LABORATORY EVALUATION OF LOCAL DENSE GRADED CRM ASPHALT MIXTURE

BY

MOHAMMED AL-TURKI

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This thesis, written by **Mohammad Al-Turki** under the direction his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN CIVIL ENGINEERING**.

Dr. Hamad I. Al-Abdul Wahhab
(Advisor)

Dr. Omar Al-Suwailem
Department Chairman (A)

Dr. Wael Alhajyaseen
(Member)

Prof. Salam A. Zummo
Dean of Graduate Studies

Dr. Ibnelwaleed Ali Hussein
(Member)

1/6/15
Date

I would like to dedicate this work to my darling family members
And to all of my friends

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First of all, I thank Allah Almighty for blessing me in so many ways and helping me in achieving one of my most cherished wishes. Secondly, I am highly grateful to my family members, especially my mother, for all the support they provided to me, cheering me up at times when I needed it the most.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

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Recycling of waste tires into modified crumb rubber for the asphalt pavement applications has become a positive method to enhance the asphalt properties, protect environment and save resources. Recently, crumb rubber materials have been applied widely in asphalt pavement, and many researchers have indicated that crumb rubber modified asphalt may enhance the performance of asphalt mixtures. However, the increased applications of CRM asphalt in recent years needs a better understanding of its influence on the engineering properties of CRM asphalt mixtures.

In this research, the influences of the crumb rubber size and content on the viscosity are investigated as part of the binder testing. To recognize the nature of the effects of these factors, lab tests have been conducted using different combinations of fine particles sizes and contents to investigate differences in asphalt binder's viscosities. A detailed laboratory investigation has also been performed to evaluate the performance of the dense CRM asphalt mixtures and compare it with control dense asphalt mixture. Laboratory tests of Indirect Tensile Strength (ITS), Durability and Resilient Modulus (Mr) have been conducted on samples compacted using superpave mix design method.

The results obtained from this research indicate that the modification of asphalt binder by crumb rubber may improve pavement performance. It significantly improves the viscosity at high temperature and leads to better stability of asphalt pavements. The crumb rubber particle sizes and content affected the viscosity of asphalt binders. By increasing the rubber content, the viscosity improvements show an increasing trend.

In general, the results concluded from the mixtures testing indicate that the crumb rubber modification improves pavement performance when compared to the use of the conventional binders. The asphalt binders modified by the fine crumb rubber particles are suited for the dense gradation asphalt mixtures type. The CRM asphalt mixtures generally displayed overall similar tensile strength characteristics as the conventional mixtures. However, the CRM mixtures generally have better characteristics in terms of durability and resilient modulus. The overall conclusions indicate that the modification of asphalt mixtures by fine crumb rubber particles is an effective way of improving the performance of asphalt pavements.

ملخص الرسالة

الاسم الكامل : محمد خالد محمد التركي

عنوان الرسالة : التقييم المختبري للخلطات الاسفلتية المحلية كثيفة التدرج المحسنة باستخدام تدوير الاطارات

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ان عملية تدوير الاطارات المستعملة الى حبيبات المطاط لتحسين الرصفات الاسفلتية هي من الطرق العملية و الاقتصادية لتطوير خصائص الاسفلت و حماية البيئة و حفظ المصادرالاقتصادية. المطاط المستخرج من تدوير الاطارات المستعملة يستخدم بشكل واسع في الرصفات الاسفلتية وأشار كثير من الباحثين الى أن الاسفلت المحسن باستخدام المطاط يطور من أداء الخلطات الاسفلتية. ومع زيادة التطبيقات المستخدمة لهذا النوع من الاسفلت في السنوات الاخيرة فان هناك حاجة كبيرة لفهم تأثيرها الحقيقي على الخصائص الهندسية للخلطات الاسفلتية.

