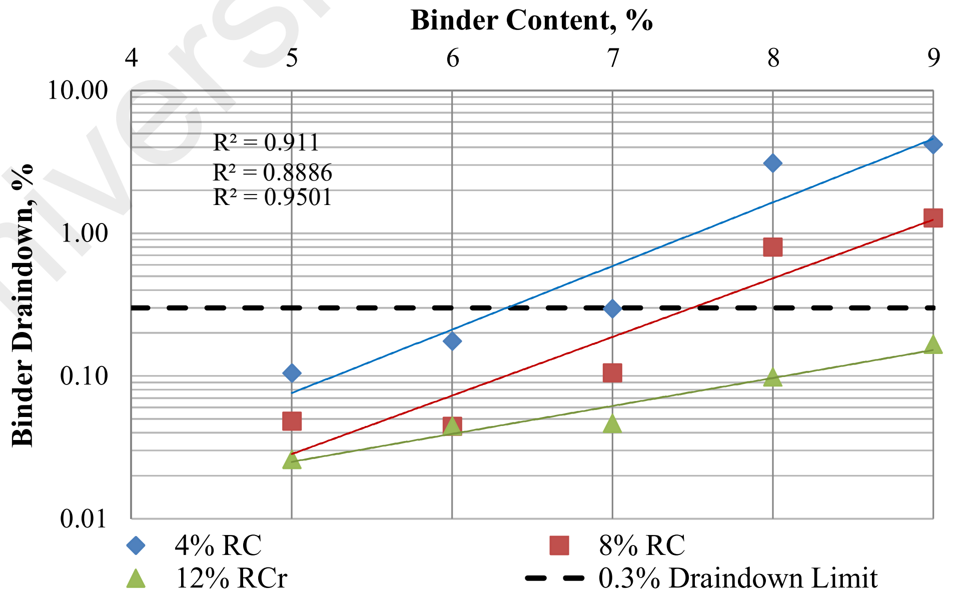

Figure 4.26: Binder draindown at different rubber content (180µm rubber crumb)

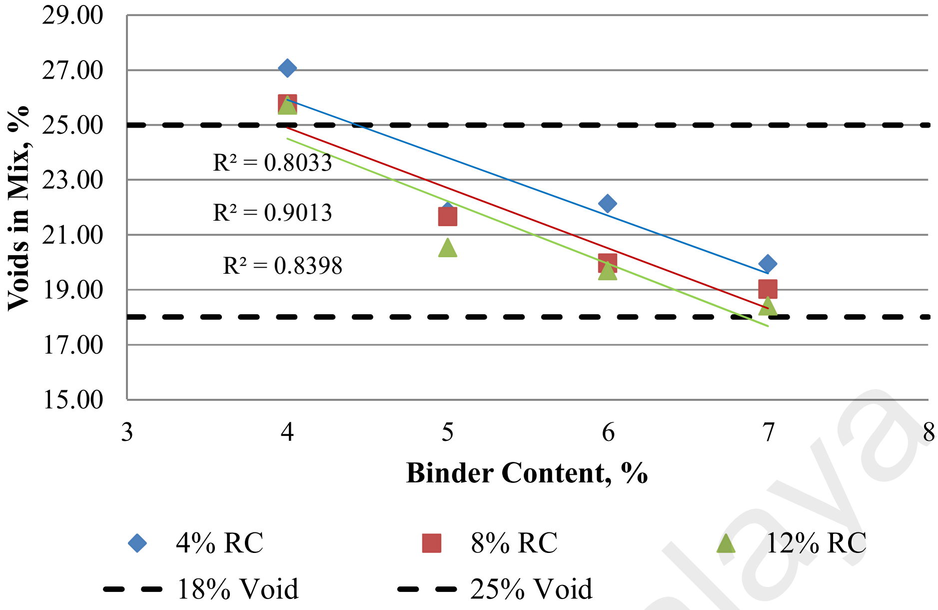

Figure 4.27: Void in Mix (VIM) at different rubber content (180µm rubber crumb)

4.6.4 Samples Modified with 150µm Nominal Size Rubber Crumb

Samples modified with 150µm crumb rubber are showing similar results with its 180µm counterpart. This is due to the difference in size between the two mesh sizes is very close.

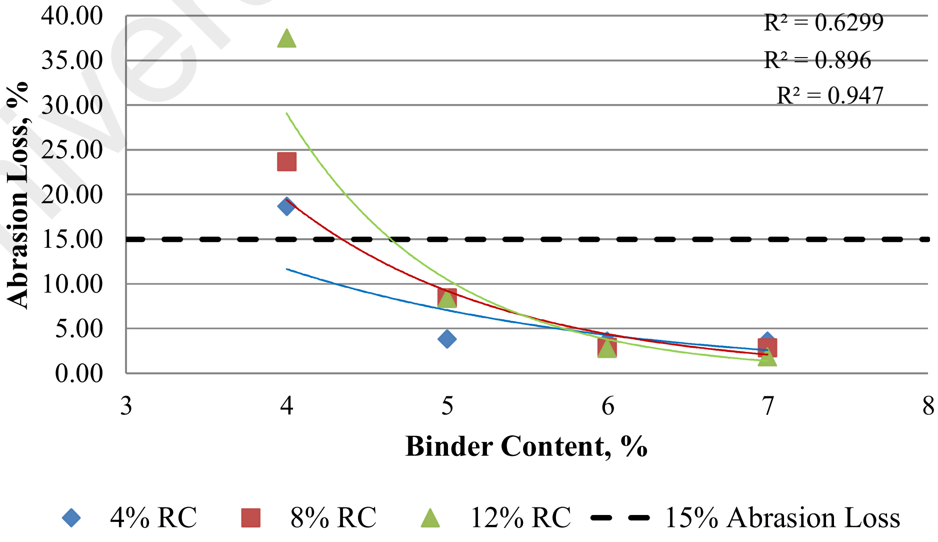

Figure 4.28: Abrasion loss at different rubber content (150µm rubber crumb)

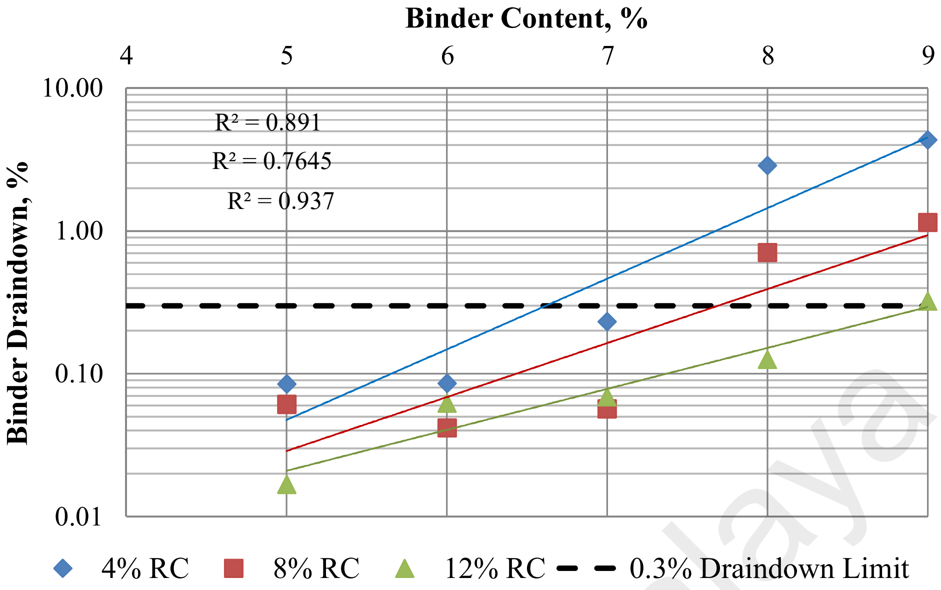

Figure 4.29: Binder draindown at different rubber content (150µm rubber crumb)

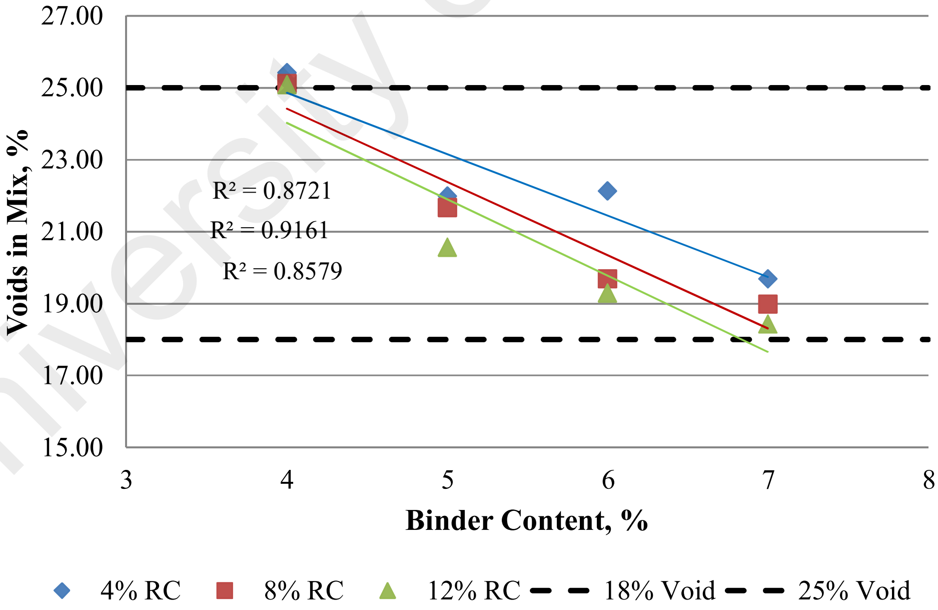

Figure 4.30: Void in Mix (VIM) at different rubber content (150µm rubber crumb)

4.6.5 Selection of Optimum Binder Content

Table 4.18 and 4.19 summarizes the average value for the abrasion loss, binder draindown and void in mix for all the rubber size, content and binder content considered in this study. Values that satisfy all the criteria required to select the optimum binder content were highlighted in bold. From the tables, it is observed that samples that were modified with 850µm rubber displays narrower window for optimum binder content selection. At 4% rubber content, 5% BC was found to provide adequate abrasion loss, binder draindown and void in mix while for 8% and 12% RC, 6% BC and 7% BC was found to satisfy the specification requirement respectively. Mixes with 425µm rubber have a slightly wider selection of optimum binder content. At 8% and 12% RC, optimum binder for the samples can be selected between 6% and 7%. However, at 4% RC only 5% BC can be selected as the optimum binder content.

Binder content of 5%, 6% and 7% can be chosen for optimum binder content for mixes modified with finer rubber crumb sizing 180µm and 150µm size. This is interesting as one would expect that finer rubber crumbs and higher binder content would produce a stiffer mix with a lower void content. Although the void content does decreases and the draindown value increases, the value of the parameters are still within acceptable standards for a wider binder content range.

Considering the factors involved and for consistency purposes, the value of optimum binder content chosen for this study is 5% for samples with 4% rubber content, 6% for samples with 8% rubber content and 7% binder content for samples with 12% rubber content. Similar binder contents are applied for all crumb rubber sizes.

Table 4.18: Abrasion loss, draindown and void in mix (850µm and 425µm samples)

850µm Sample	Average Abrasion Loss (%)	Average Binder Draindown (%)	Average Void in Mix (%)	425µm Sample	Average Abrasion Loss (%)	Average Binder Draindown (%)	Average Void in Mix (%)
4R 4B	41.19	-	23.28	4R 4B	32.14	-	24.93
4R 5B	**14.81**	**0.30**	**22.97**	4R 5B	**14.66**	**0.22**	**22.92**
4R 6B	**8.51**	0.70	**22.22**	4R 6B	**8.76**	0.42	**22.00**
4R 7B	**8.47**	2.25	**20.36**	4R 7B	**7.96**	1.29	**20.34**
4R 8B	-	3.53	-	4R 8B	-	3.11	-
4R 9B	-	6.32	-	4R 9B	-	5.29	-
8R 4B	51.04	-	22.81	8R 4B	37.18	-	24.87
8R 5B	18.89	**0.20**	22.52	8R 5B	15.20	**0.17**	22.55
8R 6B	**10.68**	**0.30**	**21.93**	8R 6B	**9.42**	**0.20**	**20.75**
8R 7B	**8.06**	0.61	**20.30**	8R 7B	**7.33**	**0.25**	**20.11**
8R 8B	-	1.50	-	8R 8B	-	0.86	-
8R 9B	-	3.09	-	8R 9B	-	1.74	-
12R 4B	56.56	-	22.41	12R 4B	37.88	-	24.71
12R 5B	23.00	**0.18**	22.27	12R 5B	17.78	**0.10**	22.21
12R 6B	16.60	**0.25**	21.81	12R 6B	**9.31**	**0.14**	**20.80**
12R 7B	**9.16**	**0.27**	**20.13**	12R 7B	**6.37**	**0.15**	**19.82**
12R 8B	-	0.40	-	12R 8B	-	0.38	-
12R 9B	-	2.15	-	12R 9B	-	1.05	-

Table 4.19: Abrasion loss, draindown and void in mix (180µm and 150µm samples)

180µm Sample	Average Abrasion Loss (%)	Average Binder Draindown (%)	Average Void in Mix (%)	150µm Sample	Average Abrasion Loss (%)	Average Binder Draindown (%)	Average Void in Mix (%)
4R 4B	29.97	-	27.08	4R 4B	18.67	-	25.43
4R 5B	**8.61**	**0.10**	**21.87**	4R 5B	**3.80**	**0.09**	**21.99**
4R 6B	**4.71**	**0.18**	**22.15**	4R 6B	**3.57**	**0.09**	**22.13**
4R 7B	**4.40**	**0.30**	**19.95**	4R 7B	**3.58**	**0.23**	**19.68**
4R 8B	-	3.10	-	4R 8B	-	2.88	-
4R 9B	-	4.19	-	4R 9B	-	4.36	-
8R 4B	31.22	-	25.77	8R 4B	23.65	-	25.12
8R 5B	**7.55**	**0.05**	**21.67**	8R 5B	**8.44**	**0.06**	**21.67**
8R 6B	**4.41**	**0.04**	**19.97**	8R 6B	**2.88**	**0.04**	**19.68**
8R 7B	**2.22**	**0.11**	**19.03**	8R 7B	**2.84**	**0.06**	**18.99**
8R 8B	-	0.80	-	8R 8B	-	0.71	-
8R 9B	-	1.28	-	8R 9B	-	1.15	-
12R 4B	39.14	-	25.73	12R 4B	37.51	-	25.09
12R 5B	**11.15**	**0.03**	**20.54**	12R 5B	**8.36**	**0.02**	**20.57**
12R 6B	**4.16**	**0.04**	**19.70**	12R 6B	**2.79**	**0.06**	**19.30**
12R 7B	**2.43**	**0.05**	**18.41**	12R 7B	**1.82**	**0.07**	**18.43**
12R 8B	-	0.10	-	12R 8B	-	**0.13**	-
12R 9B	-	0.17	-	12R 9B	-	0.32	-

4.7 Effect of Rubber Crumb Modification to the Durability of Porous Asphalt

One of the issues of asphaltic pavement is its ability to withstand traffic forces that are reacting on its surface. The durability of the pavement are mainly measured using tests such as Cantabro test, used to assess the resistance of abrasion loss due to stripping forces, Indirect Tensile Test (ITS), carried out to evaluate the ability to restrain cracking and Indirect Tensile Stiffness Modulus (ITSM) test, to evaluate the stiffness of the asphaltic mix.

4.7.1 Unconditioned (Dry) Cantabro Test

Cantabro test is a test devised to estimate the abrasion resistance or resistance of disintegration of porous mixes. The results obtained indicate the bond strength between the binder and aggregates. Figure 4.31 below shows the effect of increasing the rubber content to the abrasion loss of the mixes. Full results are attached in Appendix C5 – C8. The results show that all the mixtures provide adequate resistance to disintegration which the air abrasion loss values are located within the required specification of less than 15% (REAM-SP 5/2008).

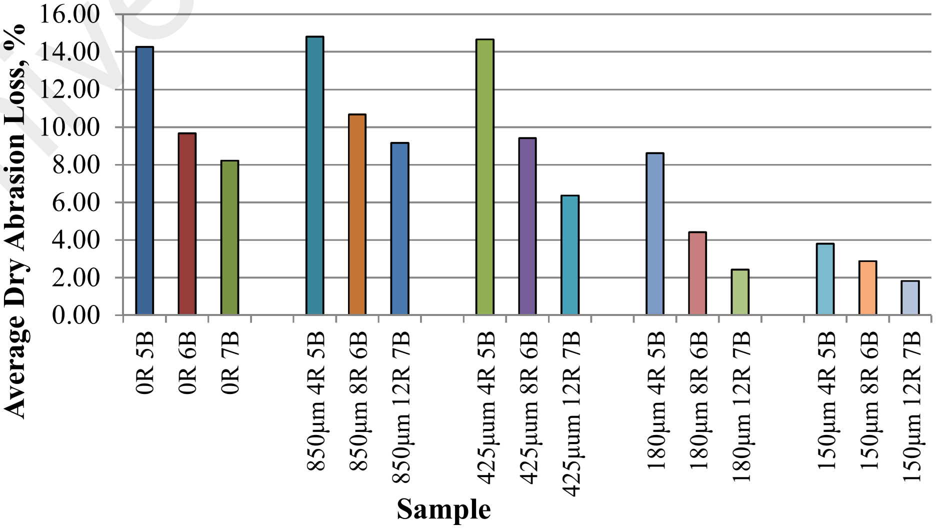

Figure 4.31: Dry abrasion loss of samples with varying rubber content

Table 4.20 Changes of Dry Abrasion Loss (DAL) relation with Rubber Content

Sample	Average Dry Abrasion Loss, %	Changes of DAL with Increasing Rubber/Binder Content, %	Total Change of DAL with Increasing rubber content, %	Average Change of DAL per Increase of Single Rubber Percentage, %
0R 5B	14.27	-	-	-
0R 6B	9.67	-32.25		
0R 7B	8.22	-14.95		
850μm 4R 5B	14.81	3.77	-38.16	-4.77
850μm 8R 6B	10.68	-27.88		
850μm 12R 7B	9.16	-14.25		
425μm 4R 5B	14.15	-0.85	-54.99	-6.87
425μm 8R 6B	9.42	-33.44		
425μm 12R 7B	6.37	-32.38		
180μm 4R 5B	8.61	-39.65	-71.84	-8.98
180μm 8R 6B	4.41	-48.74		
180μm 12R 7B	2.43	-45.05		
150μm 4R 5B	3.80	-73.34	-52.28	-6.53
150μm 8R 6B	2.88	-24.40		
150μm 12R 7B	1.82	-36.87		

Table 4.20 summarises the changes to the resistance of abrasion loss for samples with different rubber content. It is important to note that, for samples modified with 850μm crumb rubber with 4% rubber content the abrasion loss increases by 3.77% in comparison to the control mix with 5% binder content. Although the value of the loss (14.81%) is less the requirement of the maximum 15% loss, this is cannot be considered as improvement to the strength as the rubber addition does not seem to improve the abrasion resistance of the mix.

Comparing the reduction of abrasion loss for the other samples, it is clear that adding more rubber does increase the ability of the mix to resist disintegration. For instance increasing 4% of rubber content to 8% rubber content for samples with 850μm crumb rubber, improves the abrasion loss by 27.88% ([14.81%-10.68%]/14.81%) and increasing the rubber content from 8% to 12% for samples with 150μm crumb rubber increases the abrasion resistance by 36.87%.

On average, samples with 850µm rubber show an improvement 4.77% abrasion loss reduction for a single percentage of rubber content addition while for samples with 425µm and 180µm rubber the improvement is 6.87% and 8.98% respectively. The improvement of abrasion loss achieved by increasing the rubber content by a single rubber percentage increases for crumb rubber size 150µm is 6.53%.