تمت دراسة فاعلية مقاس حبيبات المطاط في تحسين أداء الخلطات الاسفلتية كثيفة التدرج وتأثير حجمها وكميتها على خصائص الاسفلت. ولمعرفة طبيعة تأثير هذه العوامل ، أجريت اختبارات معملية باستخدام أحجام مختلفة من تدرجات ناعمة ونسب مختلفة لبحث الاختلافات بين الخلطات الاسفلتية المستخدمة. كما أجريت دراسة مختبرية لتقييم أداء الخلطات الاسفلتية كثيفة التدرج المحسنة بواسطة حبيبات المطاط ومقارنتها بالخلطات الاسفلتية الغير محسنة. شملت هذه الاختبارات كل من اختبار قوة الشد و اختبارالديمومة واختبار معامل المرونة. أجريت هذه الاختبارات باستخدام خلطات اسفلتية مصممة باستخدام طريقة وزارة النقل للخلطات عالية الأداء في المملكة العربية السعودية.

أثبتت النتائج المحصلة من هذا البحث أن تحسين الاسفلت باستخدام حبيبات المطاط يطور من أداء الرصفات الاسفلتية فالمطاط يزيد من اللزوجة بشكل ملحوظ عند درجات الحرارة المرتفعة و يؤدي الى زيادة مرونة الرصفات الاسفلتية. أثبت البحث أيضا أن أحجام حبيبات المطاط وكميتها تؤثر على لزوجة الاسفلت حيث أنها زادت اللزوجة مع زيادة كمية المطاط.

بشكل عام فقد أظهرت نتائج اختبارات الخلطات الاسفلتية أن المطاط يطور من أداء الرصفات الاسفلتية مقارنة بالخلطات الغير محسنة. الاسفلت المحسن بحبيبات المطاط الناعمة مناسب للخلطات الاسفلية كثيفة التدرج. وأظهرت الخلطات الاسفلتية المحسنة بالمطاط أظهرت بشكل عام نتائج مشابهة من حيث خصائص قوة الشد مقارنة بالخلطات الغير محسنة ولكن لديها خصائص أفضل من حيث الديمومة و خصائص المرونة. وتشير النتائج العامة من هذا البحث الى أن تحسين الخلطات الاسفلتية باستخدام حبيبات المطاط الناعمة هي وسيلة فعالة لتطوير أداء الرصفات الاسفلتية.

CHAPTER 1

INTRODUCTION

1.1. Background

Conventional asphalt materials are used acceptably with lots of pavement applications. In the recent years, the increase in traffic volumes, tire pressure, worse climate situations and construction problems call for more research works because of the need for improving the performance of the conventional asphalt. Also, the increasing cost of asphalt binders and available polymers and the need of obtainable resources have encouraged the pavement materials engineers to discover alternatives for the construction and treatments works of the roads and highways. Therefore, there is a need to use additives and modifiers in Hot Mix Asphalt (HMA) applications to reduce the pavements problems and increase their service life. For example, the most known additives to the asphalt binder are natural rubber, Styrene Butadiene Styrene (SBS) and Styrene Butadiene Rubber (SBR).

The modification of the conventional asphalt can improve some asphalt mixture properties and reduce costs and maintenance. Such modifiers in HMA applications may produce stiffer mixtures at high service temperature to reduce the rutting problems. It may also enhance the fatigue resistance of asphalt mixtures and produce softer mixtures at low service temperature to enhance the resistance of low temperature cracking. Using such additives can also enhance the bond between the asphalt and aggregate, and therefore decrease the stripping problems. So, many technical reasons have been reported to encourage using such modified materials in HMA mixtures.

This research has been conducted to find out better materials that can improve the engineering properties of the asphalt pavement. Number of materials is available for modifying asphalt binder; one is the use of waste rubber from old tires to produce the Crumb Rubber Modified (CRM) asphalt. Nowadays, obtaining different useful products from waste materials recycling process has been a critical solution for waste removal issues. Recycling of these waste tires into modified crumb rubber for the asphalt pavement applications has become a positive method to enhance the asphalt mixtures properties.

Over the last 40 years, researchers around the globe have shown the enhanced performance of asphalt mixtures with the crumb rubber. Several researchers confirm that the crumb rubber materials are may enhance the mechanical performance of asphalt mixtures. In general, it is observed that the addition crumb rubber particles into the asphalt produces binders with enhanced resistance to rutting, fatigue cracking, and thermal cracking. Yet, the extensive use of the crumb rubber in asphalt pavements requests more understanding of its impacts on the different properties of CRM asphalt binders. The asphalt binders modified by crumb rubber may enhance some of the properties of asphalt pavement. However, the improved performance of the base asphalt binders depends on many factors related to the properties of the asphalt binder, crumb rubber and the process of production of the CRM asphalt binders.

Previous studies have also proved that CRM asphalt pavement increase the pavement life by improving resistance to cracking and rutting, decreasing traffic noise, and reducing maintenance costs. Even so, the performance of CRM asphalt mixtures is affected by various factors such as mixing conditions, nature of the binder, rubber size, rubber content and gradations of aggregate. Conventional CRM asphalt mixtures are frequently used with mixtures designed with open gradation or gap gradation types while not regularly used with dense graded mixtures types. In fact, there is limited but detailed research conducted on the applications of dense graded CRM asphalt mixtures. In Saudi Arabia, to date, this type of mixture is not in use yet. So, the main objective of this research is to investigate the effect of the addition of fine crumb rubber particles to the base asphalt. The other objective is to investigate the mix design and the basic characteristics of the performance of CRM asphalt mixtures using dense aggregate gradation under laboratory conditions. Also, it aims to investigate the effects of different fine sizes (CRM1, CRM2 and CRM3) and contents (3%, 7%, 10% and 15%) of crumb rubber on performance characteristics of the dense graded CRM asphalt mixtures.

1.2. Problem Statement

Distresses can be found in the asphalt pavement surfaces of Saudi Arabia due to various causes related to the quality of the used materials, poor construction and bad maintenance. These distresses may reduce the service time of the asphalt pavement and add more costs for rehabilitation and maintenance works. For example, rutting on highways surfaces is one of the most important problematic modes of deterioration in asphalt pavements mainly in areas with high temperatures like Saudi Arabia. Throughout the world including Saudi Arabia, fatigue cracking is also another significant mode of distress of asphalt pavements associated with repeated traffic loads.

The usage of the different available polymers like natural rubber, Styrene Butadiene Styrene (SBS) and Styrene Butadiene Rubber (SBR) in asphalt modification is expensive. The increasing number of vehicles on the roads generates millions of used tires every year. Removal of these used tires has become a critical problem that is a concern to the environment and considered as a topic of research. Many countries including Saudi Arabia are facing a huge challenge of disposing and reutilizing of wasted tires. There is increasing demand for recycling waste tires materials in the world. Using crumb rubber in asphalt pavement applications can improve asphalt performance and protect the environment all together.

Usage of the crumb rubber material as asphalt modifier may replace the expensive virgin polymers. CRM asphalt binder can be used in most of the asphalt pavement applications including new constructions or for treatments purposes. In Saudi Arabia, it is needed to encourage asphalt pavements engineers to use the CRM asphalt. However, CRM asphalt needs more understanding of its impact on the performance of CRM asphalt mixture. It requires clear understanding of its properties and their impact on performance of the asphalt pavements such as particle size, crumb rubber content and aggregate gradation type of the mixtures. Therefore, crumb rubber modified asphalt mixtures should be properly designed and their engineering properties be clearly investigated to ensure the preferred enchantments to the asphalt pavement performance.