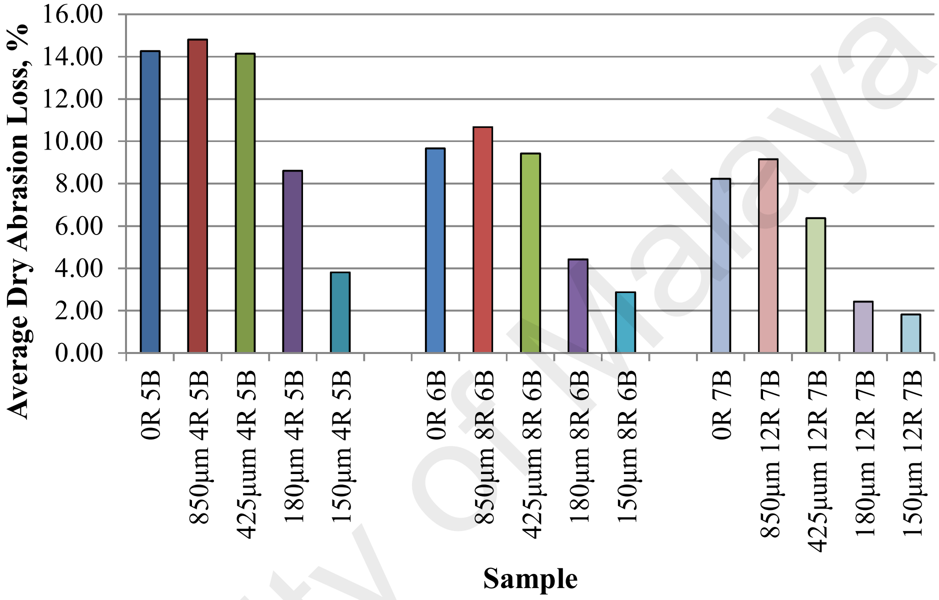

Figure 4.32 Dry abrasion loss of samples with varying rubber size

Figure 4.32 and Table 4.21 compares the effect of crumb rubber nominal size to the abrasion loss of the samples. The percentages are obtained using the abrasion loss values shown in Table 4.20. For example, the -4.45% change in abrasion loss between 850µm4R5B (14.81%) and 425µm4R5B (14.15%) is obtained by subtracting 14.81% and 14.15% and dividing with 14.81%. It is very interesting to note that, when arranged in the order of crumb rubber size, comparable to the previous comparison, again samples with 850µm crumb rubber performed inferiorly compared with control samples without any rubber addition.

Again, the abrasion loss for these samples are actually less (14.81%, 14.66% and 10.68%) than the maximum 15% abrasion specified in the specifications, however having the abrasion loss higher than control specimens means that the rubber addition for these samples does not improve the abrasion loss resistance. From table 4.21, the loss even increases with the addition of rubber. At 8% rubber content, the abrasion loss increase by 10.45% and at 12% rubber content the loss increases to 11.37%.

Examining on this issue further, the reduction of abrasion resistance only occurs with samples with larger rubber crumb (850µm) while samples with the finer rubber crumb performs very well in reducing abrasion loss. It is anticipated that in the blending process, as the maltenes are absorbed into the rubber particle, larger rubber crumbs swell into a bigger particle where it can swell up to three times its' original size; and although the viscosity of the blend increases, the larger and swollen rubber particle reduces the adhesion properties of the binder with aggregate therefore contributes to weaken the sample and increases the rate of disintegration of the mix.

Table 4.21 Changes of Dry Abrasion Loss (DAL) relation with Rubber Addition and Rubber Size

Sample	Changes of Dry Abrasion Loss with CR size, %					
	850µm	**425µm**	**180µm**	**150µm**	**150µm compared to 425µm**	**150µm compared to 850µm**
0R 5B	+3.77					
850µm 4R 5B		-4.45				-74.31
425µm 4R 5B			-39.14		-73.11	
180µm 4R 5B				-55.83		
150µm 4R 5B						
0R 6B	+10.45					
850µm 8R 6B		-11.81				-73.07
425µm 8R 6B			-53.14		-69.47	
180µm 8R 6B				-34.85		
150µm 8R 6B						
0R 7B	+11.37					
850µm 12R 7B		-30.45				-80.18
425µm 12R 7B			-61.92		-71.49	
180µm 12R 7B				-25.15		
150µm 12R 7B						

Apart from increasing rubber content to improve resistance to abrasion, reducing crumb rubber size may also help to achieve the desired properties. Reducing the crumb rubber size from 850µm to 150µm for samples with 4% rubber content for instance, reduces the abrasion loss on average by 74.31%. If the size reduction applied with mixes with 8% rubber content, the abrasion resistance can be improved by 73.07% and with 12% rubber content 80.18% of the abrasion resistance can be improved. This means, on average, for every 100µm size reduction, the abrasion loss resistance can be increased by 10.62% at 4% rubber content and by 10.45% and 11.45% for 8% and 12% rubber content respectively.

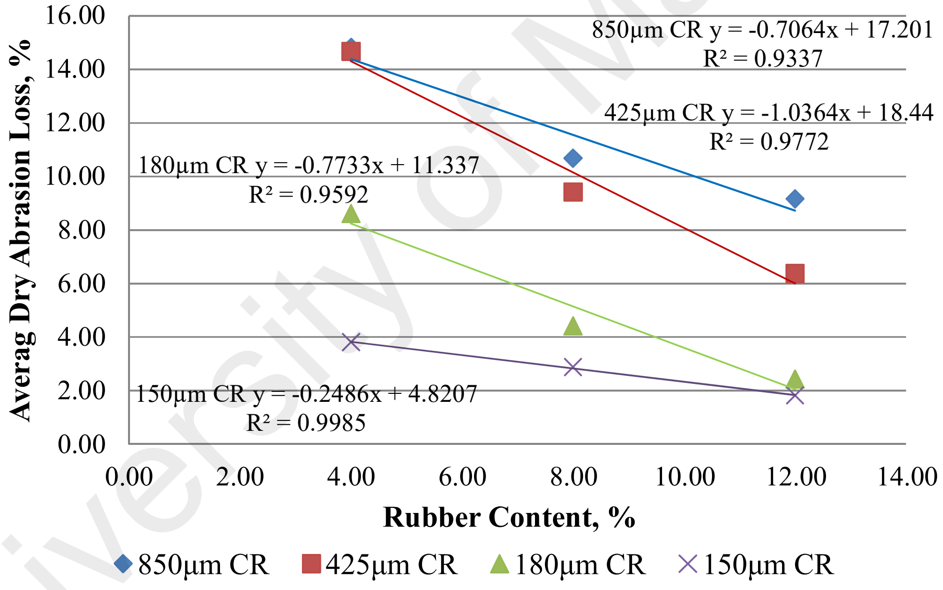

Figure 4.33 Relation between dry abrasion loss and rubber content

Figure 4.33 and 4.34 on the other hand, shows the relation between dry abrasion loss and rubber content and size. From the figures, it can be seen that increasing the rubber content decreases the abrasion loss while larger rubber crumb increases the abrasion loss. The steeper slope from the relationship between rubber content compared with rubber size indicate that rubber content influences the abrasion loss more than rubber size in terms of percent of change between rubber content and rubber size. This is confirmed by the statistical analysis shown in section 4.6.1.1.

However it is important to note that even when the slope for rubber content is steeper, the range of rubber increment is only eight units (4% to 12%) compared seven hundred units (850µm to 150µm) of size change shown in Figure 4.34. This means in terms of the change of rubber percentage compared to rubber size reduction in terms of size, i.e. microns, and the size increment/reduction of rubber crumb size can significantly affect the level of abrasion loss compared to an increase of a single percentage of rubber content increment. This is demonstrated in Table 4.21 above where at 4% rubber content, 100µm reduction of crumb rubber size can have a higher impact to abrasion loss compared to one percent increment of rubber content modified with 850µm crumb rubber size.

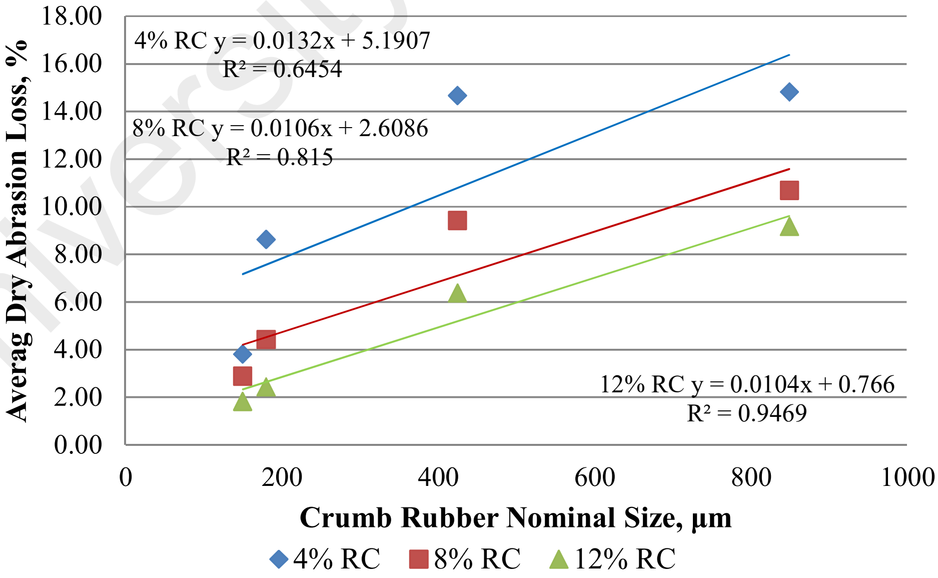

Figure 4.34 Relation between dry abrasion loss and crumb rubber size

4.7.1.1 Multiple Linear Regression Analysis on Dry Abrasion Loss

The regression analysis was conducted to determine which factors (binder content, rubber content and rubber size) were the predictors of the dry abrasion loss values.

The multiple linear regression analysis results on dry abrasion loss can be referred to in Appendix C, Tables C.2a – C.2d. Tables 4.22 – 4.23 show the summary of multiple linear regression analysis on the dry abrasion loss value. Table 4.21 indicates that two factors contribute 70.9% of the dry abrasion loss value, $R^2= 0.709$, $R^2_{adj}=0.705$, $F(2,153)=186.319$, $p<0.05$. As shown in Table 4.23, two factors were statistically significant, with rubber content recording a higher beta value (beta= -0.779) and rubber size (beta=0.320). The regression model can be written as below (Equation 4.6):

$$\textit{Dry abrasion loss} = -0.779(\textit{rubber content}) +0.320\ (\textit{rubber size}) \quad (4.6)$$

Table 4.22 Model Summary

Step	R	R^2	R^2_{adj}	ΔR^2	F_{chg}	p	df_1	df_2
Rubber content (%)	0.779	0.607	0.604	0.607	237.555	.000	1	154
Rubber size (µm)	0.842	0.709	0.705	0.102	53.735	.000	1	153

Table 4.23 Coefficients for Final Model

Step	*B*	*β*	*t*	*Bivariate r*	*Partial r*
Rubber content (%)	-9.758	-0.779	-17.858	-0.779	-0.822
Rubber size (µm)	0.015	0.320	7.330	0.320	0.510

4.7.2 Unconditioned (Dry) Indirect Tensile Test

Results of indirect tensile test show that the addition of rubber increases the tensile strength for all samples. The results are shown in Figure 4.35 – Figure 4.36. Full results are attached in Appendix C10. However, the increase of tensile strength is rather mild where for samples with 850µm rubber (Table 4.24), increasing the rubber content from 4% to 12% would only increase the tensile strength by 4.93% and for samples with 425µm rubber the increase is by 7.21%.

For samples with 180µm crumb rubber, the increase is 9.13% and for samples with 150µm crumb rubber, increasing the rubber content from 4% to 12% only increases the tensile strength by 5.78%. This means for a single rubber percentage, the average increase in tensile strength is between 0.62% and 1.14% as shown in Table 4.24.

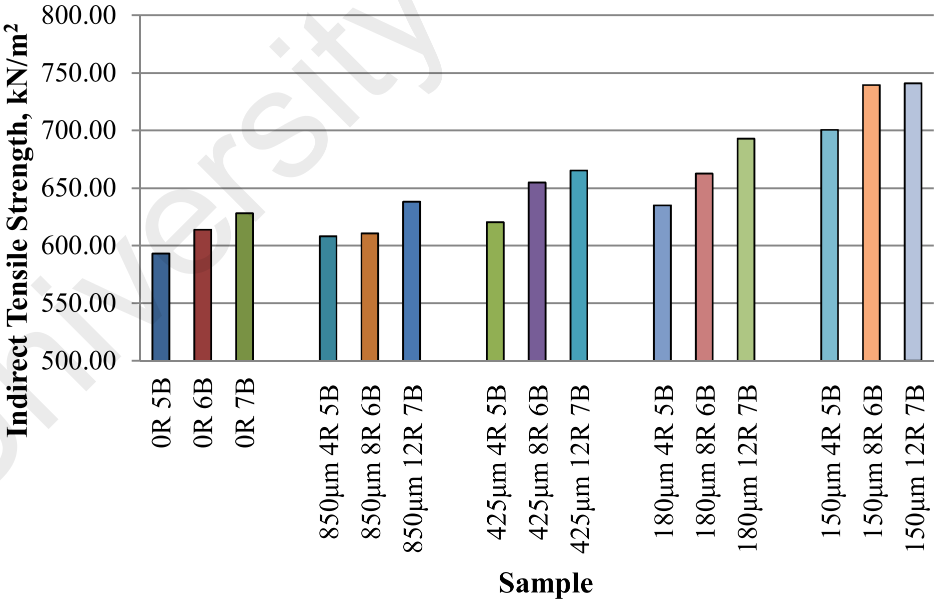

Figure 4.35: Indirect tensile strength relation with rubber content

Table 4.24 Changes of Dry Tensile Strength (DTS) relation with Rubber Content

Sample	Average Dry Tensile Strength, kN/m^2	Changes of DTS with Increasing Rubber/Binder Content, %	Total Changes of DTS with Increasing Rubber Content, %	Average Changes of DTS per Increase of Single Rubber Percentage, %
0R 5B	593.16	-	-	-
0R 6B	613.93	+3.50		
0R 7B	628.32	+2.34		
850μm 4R 5B	608.10	+2.52	+4.93	+0.62
850μm 8R 6B	610.70	+0.43		
850μm 12R 7B	638.09	4.49		
425μm 4R 5B	620.47	+4.60	+7.21	+0.90
425μm 8R 6B	654.94	+5.56		
425μm 12R 7B	665.20	+1.57		
180μm 4R 5B	635.10	+7.07	+9.13	+1.14
180μm 8R 6B	662.81	+4.36		
180μm 12R 7B	693.10	+4.57		
150μm 4R 5B	700.58	+18.11	+5.78	+0.72
150μm 8R 6B	739.46	+5.55		
150μm 12R 7B	741.09	+0.22		

Comparing the tensile strength between the different crumb rubber sizes (Table 4.25), it is observed that tensile strength increases with finer crumb rubber. At 4% and 8% rubber content, reducing the nominal crumb rubber size from 850μm to 150μm would increase the tensile strength by 15.21% and 21.08% respectively. This means for every 100μm reduced, the tensile strength would increase by 2.17% for samples with 850μm rubber and 3.01% for samples with 8% rubber. At 12% rubber content the same modification of crumb rubber size as above would increase the tensile strength by 16.14% and this means that on average, 100μm reduction of crumb rubber size would increase the tensile strength by 2.31%.

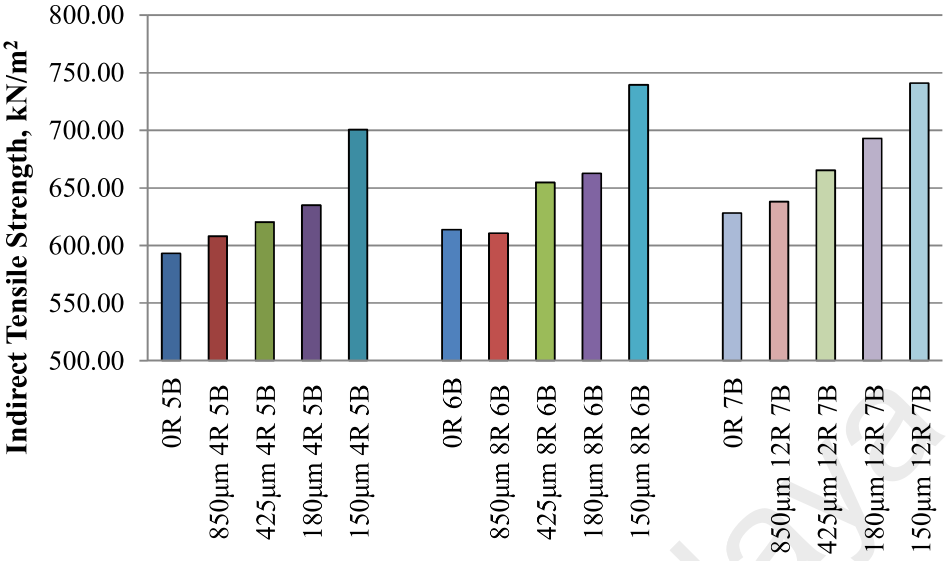

Figure 4.36: Indirect tensile strength relation with rubber size

Table 4.25 Dry Tensile Strength (DTS) relation with Rubber Addition and Rubber Size Reduction

Sample	Changes of Dry Tensile Strength with CR size, %					
	850µm	425µm	180µm	150µm	150µm compared to 425µm	150µm compared to 850µm
0R 5B	+2.52					
850µm 4R 5B		+2.04				+15.21
425µm 4R 5B			+2.36		+12.91	
180µm 4R 5B				+10.31		
150µm 4R 5B						
0R 6B	-0.53					
850µm 8R 6B		+7.24				+21.08
425µm 8R 6B			+1.20		+12.90	
180µm 8R 6B				+11.56		
150µm 8R 6B						
0R 7B	+1.55					
850µm 12R 7B		+4.25				+16.14
425µm 12R 7B			+4.19		+11.41	
180µm 12R 7B				+6.92		
150µm 12R 7B						

Figure 4.37 and Figure 4.38 on the other hand, outlines relationship between rubber content and rubber crumb size to tensile strength. While the relationship of rubber content with tensile strength is linear, the relation between tensile strength and crumb rubber size is in the form of power equation. However, it is observed that the rate of change of the slope for rubber content is higher compared to rubber size. This shows that increasing rubber content will give a higher impact on the tensile strength of the mix per unit increment.