1.3. Research Objectives

There is a great need to search for better materials that can be used in asphalt modification in terms of cost and performance. Increased demand of higher quality asphalt pavement, increased cost of conventional polymers and increased calls of recycling of waste materials have led to the usage of crumb rubber modified asphalt material. The main goals of the research focus on the evaluation of performance of CRM asphalt mixtures with dense graded aggregate gradation under laboratory conditions. Following are the main objectives aimed to be achieved from this research:

- To investigate the effectiveness of using a dense aggregate gradation type in the application of CRM asphalt mixture using fine crumb rubber particles.
- To evaluate the basic asphalt mixtures characteristics of both CRM asphalt and base asphalt binders.
- To find out the optimum parameters for the production of dense graded CRM asphalt mixture including crumb rubber size and content.

It is expected that this research will extremely be valuable to the highway community in Saudi Arabia. At the end of this research, a better understanding of the performance of CRM pavements will be obtained.

1.4. Thesis Organization

The thesis is divided to five main chapters. Chapter 1 is the introduction and includes the problem statement and the main objectives of this research. Also, the need for improving asphalt pavements has been discussed throughout this chapter. Chapter 2 contains detailed literature review about the modification of asphalt mixtures using the crumb rubber materials. In Chapter 3, the whole experimental work of the research and testing procedures of the asphalt binders and asphalt mixtures are discussed. The analysis of results and the statistical analysis of the laboratory tests are shown in Chapter 4. Finally, Chapter 5 presents the main findings of this research and some recommendations. In addition, Appendices A, B and C contain some detailed results of the data obtained from this research.

CHAPTER 2

LITERATURE REVIEW

2.1. Asphalt Binders

The asphalt binder is a black sticky semisolids and highly viscous material that can be found naturally or can be obtained by the distillation procedures from crude oil petroleum using various refining methods. The composition of the asphalt cement varies based on the properties of the crude oil and the applied method of the production; hence, its inherent characterizations will also not be the same. In general, asphalt binder is tough and durable with good waterproofing characteristics. It is used to produce the hot asphalt mixture which is used in the construction of asphalt pavements. The main role of the asphalt binder is to adhere the aggregate particles and bind them together.

In order to describe the characterizations of asphalt binders, number of methods has been applied. The most used method to find out different properties of asphalt binder is the performance based grade method developed by the Strategic Highway Research Program (SHRP) which is called Superpave binder specifications. Also, the asphalt binders may be characterized using the viscosity or penetration systems. The asphalt binder properties, by performance, are characterized at various temperatures and check it with the Superpave binder specifications [28].

2.2. Asphalt Binder Modification

Over the last three decades, many different modifiers have been used to modify the asphalt binders in order to enhance the performance of the hot asphalt mixtures. Many types of additives have been used such as Anti-stripping additives and polymer modifiers which are considered as most common modifiers. These are used to enhance the fundamental properties of asphalt binders, and therefore enhance the properties of the asphalt mixtures. Various researches have reported that the performance of modified asphalt mixtures, in general, is better than those of conventional asphalt mixtures [14].

The addition of these different modifiers has been found enhancing the overall performance of an asphalt binder. Presently, the most frequently used polymer as asphalt modifier is Styrene–Butadiene–Styrene (SBS) which is considered as elastomers that improve the elasticity of asphalt binders. It is considered as the most suitable polymers for asphalt modification. Asphalt mixtures modified by SBS have demonstrated excellent performance as shown by previous studies [14]. However, the lack of available resources and the increasing costs of asphalt and polymer modifiers materials motivate asphalt pavement materials researchers to discover better options in terms of quality and costs for the construction and maintenance applications of asphalt pavements.

2.3. Crumb Rubber Modifier (CRM) Asphalt Binders

Asphalt binder modified by crumb rubber particles is a kind of modified asphalt binder produced by using recycled used tires. The utilization of the CRM asphalt materials has been a range of enthusiasm since CRM was initially utilized as a part of asphalt paving materials in the United States more than 40 years ago. In fact, Charles McDonald turned into the first engineer to use the crumb rubber in asphalt mixtures to develop pavements in the US in 1960. From that time, many investigational researches have been conducted to have better knowledge about the use of CRM asphalt pavement [19].

Recently, the usage of crumb rubber materials in asphalt mixtures has been increased considerably worldwide, especially in the USA. It has been used more widely in seven states in the US: Arizona, California, Texas, Florida, South Carolina, Nevada and New Mexico. South Africa and Australia also started using CRM asphalt in the early 1980s. In Europe, the rubberized asphalt has successfully been used in road pavement applications in Belgium since 1981, as well as in Poland, Germany and also more recently in Greece and UK; however, countries with a higher number of applications are Portugal, Spain, Italy, Czech Republic and Sweden. Nowadays, the rubberized asphalt is gaining wider acceptance by more state departments of transportation and being adopted in many other parts of the world like Taiwan, China and Brazil [20].

The CRM asphalt mixture should be appropriately studied and developed in order to give the preferred enchantments of its performance compared with other types of asphalt mixtures. In recent years, the modification of asphalt binder by crumb rubber is used within a wide range of sizes and contents to improve asphalt pavement performance. For example, the viscosity of the CRM asphalt is based on some factors associated to the asphalt nature, crumb rubber properties and production process. These factors mainly affect the interaction of the base materials.

The enhanced performance of CRM asphalt mixtures compared with the conventional mixtures has partially related to the enhanced rheological properties of the CRM asphalt binders. As mentioned earlier, crumb rubber is produced from the used tires; in general, a tire mainly consists of four main components: rubber, carbon, steel and fiber. Rubber represents almost 60% of the total weight of the tire [1]. In fact, these used tires are collected through different sources from the industry. The original composition of these tires may differ from one to the other. Therefore, some variation exists within the rubber properties such as the amount of natural rubber existing in the tire. These variations among tire's composition will affect the mechanical behavior of the CRM asphalt. For example, according to Daquan Sun et al. (2010), more amount of natural rubber in the tire will increase the viscosity of CRM asphalt [2]. In fact, truck's tires are different from the passenger car's tires. Carl et al. found that the crumb rubber obtained from a truck's tires produced CRM binders with higher viscosity than the one obtained from a passenger car's tires [1]. It is believed that the truck's tires have more content of natural rubber than car's tires [3].

To break up these used tires into crumb rubber particles, the ambient or cryogenic procedures are used. Each procedure may produce the same size of crumb rubber of particles, but the main distinction among them is the surfaces of the particle texture. This difference influences the properties of the crumb rubber particles; therefore, it will also affect the interaction process with the base asphalt binder. The ambient grinding procedure is mainly mechanical shredding of the tires at ambient temperature to the needed particles sizes. In general, this grinding procedure has been accepted and is considered more useful to obtain the crumb rubber compared to the other procedure. By this procedure, the crumb rubber particles have high surface area, smooth surface and uneven forms with a coarse texture due to the grinding of the crump rubber particles [3]. Rubber particles created by the cryogenic procedures, in contrast, have low specific surface, sharp boundaries as a result to the grinding procedure of the nitrogen frozen tires [3]. As a result to the different procedures, the properties of the obtained crumb rubber are not same. For example, the surface area of the particles is different. Shen, J. et al. (2008), measured the surface area produced by the two procedures and found that the ambient crumb rubber particles have a surface area approximately double that of the cryogenic one [4].

Crumb rubber asphalt mixture is a mixture of CRM asphalt binder, aggregates and sometimes other additives. There are two methods used to add the modified crumb rubber, known as dry method or the wet method. The dry method is applied by adding the crumb rubber particles as filer in the aggregate blend before it mixed with the asphalt binder. In the wet method, before mixing the binder with the other paving materials, crumb rubber is added with the base asphalt at a high temperature that causes the rubber particles to swell after the interaction process. The main distinction among these two methods is that the wet method is more effective in modification of the characterizations of the asphalt binder because rubber particles directly interact with the asphalt during the mixing duration.