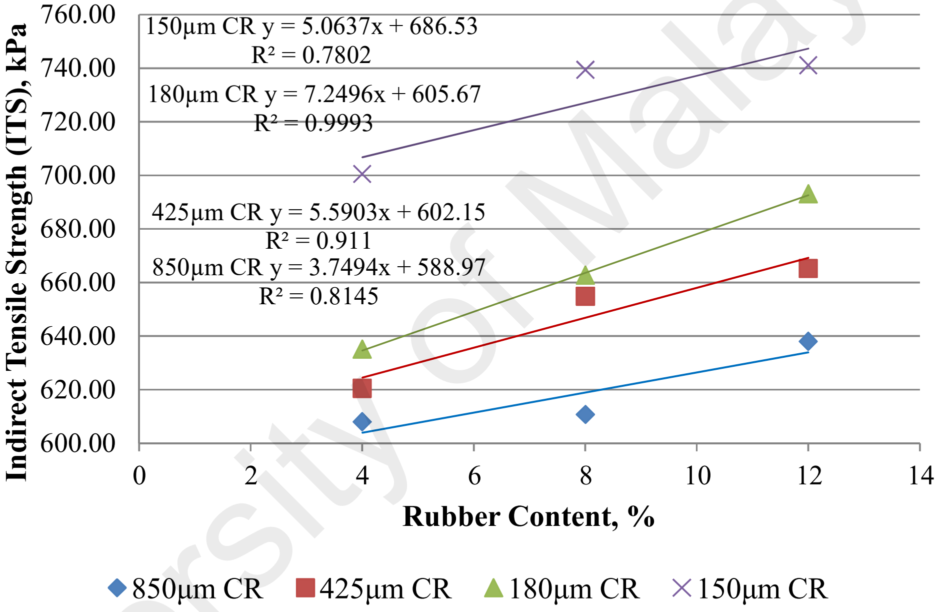

Figure 4.37: Relationship between indirect tensile strength and rubber content

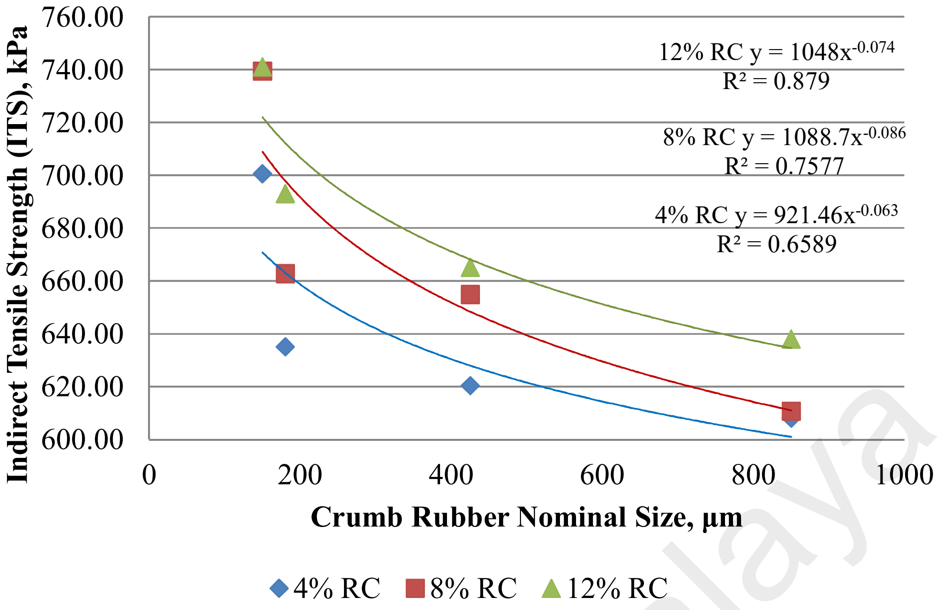

Figure 4.38: Relationship between indirect tensile strength and rubber size

4.7.2.1 Multiple Linear Regression on Indirect Tensile Value for Unconditioned Sample

The multiple linear regression analysis results on indirect tensile value for unconditioned sample can be referred to in Appendix C, Tables C. 3a – C.3d. The summary is listed in Tables 4.26 – 4.27. The regression analysis was conducted to determine which factors (binder content, rubber content and rubber size) were the predictors of the indirect tensile values. The regression results indicate an overall model of rubber content and rubber size that significantly predicts the indirect tensile value, R^2=0.299, R^2_{adj}=0.272, $F(2,52)$=31876.662, p<0.05. This model accounted for 29.9% of variance in indirect tensile. Equation 4.7 is the regression model based on the beta weight for predicting the indirect tensile value:

Dry ITS =0.576 (rubber content) -0.450 (rubber size) (4.7)

Table 4.26 Model Summary

Step	R	R^2	R^2_{adj}	ΔR^2	F_{chg}	p	df_1	df_2
Rubber content (%)	0.371	0.138	0.122	0.138	8.485	.005	1	53
Rubber Size (µm)	0.547	0.299	0.272	0.161	11.916	.001	1	52

Table 4.27 Coefficients for Final Model

Step	*B*	*β*	*t*	*Bivariate r*	*Partial r*
Rubber content (%)	8.098	0.576	4.419	0.371	0.522
Rubber Size (µm)	-0.096	-0.450	-3.452	-0.188	-0.432

4.7.3 Unconditioned (Dry) Indirect Tensile Stiffness Modulus

The indirect tensile stiffness modulus test measures the stiffness of an asphaltic mix. Higher value shows that the mix is stiff and resistant to change while lower stiffness modulus value shows that the mix is becoming rather elastic where the deformation of the sample increases. The outcomes of the test are shown in Figure 4.39 - 4.40 and Table 4.28 and Table 4.29. Full results are attached in Appendix C12.

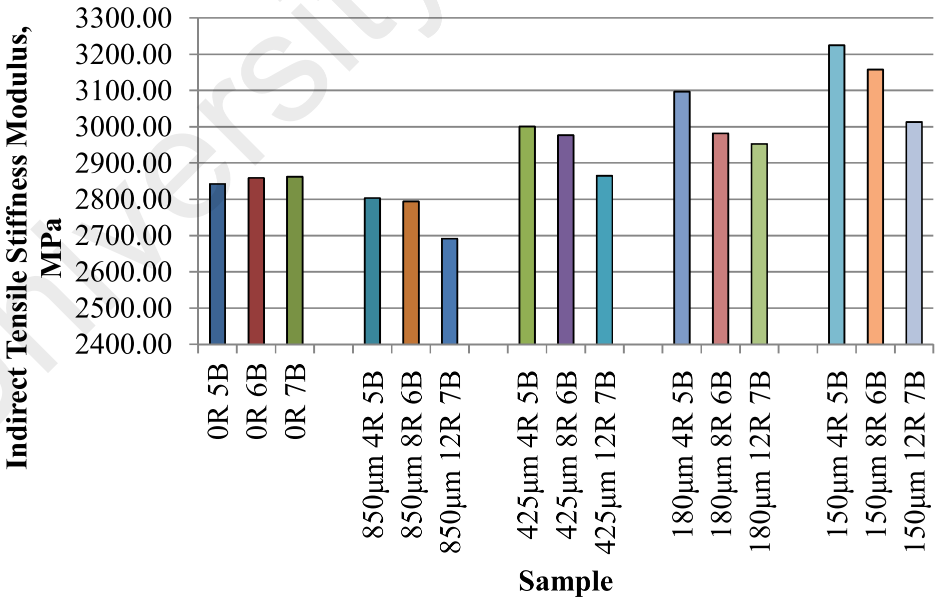

Figure 4.39: Indirect tensile stiffness modulus relation with rubber content

Table 4.28 Dry Stiffness Modulus (DSM) relation with Rubber Content

Sample	Average Dry Stiffness Modulus, MPa	Changes of DSM with Increasing Rubber/Binder Content, %	Total Changes of DSM with Increasing Rubber Content, %	Average change of DSM per Increase of Single Rubber Percentage, %
0R 5B	2842.50	-	-	-
0R 6B	2858.53	+0.56		
0R 7B	2862.06	+0.12		
850μm 4R 5B	2878.25	+1.26	-6.49	-0.81
850μm 8R 6B	2794.11	-2.92		
850μm 12R 7B	2691.39	-3.68		
425μm 4R 5B	3000.77	+5.57	-4.53	-0.57
425μm 8R 6B	2976.25	-0.82		
425μm 12R 7B	2864.96	-3.74		
180μm 4R 5B	3097.14	+8.96	-4.67	-0.58
180μm 8R 6B	2981.33	-3.74		
180μm 12R 7B	2952.45	-0.97		
150μm 4R 5B	3224.77	+13.45	-6.56	-0.82
150μm 8R 6B	3157.73	-2.08		
150μm 12R 7B	3013.12	-4.58		

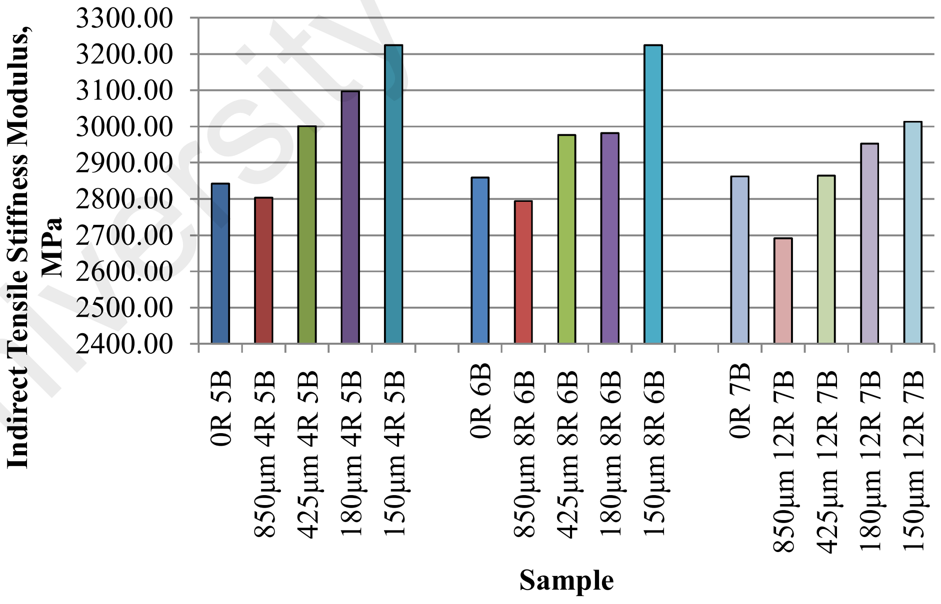

Figure 4.40: Indirect tensile stiffness modulus relation with rubber size

It is observed that the stiffness modulus decreases with the addition of rubber for all rubber sizes. Samples with 850µm crumb rubber shows a decrease of stiffness modulus by 6.49% while samples with 425µm and 180µm crumb rubber records a reduction of 4.53% and 4.67% respectively.

A higher decline of stiffness modulus is shown by samples with 150µm with 6.56% reduction. The reductions in the values of stiffness modulus average out to 0.81% reduction of stiffness modulus with every one percent rubber content increment for samples with 850µm crumb rubber. This followed by 0.57% reduction by samples with 425µm crumb rubber and 0.58% and 0.82% reduction for samples with 180µm and 150µm respectively.

Comparing different rubber sizes, it is interesting to note that as the crumb rubber size decreases, the stiffness modulus increases; as opposed the decreasing stiffness modulus with increased rubber content described above. At 4% rubber content, a reduction of crumb rubber size from 850µm to 150µm would increase the stiffness modulus by 12.04%. The same reduction of crumb rubber size would increase the stiffness modulus by 13.01% and 11.95% for samples with 8% and 12% rubber content respectively.

This avarages to 1.72% increase in stiffness modulus for samples with 4% rubber content, 1.86% increase for samples 8% rubber content and 1.71% stiffness modulus increase for samples with 12% rubber content.

Table 4.29 Changes of Dry Stiffness Modulus (DSM) relation with Rubber Addition and Rubber Size

Sample	Changes of Dry Stiffness Modulus with CR size, %					
	850µm	425µm	180µm	150µm	150µm compared to 425µm	150µm compared to 850µm
0R 5B	+1.26					
850µm 4R 5B		+4.26				+12.04
425µm 4R 5B			+3.21		+7.46	
180µm 4R 5B				+4.12		
150µm 4R 5B						
0R 6B	-2.25					
850µm 8R 6B		+6.52				+13.01
425µm 8R 6B			+0.17		+6.10	
180µm 8R 6B				+5.92		
150µm 8R 6B						
0R 7B	-5.96					
850µm 12R 7B		+6.45				+11.95
425µm 12R 7B			+3.05		+5.17	
180µm 12R 7B				+2.06		
150µm 12R 7B						

Refferring to Figure 4.41 and Figure 4.42, it can be seen that the relationship between stiffness modulus and rubber content as well as crumb rubber size can be represented by linear relationship with reasonable goodness of fit. Graphically the figures show that stiffness mudulus would decrease as a result of higher content of crumb rubber addition and the stiffness modulus, can, on the other hand be improved with finer crumb rubber sizes.

In terms or the relationship between stiffness modulus and rubber content (Figure 4.42), on average the decline of the slopes of the functions are much steeper compared to the functions of relation between stiffness modulus and crumb rubber size (Figure 4.41). This, once again, shows that per unit increment, rubber content have a higher impact in reducing the stiffness modulus compared to crumb rubber size.

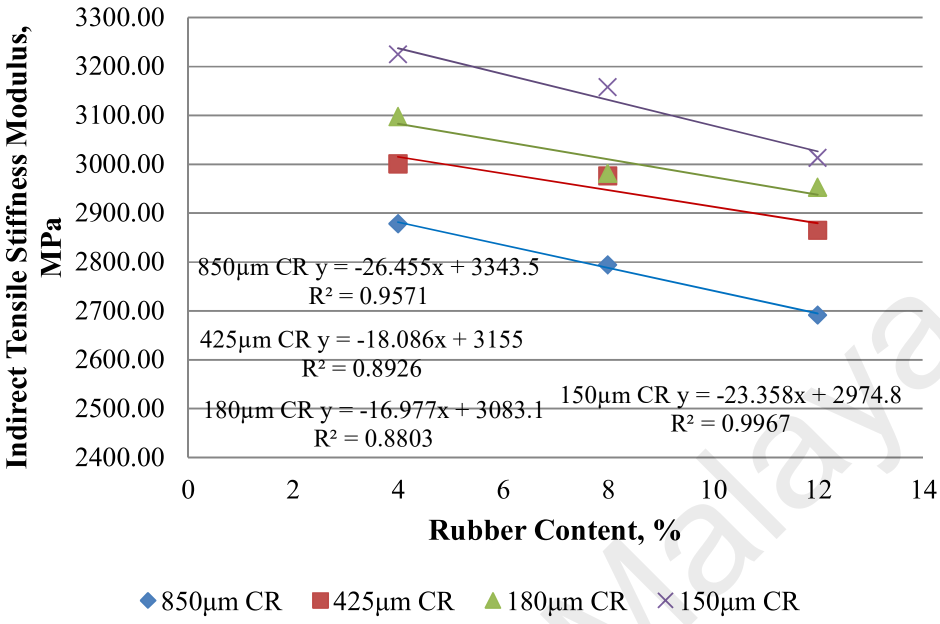

Figure 4.41: Indirect stiffness modulus relation with rubber content

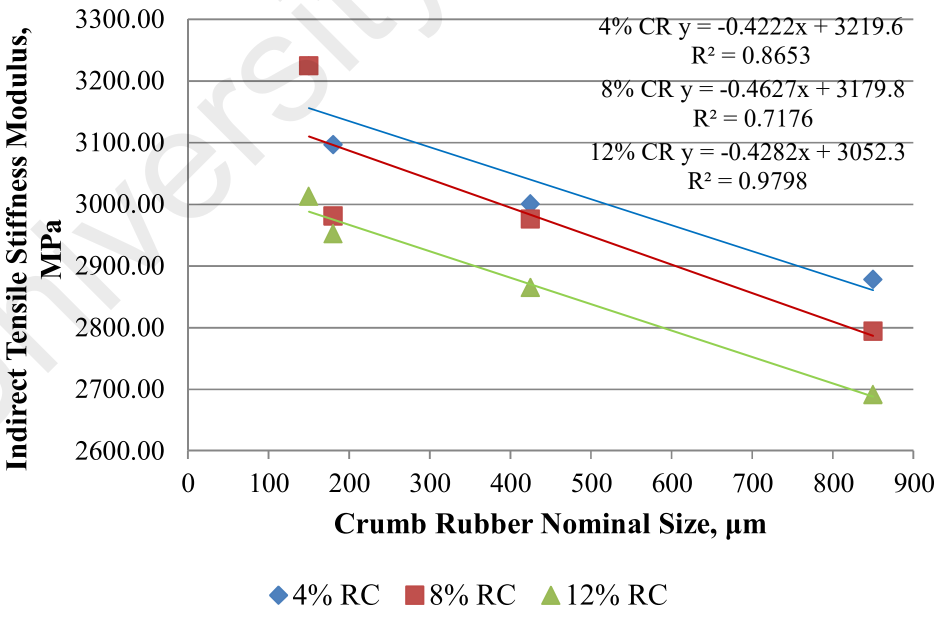

Figure 4.42: Indirect stiffness modulus relation with crumb rubber size

4.7.3.1 Multiple Linear Regression on Indirect Tensile Stiffness Modulus Value for Unconditioned Sample

Table 4.30 and Table 4.31 show the multiple linear regression analysis using the stepwise method to assess the ability of the factors (rubber size, rubber content and binder content) to predict indirect tensile stiffness modulus value for unconditioned sample (Appendix C, Tables C.4a – C.4d). The factors can explain 47.7% of the variance in indirect tensile stiffness modulus value, $F(3,86)=26.188$, $p<.05$. In the final model, two factors were statistically significant, with the rubber content recording a higher beta value (beta= -0.678, p =0.000 <0 .05), followed by rubber size (beta= -0.666, p= 0.000<.05) (see Table 4.31). Equation 4.8 is the regression equation that can be used to estimate indirect tensile stiffness modulus value for unconditioned sample:

$$Dry\ ITSM = -0.678\ (Rubber\ content)\ -0.666\ (Rubber\ size) \qquad (4.8)$$

Table 4.30 Model Summary

Step	R	R^2	R^2_{adj}	ΔR^2	F_{chg}	p	df_1	df_2
Rubber Content (μm)	0.480	0.230	0.221	0.230	26.317	.000	1	88
Rubber Size (%)	0.610	0.372	0.358	0.142	19.656	.000	1	87

Table 4.31 Coefficients for Final Model

Step	B	β	t	*Bivariate r*	*Partial r*
Rubber Content (μm)	-0.324	-0.678	-7.423	-0.480	-0.625
Rubber Size (%)	-115.989	-0.666	-6.377	-0.377	-0.567

4.8 The Effect of Water to the Durability of Porous Asphalt

The main function of porous pavement is to allow water to flow to the underlying structure. This greatly reduces splash and spray from the vehicles and also prevents aquaplaning on the surface of the road. However the porous structure the asphalt leaves a higher surface area within the pavement that is in contact with water and air. This speeds up the oxidation process and subsequently the deterioration of the pavement. Therefore, it is vital that a complete porous asphalt design should include water resistance tests in order to evaluate the behaviour and durability of the mix towards the effect of water. Two tests were conducted in this study to evaluate the water effect; namely the Wet (Conditioned) Cantabro Test and the Wet (Conditioned) Indirect Tensile Test. The Indirect Tensile Stiffness Modulus test was also conducted using water conditioned samples to study if water reduces the stiffness modulus of the mix and to investigate if this test can be used to quantify the water effect to the deterioration of porous asphalt as well as the previous two tests. Full results of the Conditioned (Wet) Abrasion Loss, Indirect Tensile Strength and Indirect Tensile Stiffness Modulus are given in Appendix C9, C11 and C13 respectively.

4.8.1 Wet (Conditioned) Abrasion Loss

Figure 4.43 shows the abrasion loss pattern for conditioned samples compared with the unconditioned samples where it can be observed that the abrasion loss for conditioned samples were greatly affected by the conditioning process and the amount of abrasion loss reduces with higher amount of crumb rubber addition which is a comparable trend to that of the unconditioned samples.

The effect of increasing rubber content can be seen in Table 4.32. In a general view, for the control specimens, the conditioned samples show an abrasion loss between 27.5% and 52.7 %, which is almost 4 times the value of unconditioned samples. Similar pattern can be seen for samples modified with 850µm and 425µm rubber crumb where for samples with 850µm rubber, the abrasion loss is between 27.18% and 53.52% and for samples with 425µm the abrasion loss is between 49.08% and 18.26%. Samples modified with medium sized rubber crumb shows a smaller loss value with a loss between 11.99% and 41.77% loss for samples with 180µm crumb rubber while samples with 150µm crumb rubber shows a loss between 10.24% and 39.48%.

Compared with control mixes, all samples show an increased resistance of wet abrasion loss with the addition of rubber except for mix modified with 850µm crumb rubber and 4% rubber content where the abrasion resistance decreased by 1.55%. This is due to the sensitivity of samples with larger rubber crumb and lower rubber content. Samples modified with 850µm crumb rubber, increasing rubber content from 4% to 8% decreases the abrasion loss by 26.22% and at 12% rubber, the loss is further reduced to 31.16%.

Similar trend are found with samples with 425µm crumb rubber where the amount of abrasion loss reduction are at 39.93% and 38.07% for 8% and 12% rubber. Samples with finer rubber crumb show very good resistance of wet abrasion where reduction of loss at 8% and 12% crumb rubber are 48.54% and 44.24% reduction for mixes with 180µm crumb rubber while samples with 150µm crumb rubber shows a reduction of 47.41% and 50.66% for samples with 8% and 12% crumb rubber.

From the values obtained, it can be seen that for samples with 850µm crumb rubber, the increase of rubber content from 4% to 12% reduces the abrasion loss to 49.21% which makes the average reduction of 6.68% per single percent of rubber content increment. This value continue to grow with samples with smaller rubber size where samples with 180µm rubber records an average of 8.91% loss reduction per single rubber increment and samples with 150µm shows a 9.26% loss reduction per single rubber content increment.