The attention of using crump rubber materials in asphalt mixtures has been increased to enhance the performance of the asphalt binder. Based on the literature reviewed, the modification of the asphalt binder by crumb rubber can increase the viscosity, elastic recovery, softening point and complex modulus, and also decrease the penetration, ductility and phase angle of the CRM asphalt binders [6, 9].

The rutting (permanent deformations) on the wheel tracks originated by tires loads on roads surfaces is one of the main sorts of deterioration in pavement designs, particularly in the hot areas. Like these deformations increase the needs of maintenance. However, the rutting resistance of the asphalt binders can be improved by adding the crumb rubber into the asphalt that mostly resulted from the improvement of the viscosity [1, 3, 6, and 7]. But, it is important to produce asphalt binder that accomplishes the viscosity requirements.

There are some factors which should be kept under consideration as they will affect the CRM asphalt viscosity. Based on the literature review, these factors may be related to the base asphalt properties, crumb rubber properties and process of the production of the

CRM asphalt binders [1, 3, and 9]. These factors mainly affect the interaction process between the base materials such as the swelling and the degradation process of the crumb rubber particles.

In general, these factors include the following:

- Rubber type (source-variability of the composition of the tire)
- Crumb rubber particles properties (surface area, particle size)
- Base asphalt properties
- Rubber content in the base asphalt
- Rubber swelling (oil absorption by rubber-curing temperature)
- Mixing conditions (mixing temperature, mixing duration)

Daquan Sun et al. (2010) studied the factors that may influence the viscosity of the CRM asphalt binders and concluded that the important factors are, in rank, rubber content, curing condition, crumb rubber particles size, and mixing duration [2].

Crumb rubber can be obtained by applying different procedures. Studies' results have shown that the CRM asphalt produced by ambient method will produce higher viscosity values than one produced by cryogenic method [1, 3, 6, and 8]. The reason behind this fact is associated with the surface area of the rubber particles. The larger surface area of ambient rubber will result in greater interaction areas with the asphalt that will improve the process of swelling. Silvrano et al. (2006) concluded that the decrease of particular surface of the particles of crumb rubber created by the cryogenic procedures, reduce their ability to interact with the base binder. The absorption of light fractions of the asphalt by the cryogenic rubber particles is less compared with the particles produced by the ambient procedures [3]. The distinction in particle surface areas results in the ambient particles that have higher surface area than the cryogenic ones, and accordingly a superior swelling degree.

When asphalt is mixed with crumb rubber, a chemical reaction starts in which asphaltenes and light fractions of the asphalt interact with the crumb rubber to create a gel covered particle. Then, during the interaction, the crumb rubber particles will swell like happens in the polymers asphalt systems. This swelling is caused by the absorption of the light fractions of the asphalt by rubber particles. However, the interaction process of the crumb rubber with the binder is based on the crumb rubber properties and the base binder in addition to the curing and mixing conditions.

The interaction between the base materials has been found in the literature in two mechanisms: rubber swelling and degradation. As mentioned above, the rubber particles will swell during the interaction which will reduce the distance between the crumb rubber particles. It should be noticed that the increase of the swelled particles will increase the viscosity due to the reduction in the distance between the rubber particles which caused less freedom to the particles of movement [4]. Then, degradation will occur which includes the depolymerization of the particles. At this stage, some of crumb rubber components are broken away and disperse into the asphalt. As a result, the volume of swollen rubber is reduced and causes a reduction in the viscosity of the CRM asphalt.

The complete process is shown in Fig.2.1 provided by Davide Lo Presti [20]. He also added that the particle responds in a time temperature relation way. When temperature is very high or time is extended, the swelling will keep going till the point where it is changed by depolymerisation of the particles because of the exposure to the high temperature which origins dispersal of the rubber particle into the asphalt [20].

Daquan Sun et al. (2010), in their study, found that the highest viscosity happens when swelling and depolymerization are at balance stage. At this stage, the increase in the viscosity by the swelling of crumb rubber is counterbalance by the depolymerization of crumb rubber which leads to a reduction in viscosity [2].

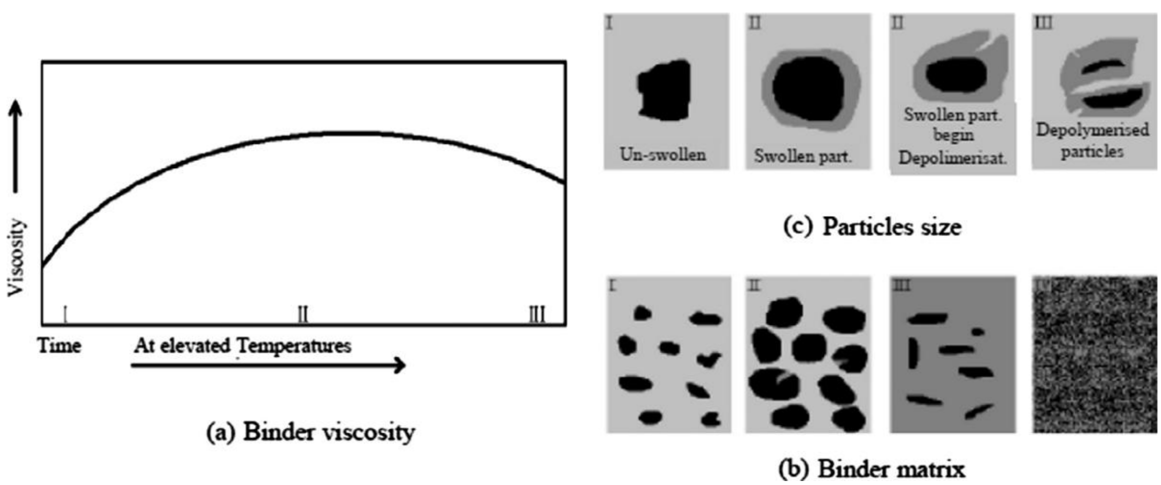

Figure 2.1 CRM asphalt interaction at elevated temperatures by Davide Lo Presti [20]

The interaction between rubber and asphalt depends on some factors related to used materials and production method. One of these factors is the curing condition of the CRM asphalt before the mixing stage. Daquan Sun et al. (2010) mentioned in their study that during the mixing duration when viscosity arrives at its highest value, its difference based on the curing temperatures. They found that the viscosity increases continually over the mixing duration at low curing temperature (150°C) which shows that the swelling of crumb rubber particles is stable. At the intermediate temperature (175°C or 200°C), the viscosity increases fast at first, then varies slightly and finally, reduces which shows that the depolymerization of the rubber particles is predominant over swelling. Also, they noticed that the improvement of viscosity is better at 200°C than at 175°C which shows that the high temperatures improves swelling ability [2].

From the literatures, it was concluded that rubber size is also a critical factor that affects the interaction process between the base materials of the CRM asphalt. In fact, the size effects involve two parts: particle size and particle surface area. J. Shen et al. (2008) studied the influences of these two on the high temperature characterizations of the CRM asphalt by the use of Dynamic Shear Rheometer (DSR). They found that the phase angle of the CRM asphalt increased as the surface area of the crumb rubber increased, but it was not clearly influenced by the crumb rubber average sizes of the particles. Also, they found that the complex modulus decreased as the surface area increased, and increased as the crumb rubber average size increased. From these findings, they concluded that the large surface area of the particle will cause faster and higher amount absorption of light fractions into the CRM asphalt and so that will cause faster interaction.

The size of the rubber particle has a major influence on the viscosity of the CRM asphalt as a result to its effect on the interaction with the base asphalt. In Daquam Sun et al. (2010) study, results showed that the particle size can affect the speed and extent of the swelling and depolymerization of the rubber. H. Wang et al. (2012), their study also showed that the particle size affects the CRM asphalt viscosity. They have found that the finer crumb rubber has a higher surface area that can absorb more light fractions from the asphalt which results in a better swelling process during the mixing time [7].