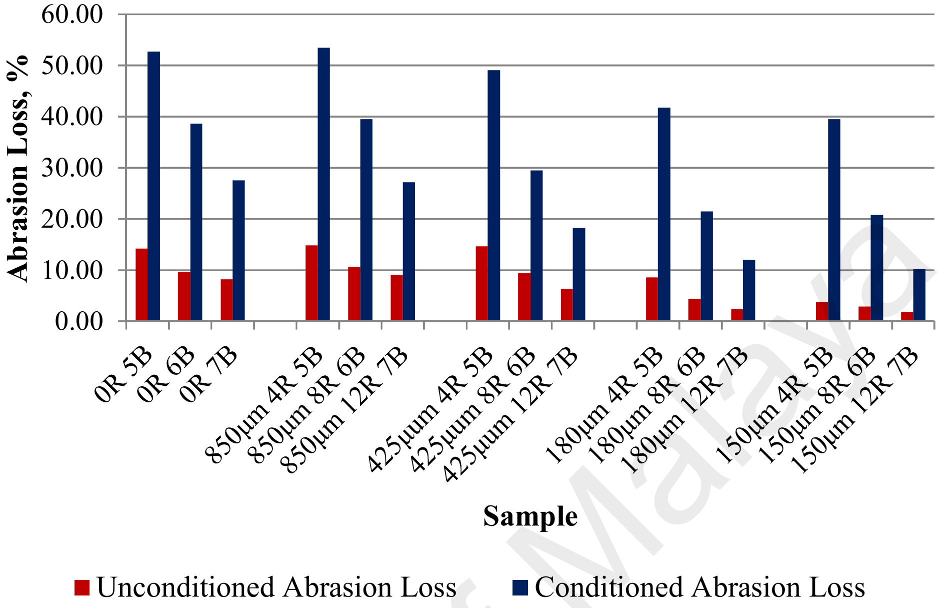

Figure 4.43: Conditioned (wet) and unconditioned (dry) abrasion loss versus rubber content

Table 4.32: Changes of Wet Abrasion Loss (WAL) relation with Rubber Content

Sample	Average Wet Abrasion Loss, %	Changes of WAL with Increasing Rubber/Binder Content, %	Total Changes of WAL with Increasing Rubber Content, %	Average Changes of WAL per Increase of Single Rubber Percentage, %
0R 5B	52.70	-	-	-
0R 6B	38.66	-26.64		
0R 7B	27.53	-28.79		
850µm 4R 5B	53.52	+1.55	-49.21	-6.68
850µm 8R 6B	39.48	-26.22		
850µm 12R 7B	27.18	-31.16		
425µm 4R 5B	49.08	-6.88	-62.80	-7.85
425µm 8R 6B	29.48	-39.93		
425µm 12R 7B	18.26	-38.07		
180µm 4R 5B	41.77	-20.74	-71.31	-8.91
180µm 8R 6B	21.50	-48.54		
180µm 12R 7B	11.99	-44.24		
150µm 4R 5B	39.48	-25.08	-74.05	-9.26
150µm 8R 6B	20.76	-47.41		
150µm 12R 7B	10.24	-50.66		

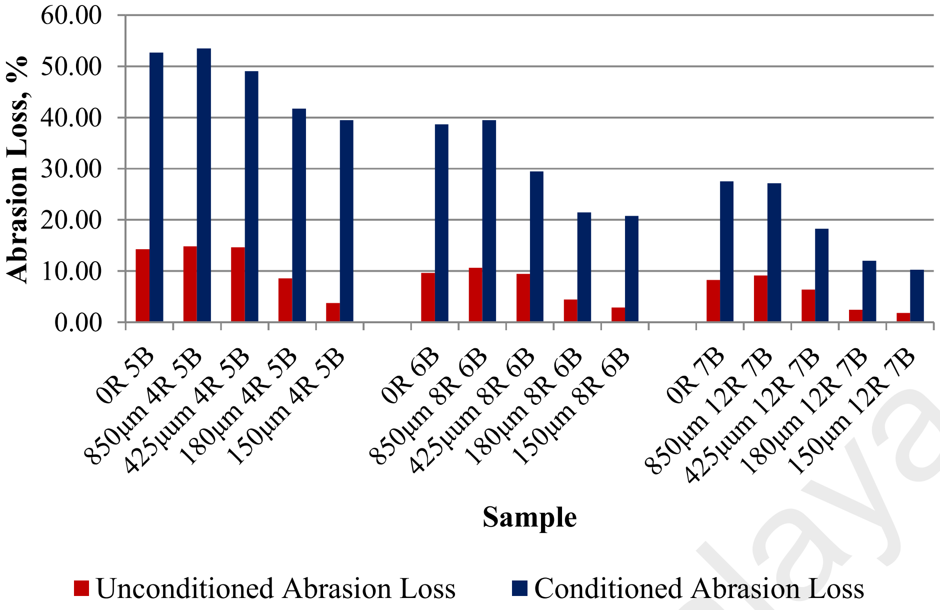

Figure 4.44: Conditioned and unconditioned abrasion loss

Table 4.33: Changes of Wet Abrasion Loss (WAL) relation with Rubber Addition and Rubber Size

Sample	Changes of Wet Abrasion Loss with CR size, %					
	850µm	425µm	180µm	150µm	150µm compared to 425µm	150µm compared to 850µm
0R 5B	+1.55					
850µm 4R 5B		-8.30				-26.22
425µm 4R 5B			-14.88		-19.55	
180µm 4R 5B				-5.48		
150µm 4R 5B						
0R 6B	+2.13					
850µm 8R 6B		-25.34				-47.41
425µm 8R 6B			-27.08		-29.56	
180µm 8R 6B				-3.40		
150µm 8R 6B						
0R 7B	-1.27					
850µm 12R 7B		-32.83				-62.31
425µm 12R 7B			-34.35		-43.88	
180µm 12R 7B				-14.53		
150µm 12R 7B						

Figure 4.44 and Table 4.33 on the other hand, compares the abrasion loss of samples modified between different crumb rubber sizes. It is observed that samples modified using 850µm crumb rubber with 4% and 8% rubber content shows slightly higher

abrasion loss percentage (1.55% and 2.13% respectively) compared control samples. This is anticipated as a somewhat similar trend is found with the unconditioned samples where samples that were modified with 850µm rubber crumb at all rubber content and samples that were modified with 425µm rubber crumb with 4% rubber content have a slightly higher abrasion loss than the control samples. This is due the sensitivity of the mixes that were modified with larger crumb rubber and mixes with lower rubber content with respect to the rubber crumb size that have been explained in the previous section on optimum binder content.

At 4% rubber addition, as the crumb rubber size decreases, the reduction of abrasion loss increases. Samples modified with 425µm rubber, the reduction is at 8.3% and samples with 180µm rubber crumb shows a further 14.88% reduction compared to samples with 425µm rubber. 5.48% further reduction is recorded with samples that were modified with 150µm crumb rubber. When compared between samples that were modified with 850µm crumb rubber, samples with 150µm rubber shows a reduction of loss of 26.22%. This amounts to an average of 3.75% abrasion loss reduction per 100µm of rubber size drop.

Samples with finer rubber crumb on the other hand shows an increase of strength where, at 8% rubber addition the loss was reduced by 25.34%, 27.08% and finally by 3.4% for 425µm, 180µm and 150µm crumb rubber respectively. At 12% rubber content, the reduction of abrasion loss is even higher at 32.83%, 34.35% and 14.53% for the same of sequence of size crumb rubber as mentioned above. From the values, it is estimated that that an average of 6.8% of abrasion loss can be reduced by decreasing the crumb rubber size by 100µm.

Higher percentage of reduction of wet abrasion loss pattern is observed with samples with 12% rubber content. Mixes with 850µm rubber only shows a decrease of abrasion loss of 1.27% compared with control, however mixes with 425µm and 180µm increased the resistance of abrasion by 32.83% and 34.35% respectively. A further 14.53% decrease of abrasion loss is obtained with samples modified with 150µm crumb rubber. Comparing the reduction of abrasion loss between samples with 850µm rubber and 150µm rubber, a total of 62.61% reduction is recorded. This means that for every 100µm of crumb rubber size reduction, an average of 8.9% abrasion loss can be achieved.

4.8.1.1 The Difference of Wet and Dry Abrasion Loss

Table 4.34 shows the difference and the percentage of increment of abrasion loss between unconditioned and conditioned samples. The percentages of abrasion loss increase between wet and dry abrasion loss does not show any specific trend. In general it can be said that the increase of abrasion loss ranges from 286.62% to 1037.85%. The difference between wet and dry abrasion loss however does show a specific trend where the abrasion loss difference reduces with the increase of rubber content.

Table 4.34: Comparison between Wet and Dry Cantabro Abrasion Loss

Sample	Average Wet Abrasion Loss, %	Average Dry Abrasion Loss, %	Wet-Dry Abrasion Loss Difference, %	Wet-Dry Increase of Abrasion Loss, %
0R 5B	52.70	14.27	38.43	369.29
0R 6B	38.66	9.67	28.99	399.82
0R 7B	27.53	8.22	19.31	334.76
850µm 4R 5B	53.52	14.81	38.71	361.37
850µm 8R 6B	39.48	10.68	28.80	369.69
850µm 12R 7B	27.18	9.16	18.02	296.78
425µm 4R 5B	49.08	14.15	34.93	346.84
425µm 8R 6B	29.48	9.42	20.06	312.98
425µm 12R 7B	18.26	6.37	11.89	286.62
180µm 4R 5B	41.77	8.61	33.16	485.07
180µm 8R 6B	21.50	4.41	17.08	486.99
180µm 12R 7B	11.99	2.43	9.56	494.15
150µm 4R 5B	39.48	3.80	35.68	1037.85
150µm 8R 6B	20.76	2.88	17.89	722.02
150µm 12R 7B	10.24	1.82	8.43	564.25

Figure 4.45 and 4.46 on the other hand; show the difference between the abrasion losses of the conditioned samples to the non-conditioned samples graphically. It can be seen from both figures that the difference between the conditioned and the unconditioned samples reduces as the binder content increase and as the crumb rubber nominal size decreases. This shows that rubber modification does increase the ability of the mix to withstand abrasive forces under wet condition.

Comparing the effect between the rubber content in Figure 4.43 and crumb rubber size in Figure 4.46, it is interesting to note that the slopes of the relationships between abrasion loss difference and rubber content in Figure 4.43 is steeper; with the gradient of the trend line ranges between -2.39 and -3.41, compared to slopes in Figure 4.46 where the gradient of the trend line is between 0.01 to 0.02. This shows that the rubber content has a stronger influence in increasing the resistance of disintegration of porous mixes compared to crumb rubber size due to moisture damage.

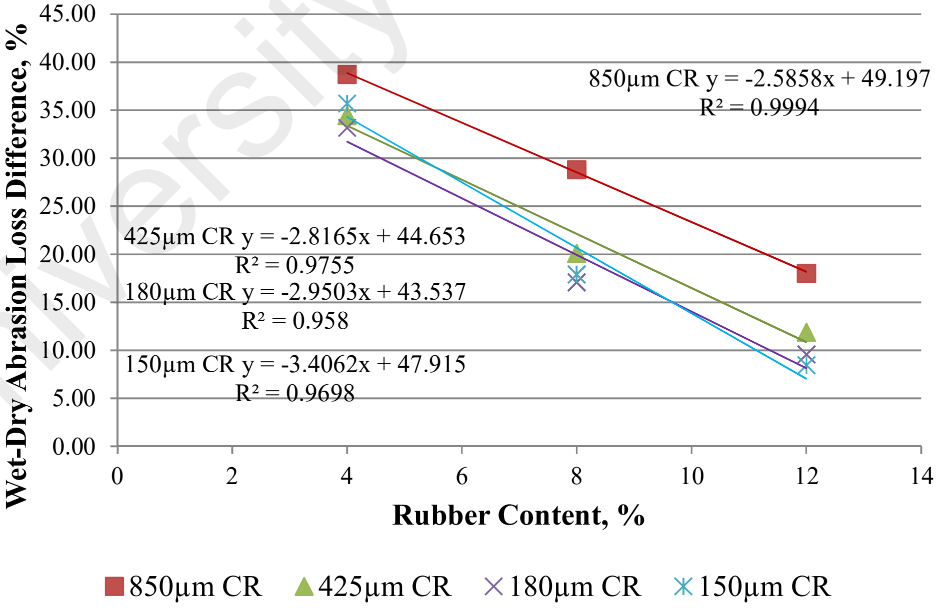

Figure 4.45: Difference of Wet and Dry Abrasion Loss (rubber content)

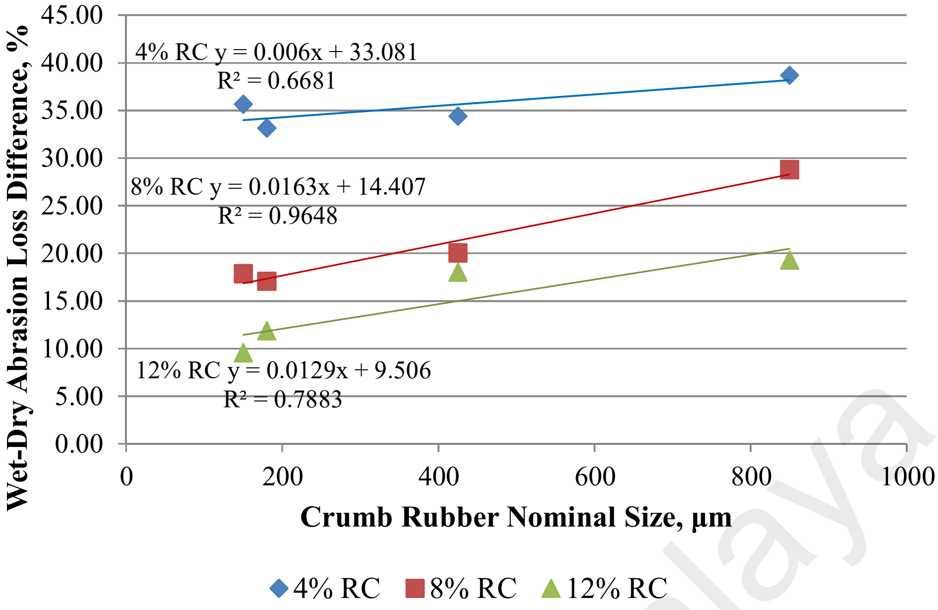

Figure 4.46: Difference of Wet and Dry Abrasion Loss (rubber size)

4.8.1.2 Abrasion Resistance Ratio (ARR)

Abrasion resistance ratio is a value introduced in this study in order to compare the results from dry and wet Cantabro test with the Tensile Strength Ratio (TSR) of the wet and dry Tensile Test. The value of abrasion resistance is obtained by subtracting the values of both wet and dry abrasion loss from 100 and the loss resistance ratio is the ratio between the dry and wet abrasion resistance. This gives a value between zero and one which can also be interpreted as a percentage when multiplied with 100. The comparison of increasing rubber content and crumb rubber size to the abrasion resistance ration is shown in Table 4.35, also in Figure 4.47 and Figure 4.48.

It can be seen from Figure 4.47 that the abrasion resistance ratio for all samples increases with a linear relationship with very good r^2 value for all crumb rubber size. The lowest value of ARR is 54.6% resistance from samples with 850µm rubber crumb and 4% rubber content and the highest resistance are recorded by samples with 150µm rubber crumb with 12% rubber content. This value increases with increasing rubber content and decreasing rubber size. The relationship between conditioned abrasion resistance value and nominal crumb rubber size on the other hand, is represented with a power relationship where the rate of conditioned abrasion resistance increase is much gentler compared to increasing rubber content. This again, show that increasing rubber content gives a higher impact on increasing the wet abrasion resistance value compared to reducing crumb rubber size. However as the regression analysis above shows, both factors are statistically significant in increasing the wet abrasion resistance.

Table 4.35: Abrasion Resistance Ratio (ARR)

Sample	Dry Abrasion Resistance, %	Wet Abrasion Resistance, %	Abrasion Resistance Ratio
0R 5B	85.73	47.30	0.552
0R 6B	90.33	61.34	0.679
0R 7B	91.78	72.47	0.790
850μm 4R 5B	85.19	46.48	0.546
850μm 8R 6B	89.32	60.52	0.678
850μm 12R 7B	90.84	72.82	0.802
425μm 4R 5B	85.34	50.92	0.597
425μm 8R 6B	90.58	70.52	0.779
425μm 12R 7B	93.63	81.74	0.873
180μm 4R 5B	91.39	58.23	0.637
180μm 8R 6B	95.59	78.50	0.821
180μm 12R 7B	97.57	88.01	0.902
150μm 4R 5B	96.20	60.52	0.629
150μm 8R 6B	97.12	79.24	0.816
150μm 12R 7B	98.18	89.76	0.914

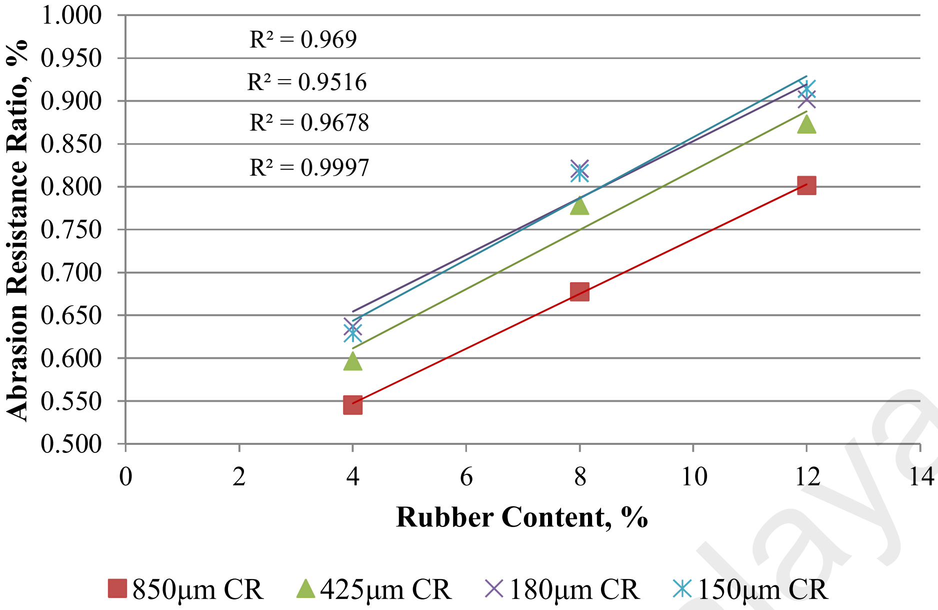

Figure 4.47: Relations between Abrasion Resistance Ratio with Rubber Content

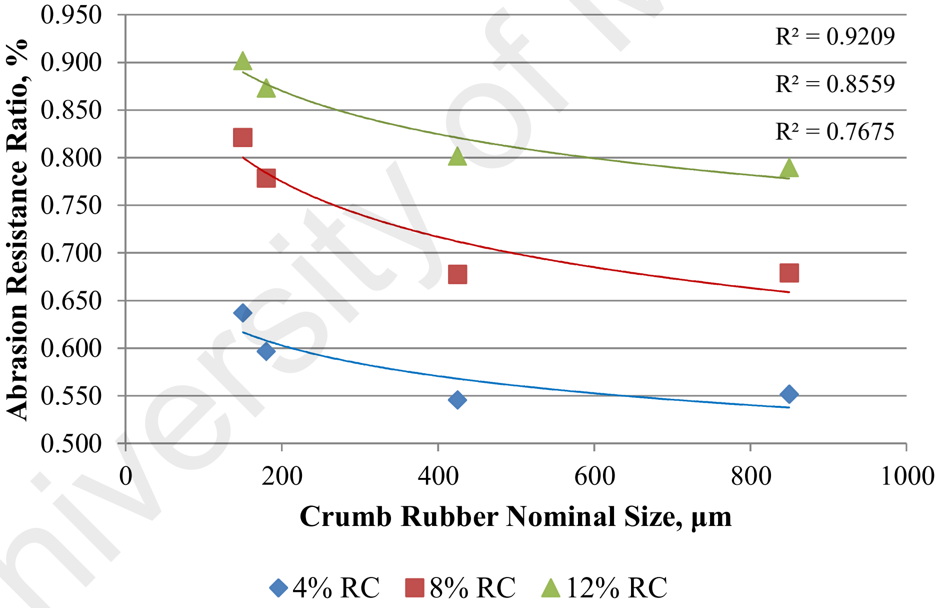

Figure 4.48: Relations of Abrasion Resistance Ratio with Crumb Rubber Size

4.8.2 Conditioned Indirect Tensile Test (ITS)

Figure 4.49, Figure 4.50 and Table 4.36 together with Table 4.37 shows the comparison between the indirect tensile strength to the amount of rubber content and crumb rubber nominal size. It is clear from the figures that tensile strength was negatively affected with the conditioning process. However, the tensile strength increases as rubber content increases. For samples modified with 850µm crumb rubber, the increase of rubber content from 4% to 12% yields a total increase of tensile strength by 11.69% while for samples with 425µm crumb rubber, the increase of tensile strength for the same amount of rubber content increase is at 14.76%. This means that, for every increase of one percent rubber content, the increase of tensile strength on average is 1.46% and 1.84% respectively for the said samples.

Samples with finer rubber crumb also shows similar trend at a higher strength where average increase of 1.78% are recorded for samples with 180µm rubber crumb and samples with 150µm rubber crumb shows an average increase of 2.25% tensile strength with an increase of one percent rubber addition. It can be said that, generally the tensile strength increases with increasing rubber content and decreasing rubber size, a similar trend with the unconditioned samples.

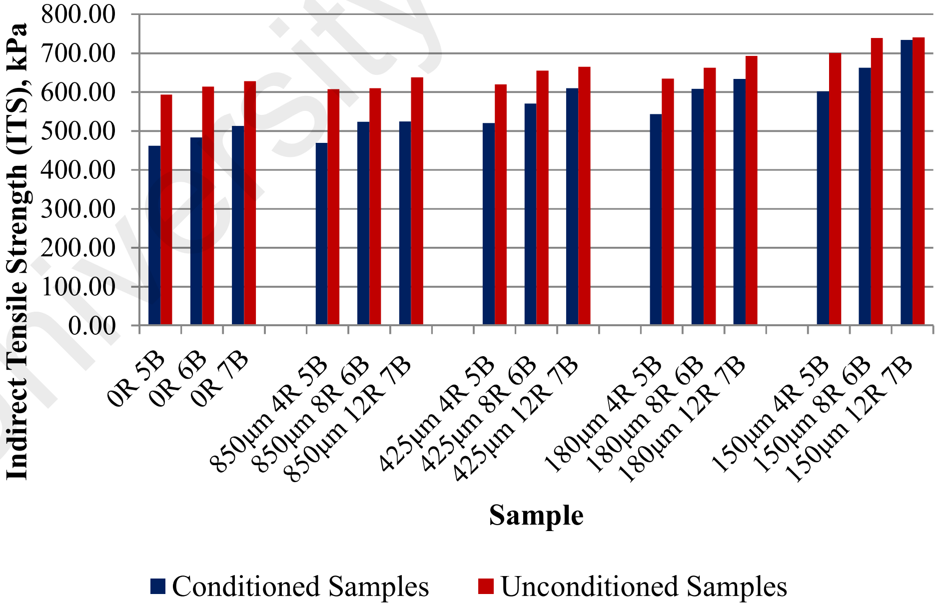

Figure 4.49: Conditioned and unconditioned tensile strength versus rubber content

Table 4.36: Changes of Wet Tensile Strength (WTS) relation with Rubber Content

Sample	Average Wet Tensile Strength, kPa	Changes of WTS with Increasing Rubber/Binder Content, %	Total changes of WTS with Increasing Rubber Content, %	Average Changes of WTS per Increase of Single Rubber Percentage, %
0R 5B	462.17	-	-	-
0R 6B	483.44	+4.60		
0R 7B	513.41	6.20		
850µm 4R 5B	470.03	+1.70	11.69	1.46
850µm 8R 6B	524.24	+11.53		
850µm 12R 7B	524.96	+0.14		
425µm 4R 5B	520.45	+12.61	14.76	1.84
425µm 8R 6B	571.22	+9.76		
425µm 12R 7B	610.57	+6.89		
180µm 4R 5B	544.21	+17.75	14.24	1.78
180µm 8R 6B	608.53	+11.82		
180µm 12R 7B	634.60	+4.28		
150µm 4R 5B	602.11	+30.28	17.97	2.25
150µm 8R 6B	663.03	+10.12		
150µm 12R 7B	733.99	+10.70		

As expected, between the different rubber sizes, it can be seen that the conditioned tensile strength increases as the crumb rubber size decreases as expected. For instance, if the rubber size is changed from 850µm to 150µm at 4% rubber content, the conditioned tensile strength increases by 28.10%. At 8% and 12% rubber content, the change of rubber size above would improve by 26.47% and 39.82% respectively. These sums up to a reduction of 4.01% per 100µm size reduction of rubber crumb being used at 4% rubber content and at 8% and 12% rubber content, the reduction of rubber crumb size by 100µm would increase the conditioned tensile strength by 3.78% and 5.63%. This is very interesting as these improvements are higher than an increase of rubber content by a single rubber percentage as explained previously.

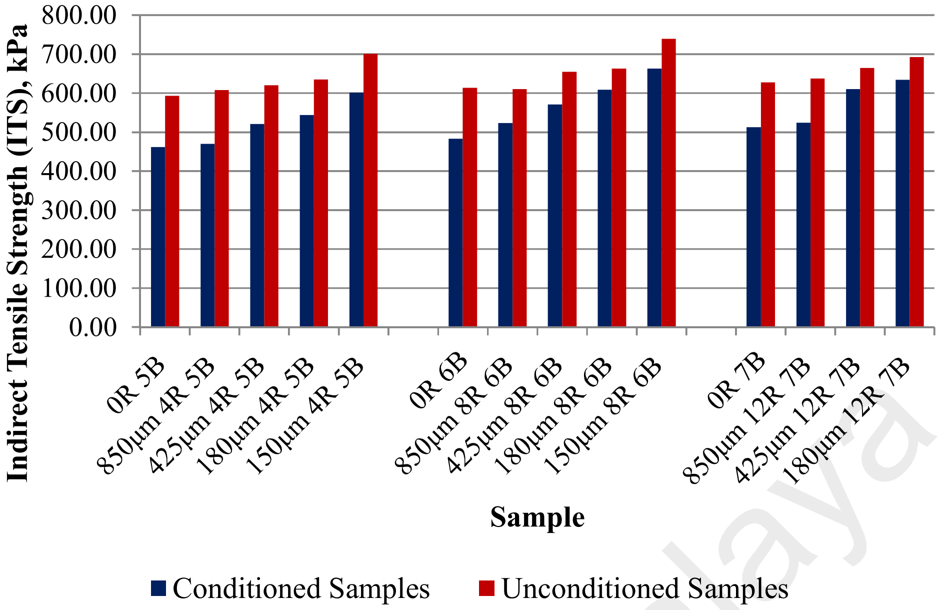

Figure 4.50: Conditioned and unconditioned tensile strength versus rubber size

Table 4.37: Wet Tensile Strength (WTS) relation with Rubber Addition and Rubber Size Reduction

Sample	Changes of Wet Tensile Strength with CR size, %					
	850µm	425µm	180µm	150µm	150µm compared to 425µm	150µm compared to 850µm
0R 5B	+1.70					
850µm 4R 5B		+10.73				+28.10
425µm 4R 5B			+4.56		+15.69	
180µm 4R 5B				+10.64		
150µm 4R 5B						
0R 6B	+8.44					
850µm 8R 6B		+8.96				+26.47
425µm 8R 6B			+6.53		+16.07	
180µm 8R 6B				+8.96		
150µm 8R 6B						
0R 7B	+2.25					
850µm 12R 7B		+16.31				+39.82
425µm 12R 7B			+3.94		+20.21	
180µm 12R 7B				+15.66		
150µm 12R 7B						

4.8.2.1 Tensile Strength Ratio

Tensile strength ration is the ratio of tensile strength between the conditioned and unconditioned samples. The relationship between tensile strength ratio (TSR) and rubber content and rubber size are shown in Figure 4.51 and Figure 4.52 where the relation between TSR and crumb rubber size can be represented by power functions while the relation between TSR and rubber content is linear. Both relationships have reasonably good fitting where the r^2 values ranges between 0.7179 and 0.992.

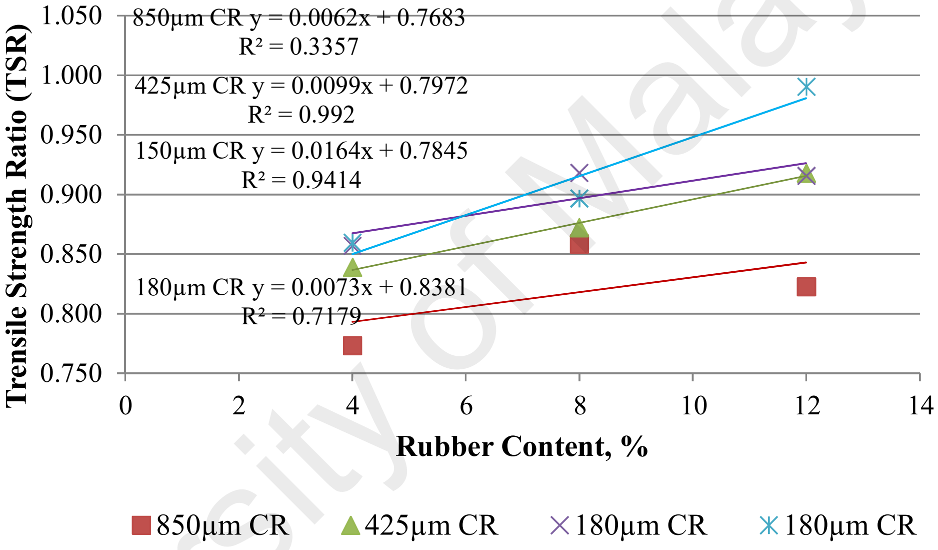

Figure 4.51: TSR relations with rubber content

From the graphs, all samples achieved at least 0.77 or 77% tensile strength ratio and it can be seen that increasing the rubber content and decreasing the crumb rubber size helps in improving the mix by increasing the tensile strength. The figures also show a trend where the slope of relationship between TSR and rubber content is steeper than that of the relationship between TSR and crumb rubber nominal size. Although both crumb rubber size and content will increase the TSR value of the mix, increasing rubber content will have a higher effect in increasing the resistance of the mix to moisture attack compared to reducing the crumb rubber size.

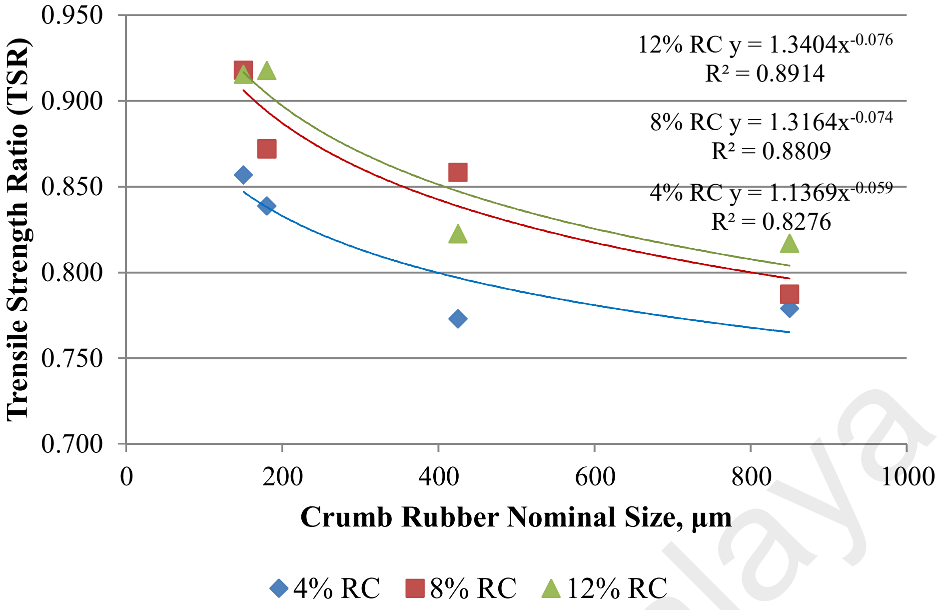

Figure 4.52: TSR relations with nominal crumb rubber size

4.8.3 Conditioned Indirect Tensile Stiffness Modulus Test (ITSM)

Figure 4.53 and 4.54 shows the relation between the stiffness modulus and the rubber content and size whereas Table 4.38 and 4.39 gives the values of stiffness modulus change with varying rubber content and size. From the figures, it is observed that the stiffness modulus of both conditioned and unconditioned mixes reduces with increasing rubber content. For samples with 850µm rubber size, increasing the rubber content from 4% to 12 percent reduces the stiffness modulus by 8.99% and for samples with 425µm the reduction is 5.22%. Stiffness modulus for samples with 180µm and 150µm also reduces by 7.38% and 9.94% respectively when the rubber content is increased. This equals to an average of 1.12% reduction in stiffness modulus per single percent rubber addition for samples with 850µm rubber, 0.65% reduction for samples with 425µm rubber, 0.92% reduction for samples with 180µm rubber and 1.24% for samples with 150µm crumb rubber.

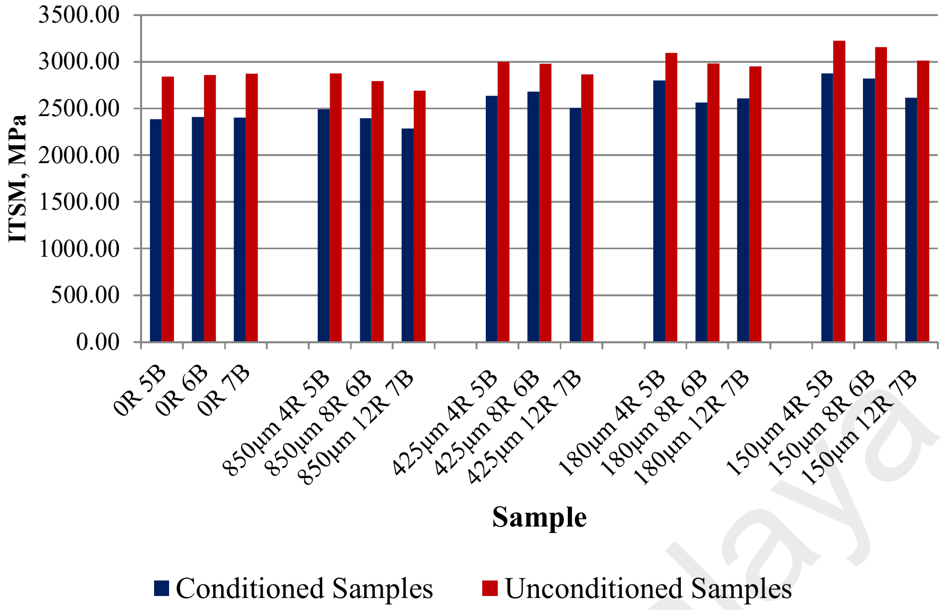

Figure 4.53: Indirect Tensile Stiffness Modulus relations with rubber content

Surprisingly, when compared with respect to the crumb rubber size, it is found that stiffness modulus improved with decreasing crumb rubber size. This is probably due to more maltenes being absorbed by smaller rubber crumbs that have a larger surface area. For instance, the stiffness modulus of samples that were modified with 850µm crumb rubber and 4% rubber content can improved by 15.49% if the rubber size is reduced to 150µm. This means that for every 100µm of rubber crumb reduced the stiffness modulus can be improved by 2.21%.

Similarly, for samples with 8% rubber content, a reduction of rubber size from 850µm to 150µm can increase the stiffness modulus by 17.64% and for samples with 12% rubber content the reduction is by 14.5%. This means that for 8% and 12% rubber content, the size reduction can increase the stiffness modulus by 2.52% and 2.07% respectively with every 100µm size reduction.

Table 4.38: Changes of Wet Stiffness Modulus (WSM) relation with Rubber Content

Sample	Average Wet Stiffness Modulus, %	Changes of WSM with Increasing Rubber/Binder Content, %	Total Changes of WSM with Increasing Rubber Content, %	Average change of WSM per Increase of Single Rubber Percentage, %
0R 5B	2385.17	-	-	-
0R 6B	2409.50	+1.02		
0R 7B	2402.50	-0.29		
850µm 4R 5B	2489.40	+4.37	-8.99	-1.12
850µm 8R 6B	2397.00	-3.71		
850µm 12R 7B	2284.00	-4.71		
425µm 4R 5B	2636.50	+10.54	-5.22	-0.65
425µm 8R 6B	2680.67	+1.68		
425µm 12R 7B	2505.67	-6.53		
180µm 4R 5B	2800.00	+17.39	-7.38	-0.92
180µm 8R 6B	2564.00	-8.43		
180µm 12R 7B	2607.50	+1.70		
150µm 4R 5B	2875.00	+20.54	-9.94	-1.24
150µm 8R 6B	2819.80	-1.92		
150µm 12R 7B	2615.17	-7.26		

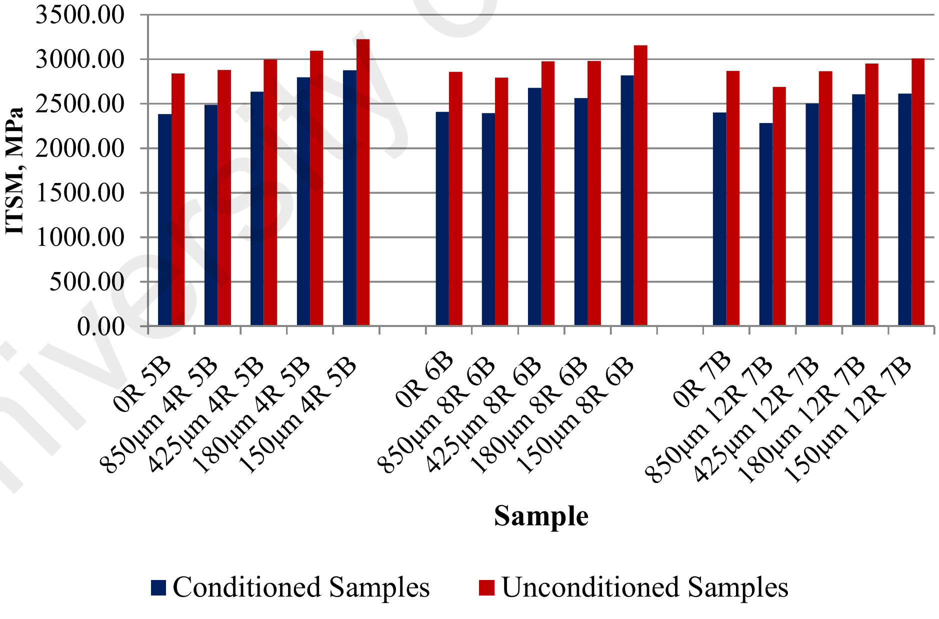

Figure 4.54: Indirect Tensile Stiffness Modulus relations with nominal crumb rubber size

Table 4.39: Changes of Wet Stiffness Modulus (WSM) relation with Rubber Addition and Rubber Size

Sample	Changes of Wet Stiffness Modulus with CR size, %					
	850µm	425µm	180µm	150µm	150µm compared to 425µm	150µm compared to 850µm
0R 5B	+4.37					
850µm 4R 5B		+5.91				+15.49
425µm 4R 5B			+6.20		+9.05	
180µm 4R 5B				+2.68		
150µm 4R 5B						
0R 6B	-0.52					
850µm 8R 6B		11.83				+17.64
425µm 8R 6B			-4.35		+5.19	
180µm 8R 6B				+9.98		
150µm 8R 6B						
0R 7B	-4.93					
850µm 12R 7B		+9.71				+14.50
425µm 12R 7B			+4.06		+4.37	
180µm 12R 7B				+0.29		
150µm 12R 7B						

4.8.3.1 Stiffness Modulus Ratio

Stiffness modulus ratio is another parameter introduced in this study to permit comparison of the outcomes of conditioned and unconditioned stiffness modulus with tensile strength ratio (TSR). The value of the ratio is obtained by dividing the conditioned stiffness modulus value with the unconditioned results. Figure 4.55 and 4.56 show the relationship between stiffness modulus with rubber content and rubber crumb size. As in previous tests, the stiffness modulus ratio also shows that the stiffness increases with higher crumb rubber content. This shows that increasing rubber content does help in decreasing the effect of water to the stiffness modulus of the mix. In contrast, there are no relationship can be established with decreasing crumb rubber size to the stiffness modulus ratio as the r^2 value of the data set are very low.

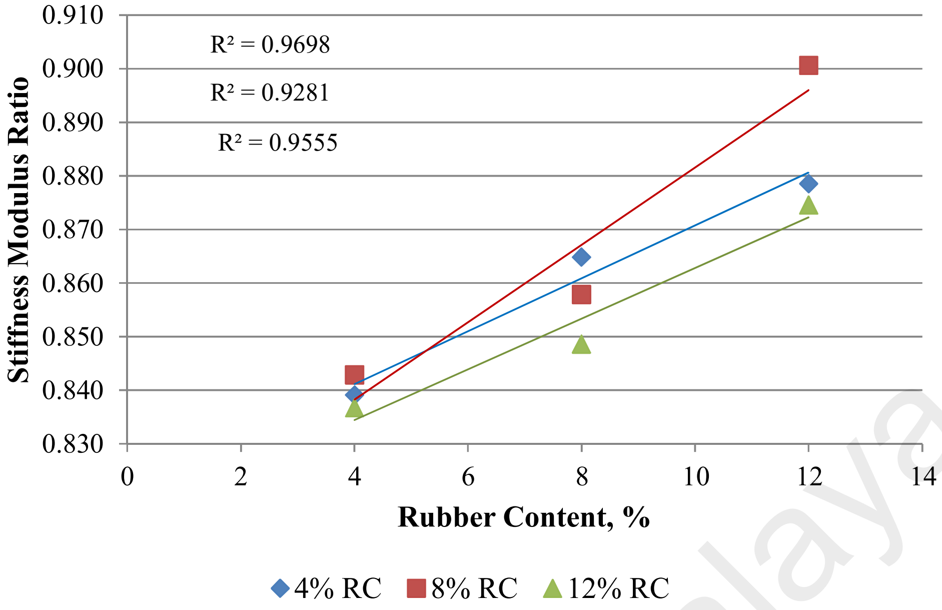

Figure 4.55: Stiffness Modulus Relations with Rubber Content

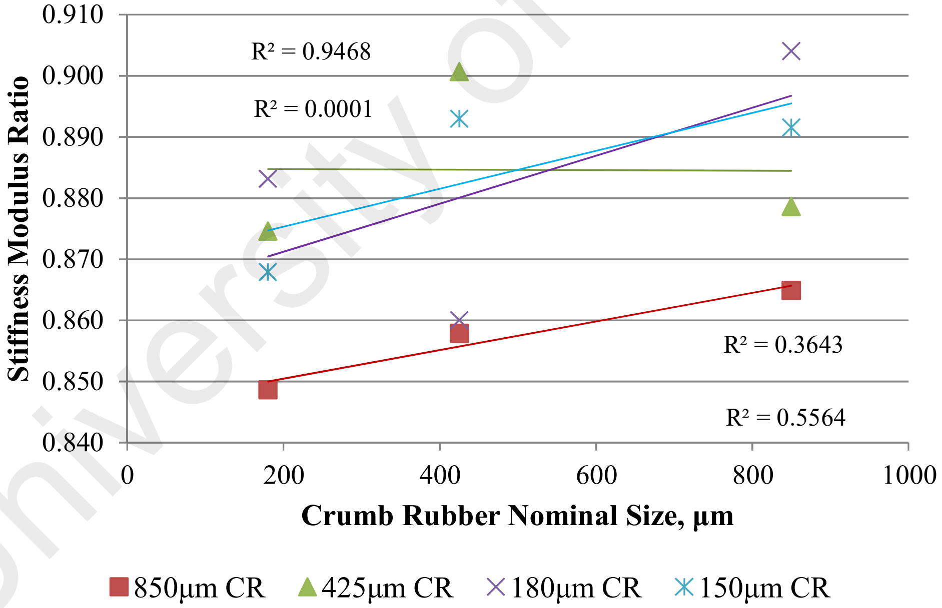

Figure 4.56: Stiffness Modulus Relations with Nominal Crumb Rubber Size

4.8.4 Comparison of Tensile Strength Ratio, Abrasion Resistance Ratio and Stiffness Modulus Ratio

Table 4.40 and Figure 4.57 through Figure 4.59 show the relation between abrasion retention ratio (ARR), Tensile Strength Ratio (TSR) and Stiffness Modulus Ration (SMR) with crumb rubber size. In general, all ratios do reflect the effect of water and the resistance of the mix with varying crumb rubber size. However the lower consistency of stiffness modulus data seems to affect the goodness of fit for one the stiffness modulus ratio curve.

Table 4.40: Comparison of ARR, TSR and SMR values according to crumb rubber content

Sample	Abrasion Retention Ratio (ARR)	Tensile Strength Ratio (TSR)	Stiffness Modulus Ratio (SMR)
850μm 4R 5B	0.55	0.77	0.86
425μm 4R 5B	0.60	0.84	0.88
180μm 4R 5B	0.64	0.86	0.90
150μm 4R 5B	0.63	0.86	0.89
850μm 8R 6B	0.68	0.86	0.86
425μm 8R 6B	0.78	0.87	0.90
180μm 8R 6B	0.82	0.92	0.86
150μm 8R 6B	0.82	0.90	0.89
850μm 12R 7B	0.80	0.82	0.85
425μm 12R 7B	0.87	0.92	0.87
180μm 12R 7B	0.90	0.92	0.88
150μm 12R 7B	0.91	0.99	0.87

At 4% rubber content, the slope of ARR is calculated at $dy/dx = 0.07x^{-1.079}$, while TSR shows a slope of $dy/dx\ 0.07x^{-1.059}$ and SMR at $dy/dx = 0.04x^{-1.037}$. It can be seen from the figures, the ARR shows the steepest slope of curve, followed by TSR and SMR. Table 4.41 summarises the slope for the equations at different rubber content.

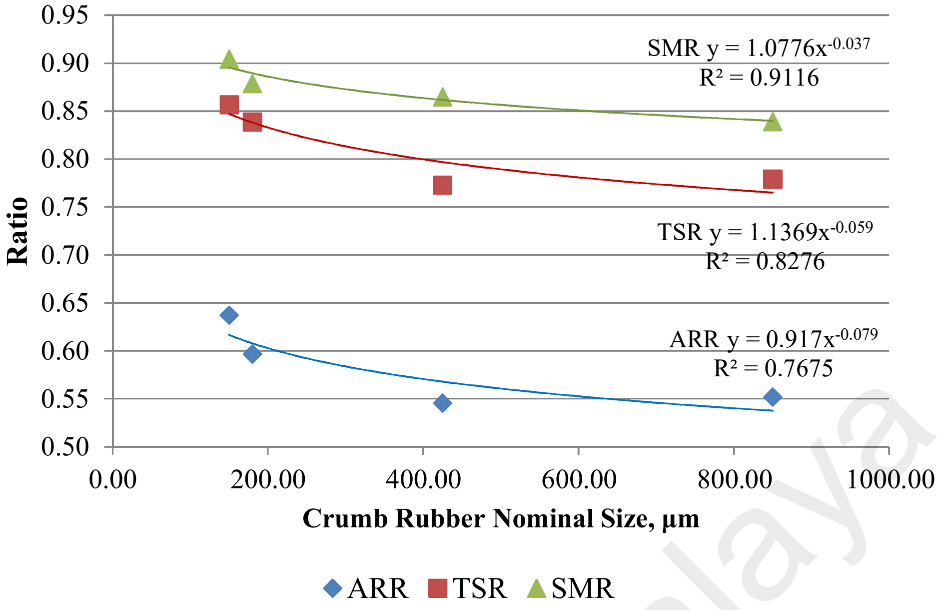

Figure 4.57: Relation of ARR, TSR and SMR to different crumb rubber sizes at 4% rubber content

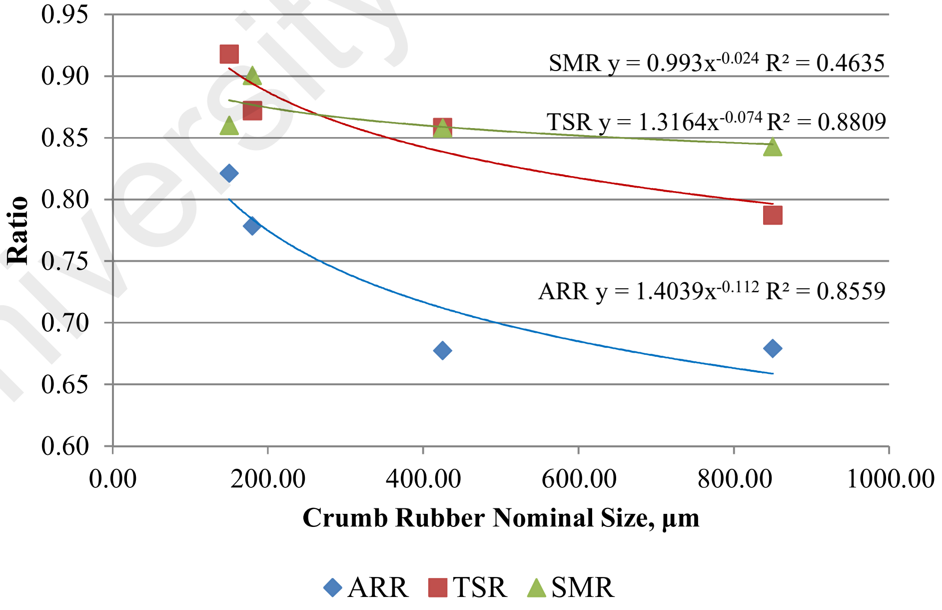

Figure 4.58: Relation of ARR, TSR and SMR to different crumb rubber sizes at 8% rubber content

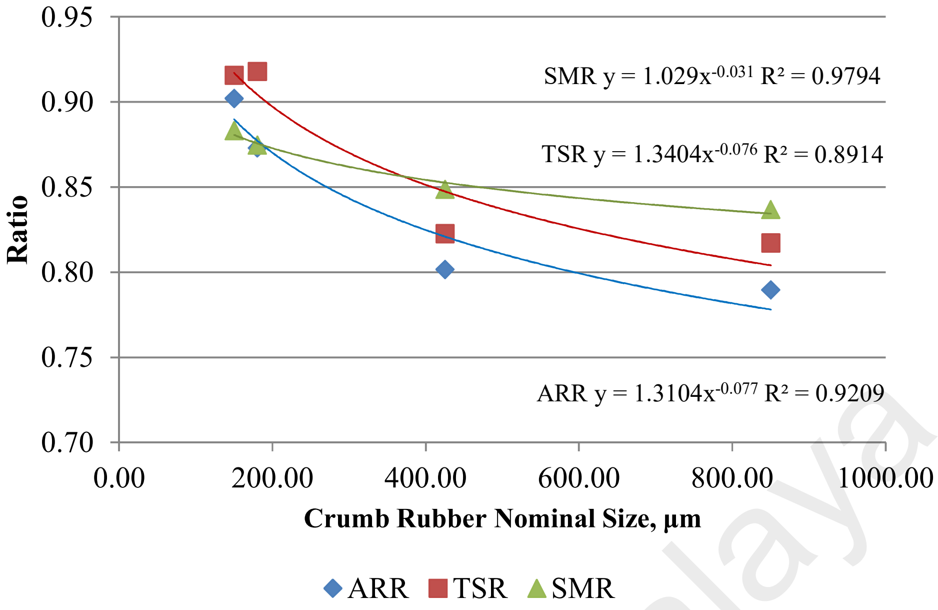

Figure 4.59: ARR, TSR and SMR to crumb rubber sizes at 12% rubber content

Table 4.41: Slopes for the function of ARR, TSR and SMR at different rubber content

Rubber Content	Type of Ratio	Slope
4%	SMR	$dy/dx = 0.0398x^{-1.037}$
	TSR	$dy/dx = 0.0670x^{-1.059}$
	ARR	$dy/dx = 0.0724^{x-1.079}$
8%	SMR	$dy/dx = 0.0238x^{-1.024}$
	TSR	$dy/dx = 0.0974^{x-1.074}$
	ARR	$dy/dx = 0.1572x^{-1.112}$
12%	SMR	$dy/dx = 0.032x^{-1.031}$
	TSR	$dy/dx = 0.1019x^{-1.076}$
	ARR	$dy/dx = 0.1009x^{-1.077}$

As can be seen from the figures and Table 4.41, ARR is the most sensitive ratio compared with TSR and SMR. Other than the steepness of the slope, ARR shows a larger range of ratio with the varying rubber crumb size and content. This can be seen in the Table 4.39 where, at 4% rubber content the value of the ARR ratio curve varies from 0.55 to 0.63 whereas the value of TSR and SMR ratio varies from 0.77 to 0.86 and 0.86 to 0.90 respectively.

At 8% rubber content the values of ARR ratio ranges from 0.68 to 0.82 while TSR and SMR values are still within 0.86 to 0.90. ARR value range narrows at 12% rubber content where the value ranges from 0.80 to 0.91 while TSR value ranges from 0.82 to 0.99. SMR value on the other hand maintains to range from 0.85 to 0.88 which, as in the previous rubber content is very narrow.

Sorted according to crumb rubber size in Table 4.42, the varying value of the ratios with increasing rubber content can be appreciated. Larger range are shown for all type of ratios with ARR showing the largest range (between (0.6 and 0.9) thus can be regarded as being the most sensitive. SMR values are rather inconsistent and can be regarded as unsuitable to be used to evaluate the effect of moisture to the stiffness modulus. The steepness of the slope and range of values shown in varying rubber content and size, shows that among ARR, TSR and SMR, only ARR and TSR can be considered to be a good measure of moisture effect with ARR showing more sensitivity to change compared to TSR.

Table 4.42: Comparison of ARR, TSR and SMR values according to rubber size

Sample	Abrasion Retention Ratio (ARR)	Tensile Strength Ratio (TSR)	Stiffness Modulus Ratio (SMR)
850µm 4R 5B	0.55	0.77	0.86
850µm 8R 6B	0.68	0.86	0.86
850µm 12R 7B	0.8	0.82	0.85
425µm 4R 5B	0.6	0.84	0.88
425µm 8R 6B	0.78	0.87	0.9
425µm 12R 7B	0.87	0.92	0.87
180µm 4R 5B	0.64	0.86	0.9
180µm 8R 6B	0.82	0.92	0.86
180µm 12R 7B	0.9	0.92	0.88
150µm 4R 5B	0.63	0.86	0.89
150µm 8R 6B	0.82	0.9	0.89
150µm 12R 7B	0.91	0.99	0.87

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

This chapter summarises the findings that was discovered from the four objectives of this study. Several conclusions can be drawn and the findings are as follows:

5.1 Rheological Properties of Rubberised Bitumen

Several tests have been carried out to study the rheological properties of rubberised bitumen. For penetration test, it was found that it is quite difficult to obtain consistent result as in some cases the values that were recorded can be quite high especially with larger crumb rubber size. This is probably happens when the penetration needle hits the rubber particle that are already swelling from the mixing process. From the statistical test that had been carried out, it was found that both rubber content and rubber size plays a role in influencing the penetration value where the rubber content has a larger influence compared to rubber size.

The softening point increases with increasing rubber content and decreasing rubber size. Rubber size influences the softening point more compared to rubber content. The significance of rubber size over rubber content was reflected in the statistical test.

Viscosity of rubberised binder as anticipated, are higher than unmodified bitumen. Statistical test shows that rubber content plays a more significant role in the increase of the viscosity values compared to rubber size. The viscosity of finer crumb rubber is more apparent at higher rubber concentrations. This due to the higher surface area of finer rubber crumb absorbing higher amounts of aromatic oils in the bitumen.

The complex modulus for the elastic portion, $G^*/\sin\delta$, increases with higher rubber content and finer rubber crumb. According to statistical analysis, the temperature of the binder and rubber content influences the value of $G^*/\sin\delta$ where at higher temperatures, the effect of binder are more noticeable and blends with higher rubber content shows the highest increase of the G*/sin δ value.

5.2 Optimum Binder Content of Rubberised Porous Asphalt

In the optimum binder content selection process it was found that mixes modified with coarser rubber crumb and lower bitumen content tends to have a higher abrasion loss. This is due to inadequate binder content to compensate to the addition of rubber crumb resulting in a mix that is brittle and shatters upon impact.

Coarser rubber crumb have a narrower window of selection of optimum binder content. As the mesh size reduces, higher binder and crumb rubber content and can be used. While extra bitumen provides higher strength, mixes with higher binder content are subject to greater binder draindown value. Higher rubber content also increases the viscosity of bitumen which also increases the film thickness and subsequently lowering the void in mix. However, finer rubber crumbs seems to be less sensitive to the increment of rubber and binder content. This results in a wider window for selection of the optimum binder content.

5.3 The Durability of Rubberised Porous Asphalt

Three tests have been undertaken to evaluate the performance of rubberised porous pavement in terms of stripping, tensile strength and stiffness. Statistical testing indicate that rubber content have a higher influence to the abrasion loss compared to rubber size. However, the reduction of abrasion loss when the crumb rubber size was reduced by 100µm is higher than the increase of one percent of rubber content.

Similar findings are observed in the tensile strength properties where the tensile strength increases with rubber content and size, where statistically, the rubber content have a higher influence compared to crumb rubber size. This means the tensile strength increases with increasing rubber content and finer rubber crumb nominal size. Again, the improvement of tensile strength with a reduction of crumb rubber size by 100µm is higher that the increase of rubber content by one percent.

The stiffness modulus results show an interesting trend where the stiffness modulus decreases with increasing rubber content. However, as the rubber crumb becomes finer, the stiffness modulus increases. Therefore, it is vital that every rubberised mix design must undergone the indirect tensile stiffness test to ascertain the effect of the selected rubber content and size to the stiffness of the mix.

5.4 The Performance of Rubberised Porous Asphalt towards Water

In order to evaluate the resistance of rubberised porous asphalt towards water, the conditioned version of the Cantabro Test, Indirect Tensile Test and the Indirect Tensile Stiffness Modulus Test are carried out. The results from the conditioned samples are compared with the unconditioned samples and this produces ratio values that are used to quantify how well the mix resists the attack of moisture. The ratios, namely the Abrasion Resistance Ratio (ARR) are obtained from the abrasion loss values and the Tensile Strength Ratio (TSR) are obtained from the tensile test results while the Stiffness Modulus Ratio (SMR) are acquired from the indirect tensile stiffness modulus test values. The TSR is the worldwide standard used to evaluate water effect to porous asphalt while ARR and SMR are ratios developed in this study.

In general, it was established that crumb rubber addition does increase the resistance of all the mixes towards water susceptibility with rubber content affects the resistance with higher significance compared to crumb rubber size. Comparing the ratios ARR, TSR and SMR, it was found that ARR is much more sensitive to changes in rubber content and size. The values obtained shows a larger difference compared to TSR and SMR. SMR on the other hand is the least responsive to the change of rubber content and size.

5.5 Recommendations

The following are the recommendations for future study that was inspired from the finding of this research:

1. The relation and effect of crumb rubber size and content to the mixing temperature of porous asphalt.
2. The effect of mixing type (high shear and propeller) to the rheology and storage stability of rubberised bitumen prepared with coarse, medium and fine crumb rubber.
3. The rutting and fatigue properties of rubberised porous asphalt prepared with different rubber content and crumb rubber sizes.
4. The adhesion properties of rubberised bitumen with different type of mixing and rubber size.

REFERENCES

Alvarez, A. E., Martin, A. E., Estakhri, C. K., Button, J. W., Glover, C. J., & Jung, S. H. (2006). Synthesis of current practice on the design, construction, and maintenance of porous friction courses (*No. FHWA/TX-06/0-5262-1*).

A. A. Tayebali, B. B. Vyas, and G. A. Malpass, "Effect of crumb rubber particle size and concentration on performance grading of rubber modified asphalt binders," in Progress of Superpave (Superior Performing Asphalt Pavement): Evaluation and Implementation, R. N. Jester, Ed., ASTM STP1322, *American Society of Testing and Materials*,, 1997.

A. E. Alvarez, A. E. Martin, and C. Estakhri, "A review of mix design and evaluation research for permeable friction course mixtures," *Construction and Building Materials*, vol. 25, no. 3, pp. 1159–1166, 2011.

A. Ghavibazoo and M. Abdelrahman, "Composition analysis of crumb rubber during interaction with asphalt and effect on properties of binder," *International Journal of Pavement Engineering,* vol. 14, no. 5, pp. 517–530, 2012.

A. H. Ali, N. S. Mashaan, and M. R. Karim, "Investigations of physical and rheological properties of aged rubberised bitumen," *Advances in Materials Science and Engineering,* vol. 2013, Article ID 239036, 7 pages, 2013.

Airey, G. D., Rahman, M. M., & Collop, A. C. (2003). Absorption of bitumen into crumb rubber using the basket drainage method. *International Journal of Pavement Engineering,* 4(2), 105-119.

Airey, G., Rahman, M., & Collop, A. C. (2004). Crumb rubber and bitumen interaction as a function of crude source and bitumen viscosity. *Road materials and pavement design,* 5(4), 453-475.

Akisetty, C. K., Lee, S. J., & Amirkhanian, S. N. (2009). Effects of compaction temperature on volumetric properties of rubberized mixes containing warm-mix additives. *Journal of Materials in Civil Engineering*, 21(8), 409-415.

Akisetty, C., Xiao, F., Gandhi, T., & Amirkhanian, S. (2011). Estimating correlations between rheological and engineering properties of rubberized asphalt concrete mixtures containing warm mix asphalt additive. *Construction and Building Materials*, 25(2), 950-956.

Al-Mansob, R. A., Ismail, A., Alduri, A. N., Azhari, C. H., Karim, M. R., & Yusoff, N. I. M. (2014). Physical and rheological properties of epoxidized natural rubber modified bitumens. *Construction and Building Materials*, 63(0), 242-248.

Alvarez, A. E., Fernandez, E. M., Martin, A. E., Reyes, O. J., Simate, G. S., & Walubita, L. F. (2012). Comparison of permeable friction course mixtures fabricated using asphalt rubber and performance-grade asphalt binders. *Construction and Building Materials*, 28(1), 427-436.

Ameri, M., & Esfahani, M. A. (2008). Evaluation and performance of hydrated lime and limestone powder in porous asphalt. *Road Materials and Pavement Design*, 9(4), 651-664.

Anfosso-Lédée, F., & Dangla, P. (2006). Sound propagation above a porous road surface by boundary element method. *Road materials and pavement design,* 7(3), 289-312.

Asim Hassan Ali, Nuha S. Mashaan, and Mohamed Rehan Karim, "Investigations of Physical and Rheological Properties of Aged Rubberised Bitumen," *Advances in Materials Science and Engineering,* vol. 2013, Article ID 239036, 7 pages, 2013. doi:10.1155/2013/239036

ASTM D 2041 Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures, *Annual book of ASTM standards*, vol. 04.04, Easton, MD, USA; 2000.

ASTM D1559. Standard test method for marshal test. Annual book of ASTM standards, vol. 04.03. West Conshohocken: *American Society for Testing and Materials*; 2002.

ASTM D2726, Standard Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Bituminous Mixtures, *Annual book of ASTM standards*, vol. 04.04, Easton, MD, USA; 2000.

ASTM D36 Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus), *Annual book of ASTM standards*, vol. 04.04, Easton, MD, USA; 2000.

ASTM D36-06. Test method for softening point of bitumen (ring-and-ball apparatus), *Annual book of ASTM standards*, vol. 04.04, Easton, MD, USA; 2000.

ASTM D4402-87. Test method for viscosity determinations of unfilled asphalts using the Brookfield thermosel apparatus, *Annual book of ASTM standards*, Vol. 04.04, Easton, MD, USA; 2000.

ASTM D5 Standard Test Method for Penetration of Bituminous Materials, *Annual book of ASTM standards* vol. 04.04, Easton, MD, USA; 2000.

ASTM D5-97. Standard Test method for penetration of bituminous materials,. *Annual book of ASTM standards* vol. 04.03, Easton, MD, USA; 2000.

ASTM D6926 - 10 Standard Practice for Preparation of Bituminous Specimens Using Marshall Apparatus, *Annual book of ASTM standards*, vol. 04.04, Easton, MD, USA; 2000.

ASTM D6927 - 15 Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures, *Annual book of ASTM standards*, vol. 04.04, Easton, MD, USA; 2000.

ASTM D6931. Standard test method for indirect tensile (IDT) strength of bituminous mixtures; 2012, *Annual book of ASTM standards*, vol. 04.04, Easton, MD, USA; 2000.

ATJ 5/85, “Manual for the structural design of flexible pavement,” *Jabatan Kerja Raya Malaysia* 2013

Attia, M., & Abdelrahman, M. (2009). Enhancing the performance of crumb rubber-modified binders through varying the interaction conditions. *International Journal of Pavement Engineering,* 10(6), 423-434.

B. Ali and M. Sadek, “Experimental analysis of the influence of crumb rubber addition on the short-term aging of Syrian asphalt,” *Arabian Journal of Geosciences*, vol. 6, no. 1, pp. 85–90, 2013.

B. Celauro, C. Celauro, D. Lo Presti, and A. Bevilacqua, “Definition of a laboratory optimization protocol for road bitumen improved with recycled tire rubber,” *Construction and Building Materials*, vol. 37, pp. 562–572, 2012.

B. J. Putman and S. N. Amirkhanian, “Crumb rubber modification of binders: interaction and particle effects,” *Road Materials and Pavement Design*, vol. 10, no. 10, pp. 1–23, 2006.

B. Putman and L. Kline, “Comparison of mix design methods for porous asphalt mixtures,” *Journals of Material Civil Engineering*, vol. 24, no. 11, pp. 1359–1367, 2012.

Bäckström, M. (2000). Ground temperature in porous pavement during freezing and thawing. *Journal of Transportation Engineering*, 126(5), 375-381.

Billiter, T. C., Chun, J. S., Davison, R. R., Glover, C. J., & Bullin, J. A. (1997). Investigation of the curing variables of asphalt-rubber binder. Petroleum science and technology, 15(5-6), 445-469.

C. C. Wong and W.-g. Wong, “Effect of crumb rubber modifiers on high temperature susceptibility of wearing course mixtures,” *Construction and Building Materials*, vol. 21, no. 8, pp. 1741–1745, 2007.

C. Fanga, C. Wua, R. Yua, Z. Zhangb, M. Zhanga, and S. Zhoua, “Aging properties and mechanism of the modified asphalt by packaging waste polyethylene and waste rubber powder,” *Polymers for Advanced Technologies*, vol. 24, no. 1, pp. 51–55, 2013.

C. L. Wong, R. Venneker, S. Uhlenbrook, A. B. M. Jamil, and Y. Zhou, “Variability of rainfall in Peninsular Malaysia,” *Hydrology and Earth System Sciences*, vol. 6, pp. 5471–5503, 2009.

C. Nah and H. Kim, “Effect of loading and particle size of rubber powder vulcanizate on physical properties of natural rubber compound,” *Polymer*, vol. 21, no. 4, pp. 648–656, 1997.

C. Thodesen, K. Shatanawi, and S. Amirkhanian, “Effect of crumb rubber characteristics on crumb rubber modified (CRM) binder viscosity,” *Construction and Building Materials*, vol. 23, no. 1, pp. 295–303, 2009.

C. Thodesen, K. Shatanawi, S. Amirkhanian, and W. Bridges, "Development of an empirical model for determining G*/sin δ in crumb rubber modified binders," *Construction and Building Materials*, vol. 23, no. 5, pp. 1922–1927, 2009.

Caltrans-California Department of Transportation, Open Graded Friction Course Usage Guide, *Sacramento, Calif, USA*, 2006.

Cao, W. (2007). Study on properties of recycled tire rubber modified asphalt mixtures using dry process. Construction and Building Materials, 21(5), 1011-1015.

Celik, O. N., & Atiş, C. D. (2008). Compactibility of hot bituminous mixtures made with crumb rubber-modified binders. *Construction and Building Materials,* 22(6), 1143-1147.

Chen, J. S., Sun, Y. C., Liao, M. C., Huang, C. C., & Tsou, K. W. (2012). Evaluation of Permeable Friction Course Mixes with Various Binders and Additives. *Journal of Materials in Civil Engineering*, 25(5), 573-579.

Chen, Y., Tebaldi, G., Roque, R., Lopp, G., & Su, Y. (2012). Effects of interface condition characteristics on open-graded friction course top-down cracking performance. *Road Materials and Pavement Design*, 13(sup1), 56-75.

Colandini, V., Legret, M., Brosseaud, Y., & Baladès, J. D. (1995). Metallic pollution in clogging materials of urban porous pavements. *Water Science and Technology,* 32(1), 57-62.

"Crumb rubber modifier design procedures and construction practices," Workshop Notes FHWA-SA-93-011, Design procedure and construction practices, US Department of Transportation, *Federal Highway Administration*, 1993.

"Crumb rubber modifier design procedures and construction practices," Workshop Notes FHWA-SA-93-011, Design procedure and construction practices, US Department of Transportation, *Federal Highway Administration*, 1993.

D. Lo Presti, G. Airey, and P. Partal, "Manufacturing terminal and field bitumen-tyre rubber blends: the importance of processing conditions," *Procedia*, vol. 53, pp. 485–494, 2012.

D. Q. Sun and L. H. Li, "Factors affecting the viscosity of crumb rubber-modified asphalt," *Petroleum Science and Technology*, vol. 28, no. 15, pp. 1555–1566, 2010.

D. X. Cheng and R. G. Hicks, "Summary of Rubber Modified Asphalt Product Specifications from around the World," *Ontario Tire Stewardship*, pp. 1–218, 2012.

Dong, D., Huang, X., Li, X., & Zhang, L. (2012). Swelling process of rubber in asphalt and its effect on the structure and properties of rubber and asphalt. *Construction and Building Materials*, 29, 316-322.

Dong, F., Yu, X., Liu, S., & Wei, J. (2016). Rheological behaviors and microstructure of SBS/CR composite modified hard asphalt. *Construction and Building Materials*, 115, 285-293.

Dreelin, E. A., Fowler, L., & Carroll, C. R. (2006). A test of porous pavement effectiveness on clay soils during natural storm events. *Water Research*, 40(4), 799-805.

Dubkov, K. A., Semikolenov, S. V., Ivanov, D. P., Babushkin, D. E., Panov, G. I., & Parmon, V. N. (2012). Reclamation of waste tyre rubber with nitrous oxide. *Polymer degradation and stability*, 97(7), 1123-1130.

E. Thelen and L. F. Howe, Porous Pavements, *The Franklin Institute Press*, 1978.

Edwards, J. B. (2002). Motorway speeds in wet weather: the comparative influence of porous and conventional asphalt surfacings. *Journal of Transport Geography,* 10(4), 303-311.

Elvik, R., & Greibe, P. (2005). Road safety effects of porous asphalt: a systematic review of evaluation studies. *Accident Analysis & Prevention*, 37(3), 515-522.

F. J. Navarro, P. Partal, F. J. Martínez-Boza, and C. Gallegos, "Influence of processing conditions on the rheological behavior of crumb tire rubber-modified bitumen*," Journal of Applied Polymer Science*, vol. 104, no. 3, pp. 1683–1691, 2007.

F. J. Navarro, P. Partal, F. Martínez-Boza, and C. Gallegos, "Thermo-rheological behaviour and storage stability of ground tire rubber-modified bitumens," *Fuel*, vol. 83, no. 14-15, pp. 2041–2049, 2004.

F. J. Navarro, P. Partal, F. Martínez-Boza, C. Valencia, and C. Gallegos, "Rheological characteristics of ground tire rubber-modified bitumens," *Chemical Engineering Journal,* vol. 89, no. 1–3, pp. 53–61, 2002.

F. M. Nejad, P. Aghajani, A. Modarres, and H. Firoozifar, "Investigating the properties of crumb rubber modified bitumen using classic and SHRP testing methods," *Construction and Building Materials*, vol. 26, no. 1, pp. 481–489, 2012.

Fang, Y., Zhan, M., & Wang, Y. (2001). The status of recycling of waste rubber. *Materials & Design*, 22(2), 123-128.

Fontes, L. P., Pereira, P. A., Pais, J. C., & Trichês, G. (2006). Behaviour of asphalt rubber mixtures with different crumb rubber and asphalt binder sources.

Fontes, L. P., Triches, G., Pais, J. C., & Pereira, P. A. (2010). Evaluating permanent deformation in asphalt rubber mixtures. *Construction and Building Materials,* 24(7), 1193-1200.

Freitas, E., Pereira, P., de Picado-Santos, L., & Santos, A. (2009). Traffic noise changes due to water on porous and dense asphalt surfaces. *Road Materials and Pavement Design,* 10(3), 587-607.

Fujiwara, T., Meiarashi, S., Namikawa, Y., & Hasebe, M. (2005). Reduction of equivalent continuous A-weighted sound pressure levels by porous elastic road surfaces. *Applied Acoustics*, 66(7), 766-778.

G. Cheng, B. Shen, and J. Zhang, "A study on the performance and storage stability of crumb rubber-modified asphalts," *Petroleum Science and Technology*, vol. 29, no. 2, pp. 192–200, 2011.

G. Yadollahi and H. Sabbagh Mollahosseini, "Improving the performance of crumb rubber bitumen by means of poly phosphoric acid (PPA) and vestenamer additives," *Construction and Building Materials*, vol. 25, no. 7, pp. 3108–3116, 2011.

Garcia-Morales, M., Partal, P., Navarro, F. J., & Gallegos, C. (2006). Effect of waste polymer addition on the rheology of modified bitumen. *Fuel*, 85(7), 936-943.

Gawel, I., Stepkowski, R., & Czechowski, F. (2006). Molecular interactions between rubber and asphalt. *Industrial & engineering chemistry research*, 45(9), 3044-3049.

GHAFARPOUR, J. S., & KHODAEI, A. (2008). Empirical model for determining rutting parameter in rubber modified bitumen.

Green, E. L., & Tolonen, W. J. (1977). The Chemical and Physical Properties of Asphalt Rubber Mixtures. Part I. *Basic Material Behavior* (No. ADOT-RS-14 (162)-1).

H. A. Khalid and I. Artamendi, "Performance based characterisation of crumb rubber asphalt modified using the wet process," *Road Materials and Pavement Design*, vol. 4, no. 4, pp. 385–399, 2003.

H. Asli, E. Ahmadinia, M. Zargar, and M. R. Karim, "Investigation on physical properties of waste cooking oil—rejuvenated bitumen binder," *Construction and Building Materials*, vol. 37, pp. 398–405, 2012.

H. Li, H. Zhao, and K. Liao, "Study on the technological conditions of crumb tire rubber-modified bitumens," *Petroleum Science and Technology*, vol. 27, no. 14, pp. 1521–1533, 2009.

H. Wang, Z. You, J. Mills-Beale, and P. Hao, "Laboratory evaluation on high temperature viscosity and low temperature stiffness of asphalt binder with high percent scrap tire rubber," *Construction and Building Materials*, vol. 26, no. 1, pp. 583–590, 2012.

Hamzah, M. O., MOHAMED, A., & Ismail, H. (2006). LABORATORY INVESTIGATION OF THE PROPERTIES OF A NEWLY DEVELOPED CRUMB RUBBER MODIFIED (CRI1) ASPHALT MIXTURES. Emirates *Journal For Engineering Research*, 11 (2), 67, 72.

Hasan, M. R. M., Eng, J. Y., Hamzah, M. O., & Voskuilen, J. L. M. (2013). The effects of break point location and nominal maximum aggregate size on porous asphalt properties. *Construction and Building Materials*, 44, 360-367.

Heitzman, M. (1992). State of the practice-design and construction of asphalt paving materials with crumb rubber. *Federal Highway Administration* (FHWA), FHWA-SA-92-022, Washington, DC.

Hernández-Olivares, F., Witoszek-Schultz, B., Alonso-Fernández, M., & Benito-Moro, C. (2009). Rubber-modified hot-mix asphalt pavement by dry process. *International Journal of Pavement Engineering*, 10(4), 277-288.

Hossain, Z., Bairgi, B., & Belshe, M. (2015). Investigation of moisture damage resistance of GTR-modified asphalt binder by static contact angle measurements. *Construction and Building Materials*, 95, 45-53.

Hsu, T. W., Chen, S. C., & Hung, K. N. (2010). Performance evaluation of asphalt rubber in porous asphalt-concrete mixtures. *Journal of Materials in Civil Engineering*, 23(3), 342-349.

Huang, W., Lin, P., Tang, N., Hu, J., & Xiao, F. (2017). Effect of crumb rubber degradation on components distribution and rheological properties of Terminal Blend rubberized asphalt binder. *Construction and Building Materials*, 151(Supplement C), 897-906.

Huang, Y., Bird, R. N., & Heidrich, O. (2007). A review of the use of recycled solid waste materials in asphalt pavements. *Resources, Conservation and Recycling*, 52(1), 58-73.

Imaninasab, R., Bakhshi, B., & Shirini, B. (2016). Rutting performance of rubberized porous asphalt using Finite Element Method (FEM). *Construction and Building Materials*, 106, 382-391.

Imaninasab, R., Bakhshi, B., & Shirini, B. (2016). Rutting performance of rubberized porous asphalt using Finite Element Method (FEM). *Construction and Building Materials,* 106, 382-391.

J. F. Chipps, R. R. Davison, and C. J. Glover, "A model for oxidative aging of rubber-modified asphalts and implications to performance analysis," *Energy & Fuels*, vol. 15, no. 3, pp. 637–647, 2001.

J. G. Chehovits, "Design Methods for Hot Mix Asphalt—Rubber Concrete Paving Materials," *presented at the National Seminar on Asphalt-Rubber*, 1989.

J. Peralta, H. M. R. D. Silva, A. V. Machado, J. Pais, P. A. A. Pereira, and J. B. Sousa, "Changes in rubber due to its interaction with bitumen when producing asphalt rubber," *Road Materials and Pavement Design*, vol. 11, no. 4, pp. 1009–1031, 2010.

J. Shen and S. Amirkhanian, "The influence of crumb rubber modifier (CRM) microstructures on the high temperature properties of CRM binders," *The International Journal of Pavement Engineering*, vol. 6, no. 4, pp. 265–271, 2005.

J. Shen, S. Amirkhanian, and S. J. Lee, "The effects of rejuvenating agents on recycled aged CRM binders," *International Journal of Pavement Engineering*, vol. 6, no. 4, pp. 273–279, 2005.

Jeong, K. D., Hwang, S. D., Lee, S. J., & Kim, K. W. (2011). Investigation of rutting potential of Open Graded Friction Course (OGFC) mixes using asphalt pavement analyzer. *KSCE Journal of Civil Engineering*, 15(7), 1259-1262.

Jeong, K. D., Lee, S. J., Amirkhanian, S. N., & Kim, K. W. (2010). Interaction effects of crumb rubber modified asphalt binders. *Construction and Building Materials,* 24(5), 824-831.

K. M. Shatanawi, C. C. Thodesen, and S. N. Amirkhanian, "Effects of crumb rubber variability on failure temperature of crumb rubber modified binders," *Road Materials and Pavement Design,* vol. 9, no. 2, pp. 291–309, 2008.

K. M. Shatanawi, S. Biro, A. Geiger, and S. N. Amirkhanian, "Effects of furfural activated crumb rubber on the properties of rubberized asphalt," *Construction and Building Materials,* vol. 28, no. 1, pp. 96–103, 2012.

K. Shatanawi, S. Biro, C. Thodesen, and S. Amirkhanian, "Effects of water activation of crumb rubber on the properties of crumb rubber-modified binders," *International Journal of Pavement Engineering*, vol. 10, no. 4, pp. 289–297, 2009.

Karacasua, M., Er, A., & Okur, V. (2012). Energy efficiency of rubberized asphalt concrete under low-temperature conditions. *Procedia-Social and Behavioral Sciences*, 54, 1242-1249.

Keymanesh, M. R., Haghighatpour, P. J., & Joomor, N. B. (2013). Comparing the Effect of Skid Resistance on Porous Asphalt Mixes and Conventional Hot Mix Asphalt. *Basic. Appl. Sci. Res*., 3(2)838-842.

Khan, R., Grenfell, J., Collop, A., Airey, G., & Gregory, H. (2013). Moisture damage in asphalt mixtures using the modified SATS test and image analysis. *Construction and Building Materials,* 43, 165-173.

Kim, J. R. (2001). Characteristics of crumb rubber modified (CRM) asphalt concrete. *KSCE Journal of Civil Engineering*, 5(2), 157-164.

Kim, S., Roque, R., Birgisson, B., & Guarin, A. (2009). Porosity of the dominant aggregate size range to evaluate coarse aggregate structure of asphalt mixtures. *Journal of materials in civil engineering*, 21(1), 32-39.

Kementerian Perumahan dan Kerajaan Tempatan (2011). A study on scrap tyres management for peninsular Malaysia. National Solid Waste Mangement *Department Ministry of Housing and Local Government.*

L. F. M. Leite and B. G. Soares, "Interaction of asphalt with ground tire rubber," *Petroleum Science and Technology*, vol. 17, no. 9-10, pp. 1071–1088, 1999.

L. F. M. Leite, R. S. Constantino, and A. Vivoni, “Rheological studies of asphalt with ground tire rubber,” *Road Materials and Pavement Design*, vol. 2, no. 2, pp. 125–139, 2001.

Lalwani, S., Abushihada, A., & Halasa, A. (1982). RECLAIMED RUBBER-ASPHALT BLENDS: MEASUREMENT OF RHEOLOGICAL PROPERTIES TO ASSESS TOUGHNESS, RESILIENCY, CONSISTENCY AND TEMPERATURE SENSITIVITY. *In Association of Asphalt Paving Technologists Proceedings* (Vol. 51).

Lee, S. J., Amirkhanian, S. N., & Kwon, S. Z. (2008). The effects of compaction temperature on CRM mixtures made with the SGC and the Marshall compactor. *Construction and Building Materials*, 22(6), 1122-1128.

Lee, S. J., Amirkhanian, S. N., Shatanawi, K., & Thodesen, C. (2008). Influence of compaction temperature on rubberized asphalt mixes and binders. *Canadian Journal of Civil Engineering,* 35(9), 908-917.

Lee, S. J., Kim, H., Amirkhanian, S. N., & Kim, K. W. (2009). Relation of mechanical properties of recycled aged CRM mixtures with binder molecular size distribution. *Construction and Building Materials*, 23(2), 997-1004.

Legret, M., & Colandini, V. (1999). Effects of a porous pavement with reservoir structure on runoff water: water quality and fate of heavy metals. *Water Science and Technology,* 39(2), 111-117.

Legret, M., Colandini, V., Pagotto, C., & Jullien, A. (2007). The quality of infiltrated water through porous and conventional asphalt pavements. *Road Materials and Pavement Design,* 8(4), 617-641.

Lougheed, T. J., & Papagiannakis, A. T. (1996). Viscosity characteristics of rubber-modified asphalts. *Journal of materials in civil engineering*, 8(3), 153-156.

M. A. Mull, K. Stuart, and A. Yehia, “Fracture resistance characterization of chemically modified crumb rubber asphalt pavement,” *Journal of Materials Science*, vol. 37, no. 3, pp. 557–566, 2002.

M. Attia and M. Abdelrahman, “Enhancing the performance of crumb rubber-modified binders through varying the interaction conditions,” *International Journal of Pavement Engineering,* vol. 10, no. 6, pp. 423–434, 2009.

Mansour, T. N., & Putman, B. J. (2012). Influence of aggregate gradation on the performance properties of porous asphalt mixtures. *Journal of Materials in Civil Engineering,* 25(2), 281-288.

Martínez, J. D., Puy, N., Murillo, R., García, T., Navarro, M. V., & Mastral, A. M. (2013). Waste tyre pyrolysis–a review. *Renewable and Sustainable Energy Reviews,* 23, 179-213.

Miknis, F. P., & Michon, L. C. (1998). Some applications of nuclear magnetic resonance imaging to crumb rubber modified asphalts. *Fuel*, 77(5), 393-397.

Miranda, M., Pinto, F., Gulyurtlu, I., & Cabrita, I. (2013). Pyrolysis of rubber tyre wastes: a kinetic study. *Fuel,* 103, 542-552.

Mo, L., Huurman, M., Wu, S., & Molenaar, A. A. A. (2009). Ravelling investigation of porous asphalt concrete based on fatigue characteristics of bitumen–stone adhesion and mortar. *Materials & Design*, 30(1), 170-179.

Moreno, F., Rubio, M. C., & Martinez-Echevarria, M. J. (2011). Analysis of digestion time and the crumb rubber percentage in dry-process crumb rubber modified hot bituminous mixes. *Construction and Building Materials*, 25(5), 2323-2334.

Moreno, F., Rubio, M. C., & Martinez-Echevarria, M. J. (2012). The mechanical performance of dry-process crumb rubber modified hot bituminous mixes: The influence of digestion time and crumb rubber percentage. *Construction and Building Materials,* 26(1), 466-474.

Moreno, F., Sol, M., Martín, J., Pérez, M., & Rubio, M. C. (2013). The effect of crumb rubber modifier on the resistance of asphalt mixes to plastic deformation. *Materials & Design*, 47, 274-280.

Moriyoshi, A., Jin, T., Nakai, T., & Ishikawa, H. (2013). Evaluation methods for porous asphalt pavement in service for fourteen years. *Construction and Building Materials,* 42, 190-195.

Mundt, D. J., Adams, R. C., & Marano, K. M. (2009). A historical review of additives and modifiers used in paving asphalt refining processes in the United States. *Journal of occupational and environmental hygiene*, 6(11), 705-713.

N. Sunthonpagasit and M. R. Duffey, "Scrap tires to crumb rubber: feasibility analysis for processing facilities," *Resources, Conservation and Recycling*, vol. 40, no. 4, pp. 281–299, 2004.

Navarro, F. M., & Gámez, M. C. R. (2011). Influence of crumb rubber on the indirect tensile strength and stiffness modulus of hot bituminous mixes. *Journal of Materials in Civil Engineering,* 24(6), 715-724.

Neto, Silvrano Adonias Dantas, Márcio Muniz de Farias, Jorge C. Pais, and Paulo AA Pereira. "Influence of crumb rubber gradation on asphalt-rubber properties." (2006).

Ng Puga, K. L. N. (2013). Rheology and performance evaluation of Polyoctenamer as Asphalt Rubber modifier in Hot Mix Asphalt, M.Sc. *Dissertation*, Iowa State University

Nuha Salim Mashaan, Asim H. Ali, Suhana Koting, and Mohamed Rehan Karim, "Dynamic Properties and Fatigue Life of Stone Mastic Asphalt Mixtures Reinforced with Waste Tyre Rubber," *Advances in Materials Science and Engineering,* vol. 2013, Article ID 319259, 9 pages, 2013. doi:10.1155/2013/319259

Nuha Salim Mashaan, Asim H. Ali, Suhana Koting, and Mohamed Rehan Karim, "Performance Evaluation of Crumb Rubber Modified Stone Mastic Asphalt

Pavement in Malaysia," Advances in Materials Science and Engineering, vol. 2013, Article ID 304676, 8 pages, 2013. doi:10.1155/2013/304676

Nuha Salim Mashaan, Mohamed Rehan Karim, Mahrez Abdel Aziz, Mohd Rasdan Ibrahim, Herda Yati Katman, and Suhana Koting, "Evaluation of Fatigue Life of CRM-Reinforced SMA and Its Relationship to Dynamic Stiffness*," The Scientific World Journal,* vol. 2014, Article ID 968075, 11 pages, 2014. doi:10.1155/2014/968075

Oda, S., Fernandes, J. L., & Ildefonso, J. S. (2012). Analysis of use of natural fibers and asphalt rubber binder in discontinuous asphalt mixtures. *Construction and Building Materials,* 26(1), 13-20.

P. Cong, P. Xun, M. Xing, and S. Chen, "Investigation of asphalt binder containing various crumb rubbers and asphalts," *Construction and Building Materials*, vol. 40, pp. 632–641, 2013.

P. E. Sebaaly, V. T. Gopal, and J. A. Epps, "Low temperature properties of crumb rubber modified binders," *Road Materials and Pavement Design*, vol. 4, no. 1, pp. 29–49, 2003.

Palit, S. K., Reddy, K. S., & Pandey, B. B. (2004). Laboratory evaluation of crumb rubber modified asphalt mixes. *Journal of materials in civil engineering*, 16(1), 45-53.

Partl, M. N., Pasquini, E., Canestrari, F., & Virgili, A. (2010). Analysis of water and thermal sensitivity of open graded asphalt rubber mixtures. *Construction and Building Materials,* 24(3), 283-291.

Pasquini, E., Canestrari, F., Cardone, F., & Santagata, F. A. (2011). Performance evaluation of gap graded asphalt rubber mixtures. *Construction and Building Materials,* 25(4), 2014-2022.

Peralta, J., Silva, H. M., Hilliou, L., Machado, A. V., Pais, J., & Williams, R. C. (2012). Mutual changes in bitumen and rubber related to the production of asphalt rubber binders. *Construction and Building Materials*, 36, 557-565.

Pfretzschner, J., & Rodriguez, R. M. (1999). Acoustic properties of rubber crumbs. *Polymer testing*, 18(2), 81-92.

Poulikakos, L. D., & Partl, M. N. (2009). Evaluation of moisture susceptibility of porous asphalt concrete using water submersion fatigue tests. *Construction and Building materials,* 23(12), 3475-3484.

Poulikakos, L. D., & Partl, M. N. (2012). A multi-scale fundamental investigation of moisture induced deterioration of porous asphalt concrete. Construction and Building Materials, 36, 1025-1035.

Presti, D. L., Fecarotti, C., Clare, A. T., & Airey, G. (2014). Toward more realistic viscosity measurements of tyre rubber–bitumen blends. *Construction and Building Materials*, 67, 270-278.

Puga, K. L. N. N., & Williams, R. C. (2016). Low temperature performance of laboratory produced asphalt rubber (AR) mixes containing polyoctenamer. *Construction and Building Materials*, 112, 1046-1053.

PUTRI, A. M., & SUPARMA, L. B. (2009). Laboratory Study on the Durability characteristics (moisture damage evaluation) of Asphalt Concrete Wearing Course (AC-WC) utilizing bantak and clereng as aggregate (using Marshall methods). In Proceedings of the Eastern Asia Society for Transportation Studies (Vol. 2009, No. 0, pp. 291-291). *Eastern Asia Society for Transportation Studies.*

Qiu, J., Van de Ven, M. F. C., Wu, S. P., Yu, J. Y., & Molenaar, A. A. A. (2011). Investigating self healing behaviour of pure bitumen using dynamic shear rheometer. *Fuel*, 90(8), 2710-2720.

R. Cao and Q. Bai, "Laboratory evaluation of performances of asphalt rubber and gap graded mixtures," in Proceedings of the 7th International Conference of Chinese Transportation Professionals Congress: *Plan, Build, and Manage Transportation Infrastructures in China* (ISSTP '07), pp. 786–798, May 2007.

Read, J., & Whiteoak, D. (2003). *The shell bitumen handbook*. Thomas Telford.

Report (1983). Evaluation of methods to improve the characteristics of asphaltcements and concrete mixtures. *Cairo University and Massachusetts Institute of Technology*

Report (2011). The effects of digesting crumb rubber in modified binders (MB). The *University of Wisconsin-Madison Asphalt Research Group*

Roseen, R. M., Ballestero, T. P., Houle, J. J., Briggs, J. F., & Houle, K. M. (2011). Water quality and hydrologic performance of a porous asphalt pavement as a storm-water treatment strategy in a cold climate. *Journal of Environmental Engineering,* 138(1), 81-89.

Rubber Manufacturers Association. (2011). US scrap tire management summary 2005–2009. *Washington*, DC.

Rungruangvirojn, P., & Kanitpong, K. (2010). Measurement of visibility loss due to splash and spray: porous, SMA and conventional asphalt pavements. *International Journal of Pavement Engineering*, 11(6), 499-510.

S. Aflaki and M. Memarzadeh, "Using two-way ANOVA and hypothesis test in evaluating crumb rubber modification (CRM) agitation effects on rheological properties of bitumen," *Construction and Building Materials*, vol. 25, no. 4, pp. 2094–2106, 2011.

S. C. Huang, "Rheological characteristics of crumb rubber-modified asphalts with long-term aging," *Road Materials and Pavement Design*, vol. 7, supplement 1, pp. 37–56, 2006.

S. Kocevski, S. Yagneswaran, F. Xiao, V. S. Punith, D. W. Smith Jr., and S. Amirkhanian, "Surface modified ground rubber tire by grafting acrylic acid for paving applications," *Construction and Building Materials*, vol. 34, no. 3, pp. 83–90, 2012.

S. Liu, W. Cao, J. Fang, and S. Shang, "Variance analysis and performance evaluation of different crumb rubber modified (CRM) asphalt," *Construction and Building Materials,* vol. 23, no. 7, pp. 2701–2708, 2009.

S.-J. Lee, C. K. Akisetty, and S. N. Amirkhanian, "The effect of crumb rubber modifier (CRM) on the performance properties of rubberized binders in HMA pavements," *Construction and Building Materials*, vol. 22, no. 7, pp. 1368–1376, 2008.

S.-J. Lee, J. Hu, H. Kim, S. N. Amirkhanian, and K.-D. Jeong, "Aging analysis of rubberized asphalt binders and mixes using gel permeation chromatography," *Construction and Building Materials*, vol. 25, no. 3, pp. 1485–1490, 2011.

Sandra Kumar (2006), Waste Tyre Management in Malaysia, *PhD Thesis*, Universiti Putra Malaysia

SCHAFFER, A., SCHULZ, C., NICHOLLS, J., MCHALE, M., & GRIFFITHS, R. (2008). *Best practice guide for durability of asphalt pavements* (Vol. 35, No. 42).

Shatnawi, S. (2001). Performance of asphalt rubber mixes in California. *International Journal of Pavement Engineering,* 2(1), 1-16.

Shen, D. H., Wu, C. M., & Du, J. C. (2009). Laboratory investigation of basic oxygen furnace slag for substitution of aggregate in porous asphalt mixture. *Construction and Building Materials*, 23(1), 453-461.

Shen, J., Amirkhanian, S., Xiao, F., & Tang, B. (2009). Influence of surface area and size of crumb rubber on high temperature properties of crumb rubber modified binders. *Construction and Building Materials*, 23(1), 304-310.

Shu, X., & Huang, B. (2014). Recycling of waste tire rubber in asphalt and Portland cement concrete: an overview. *Construction and Building Materials*, 67, 217-224.

Singh, D., Sawant, D., & Xiao, F. (2017). High and intermediate temperature performance evaluation of crumb rubber modified binders with RAP. *Transportation Geotechnics*, 10, 13-21.

Stevenson, K., Stallwood, B., & Hart, A. G. (2008). Tire rubber recycling and bioremediation: a review. Bioremediation Journal, 12(1), 1-11.

Sukontasukkul, P. (2009). Use of crumb rubber to improve thermal and sound properties of pre-cast concrete panel. *Construction and Building Materials*, 23(2), 1084-1092.

Sun, D. Q., & Li, L. H. (2010). Factors Affecting the Viscosity of Crumb Rubber–Modified Asphalt. *Petroleum Science and Technology*, 28(15), 1555-1566.

Suresha, S. N., Varghese, G., & Shankar, A. R. (2009). A comparative study on properties of porous friction course mixes with neat bitumen and modified binders. *Construction and Building Materials*, 23(3), 1211-1217.

T. C. Billiter, J. S. Chun, R. R. Davison, C. J. Glover, and J. A. Bullin, "Investigation of the curing variables of asphalt rubber binder," *Petroleum Science and Technology,* vol. 15, no. 5-6, pp. 445–469, 1997

T. C. Billiter, R. R. Davison, C. J. Glover, and J. A. Bullin, "Physical properties of asphalt-rubber binder," Petroleum Science and Technology, vol. 15, no. 3-4, pp. 205–236, 1997.

Takahashi, S. (2013). Comprehensive study on the porous asphalt effects on expressways in Japan: based on field data analysis in the last decade. *Road Materials and Pavement Design,* 14(2), 239-255.

Takahashi, S., & Partl, M. N. (2001). Improvement of mix design for porous asphalt. *Road Materials and Pavement Design*, 2(3), 283-296.

"The Effects of digesting Crumb Rubber in Modified Binders," The University of Wisconsin—*Madison Asphalt Research Group in collaboration with the Recycled Materials Resource Center,* pp. 1–13, 2011.

Thompson, P. D. (1960). Rubber in bituminous road materials. *Research Note* RN/3775/PDT.

Thomson, D. (1964). Full scale road experiment using rubberise surfacing materials 1953-63. Road Research Technical Paper No 71, *Road Research Laboratory*.

W. C. Vonk and A. L. Bull, "Phase phenomena and concentration effects in blends of bitumen and cariflex TR," in *Proceedings of the 7th International Roofing Congress*, Munich, Germany, 1989.

Wada, Y., Miura, H., Tada, R., & Kodaka, Y. (1997). Evaluation of an improvement in runoff control by means of a construction of an infiltration sewer pipe under a porous asphalt pavement. *Water science and technology*, 36(8-9), 397-402.

Wang, S., Wang, Q., Wu, X., & Zhang, Y. (2015). Asphalt modified by thermoplastic elastomer based on recycled rubber. *Construction and Building Materials*, 93, 678-684.

Watts, G. R., Chandler-Wilde, S. N., & Morgan, P. A. (1999). The combined effects of porous asphalt surfacing and barriers on traffic noise. *Applied Acoustics*, 58(3), 351-377.

Welker, A. L., Jenkins, J. K. G., McCarthy, L., & Nemirovsky, E. (2012). Examination of the material found in the pore spaces of two permeable pavements. *Journal of Irrigation and Drainage Engineering,* 139(4), 278-284.

WU, S. P., Gang, L. I. U., MO, L. T., Zheng, C. H. E. N., & YE, Q. S. (2006). Effect of fiber types on relevant properties of porous asphalt. Transactions of Nonferrous Metals Society of China, 16, s791-s795.

Xiao, F., & Amirkhanian, S. N. (2008). Resilient modulus behavior of rubberized asphalt concrete mixtures containing reclaimed asphalt pavement. *Road Materials and Pavement Design*, 9(4), 633-649.

Xiao, F., Amirkhanian, S., & Juang, C. H. (2007). Rutting resistance of rubberized asphalt concrete pavements containing reclaimed asphalt pavement mixtures. *Journal of Materials in Civil Engineering*, 19(6), 475-483.

Xiao, F., Putman, B. J., & Amirkhanian, S. N. (2006, October). Laboratory investigation of dimensional changes of crumb rubber reacting with asphalt binder. *In Proceedings of Asphalt Rubber 2006 Conference* (pp. 693-715). California: Palms Spring.

Xiao, F., Zhao, P. W., & Amirkhanian, S. N. (2009). Fatigue behavior of rubberized asphalt concrete mixtures containing warm asphalt additives. *Construction and Building Materials,* 23(10), 3144-3151.

Xie, Z., & Shen, J. (2014). Effect of cross-linking agent on the properties of asphalt rubber. *Construction and Building Materials*, 67, 234-238.

Xu, G., & Wang, H. (2016). Study of cohesion and adhesion properties of asphalt concrete with molecular dynamics simulation. *Computational Materials Science,* 112, 161-169.

Y. Ruan, R. R. Davison, and C. J. Glover, "Oxidation and viscosity hardening of polymer-modified asphalts," *Energy & Fuels*, vol. 17, no. 4, pp. 991–998, 2003.

Yehia, A. A. (2004). Recycling of rubber waste. *Polymer-Plastics technology and engineering,* 43(6), 1735-1754.

Younger, K., Hicks, R. G., & Partl, M. (1994). EVALUATION OF POROUS PAVEMENTS FOR ROAD SURFACES. INTERIM REPORT (*No. FHWA-OR-RD-95-03)*.

Yu, G. X., Li, Z. M., Zhou, X. L., & Li, C. L. (2011). Crumb rubber–modified asphalt: microwave treatment effects. *Petroleum Science and Technology*, 29(4), 411-417.

Zanetti, M. C., Santagata, E., Fiore, S., Ruffino, B., Dalmazzo, D., & Lanotte, M. (2016). Evaluation of potential gaseous emissions of asphalt rubber bituminous mixtures. Proposal of a new laboratory test procedure. *Construction and Building Materials,* 113, 870-879.

Zhang, F., & Hu, C. (2013). The research for SBS and SBR compound modified asphalts with polyphosphoric acid and sulfur. *Construction and Building Materials*, 43, 461-468.

Zhao, S., He, T., & Duo, L. (2011). Effects of crumb rubber waste as a soil conditioner on the nematode assemblage in a turfgrass soil. *Applied soil ecology*, 49, 94-98.

LIST OF PUBLICATIONS AND PAPERS PRESENTED

MR Ibrahim, HY Katman, MR Karim, S Koting, NS Mashaan. (2013). A review on the effect of crumb rubber addition to the rheology of crumb rubber modified bitumen, Advances in Materials Science and Engineering, Vol 2013. http://dx.doi.org/10.1155/2013/415246

MR Ibrahim, HY Katman, MR Karim, S Koting, NS Mashaan. (2014). The effect of crumb rubber particle size to the optimum binder content for open graded friction course, The Scientific World Journal, Vol. 2014. http://dx.doi.org/10.1155/2014/240786