The mixing duration time and mixing temperature have considerable influence on the CRM asphalt binder characterizations [3 and 5]. The needed condition of mixing actually depends on the properties of the base materials. Silvrano et al. (2006) studied the influence of mixing time on the viscosity. They used crumb rubber particles with a size of 0.5mm to 2mm. From these results, they concluded that the viscosity increased as the mixing time increased but at a decreasing rate. According to the results, the viscosity loss was noticed when the mixing time was over 120 minutes [3]. Also, K. D. Jeong et al. (2010) said that in general, the longer mixing time will lead to increased viscosity and that is a result to the increased rubber mass due to the binder absorption. In addition, they said that the high mixing temperature will create a higher viscosity [5]. In contrast to the above findings, J. Shen and S. Amirkhanian (2005) revealed that in some cases, crumb rubber degradation may occur if we use unnecessary high mixing time or very high mixing temperature [8].

Based on the literature review, it is found that the base asphalt properties have some effects on the modified binder. As we know, the asphalt may be produced from different crude oils; therefore, the asphalt composition may differ from one source to the other. Carl et al. (2008) have found that the nature and the PG grade of the base asphalt can affect the resulted viscosity [1]. In addition, P. Cong et al. (2013) also concluded that the light fractions in asphalt improve the swelling extent of rubber particles [6]. Also, J. Shen and S. Amirkhanian (2005) found that the chemical nature of the asphalt binder determines the balance swelling and the viscosity of the base asphalt determine the swell rate of the crumb rubber particles. According to them, the swell rate will increase as the viscosity of the base asphalt decreases [8]. Khaldoun et al. (2008) have concluded from their results that the asphalt base may affect on the rutting susceptibility CRM asphalt than the properties of the used crumb rubber [12].

The amount of crumb rubber in the CRM asphalt has also an effect on the performance of the resulted CRM asphalt product. The literature review indicates, in general, high amounts of crumb rubber included into the base asphalt binder, leads to CRM asphalt binders with higher viscosity [1, 2, 3, 5, 6, and 9]. However, with the increased content of the crumb rubber, the improved viscosity showed a decreasing trend [7].

As a result of the great effect of these different factors which have been discussed above, it is very important to find out the optimum parameters for the production of CRM asphalt binders. These parameters may include curing temperature and time, and mixing temperature and duration. However, these parameters will also be affected by the properties of the base asphalt and the crumb rubber. After Silvrano et al. (2006) have studied the effect of the crumb rubber properties on the base asphalt; they concluded that guidelines should be set so that procurers of the production of the CRM asphalt can select the suitable base asphalt and crumb rubber materials, found the best dosage between the ingredients and selected a suitable mixing process [3].

2.4. Asphalt Mixtures

The asphalt pavement (flexible pavement) is comprised of generally thin wearing surface constructed over a base course and subbase course which rest upon the compacted subgrade. The Surface course layer is a relatively thin top layer and designed to optimize the desired properties of stability, durability, flexibility and skid resistance. The main purpose of designing asphalt mixture wearing course is to provide a stable mixture by means of a well graded aggregate with good mechanical interlock held together with a binder [29].

The performance of asphalt pavements is associated to the amount and frequency of the applied load. The way, in which these loads are conveyed to the surface of the road to the whole pavement structure, is related to the contact of the tire with pavement surface. The distribution of stresses, strains, and displacement over the pavement structure may be influenced by some factors such as pavement materials, layer thickness, load magnitude, load repetitions, tire type and pressure, and environmental conditions [30].

2.5. Crumb Rubber Modified (CRM) Asphalt Mixtures

CRM Asphalt could be used as a binder in different types of asphalt pavement applications including maintenances works and asphalt mixtures. Previous studies have paid more attention on the use of gap and open CRM asphalt mixtures to improve the performance of the asphalt pavement.

According to Caltrans (2006), they have mentioned that CRM asphalt is more effective and more frequently used with gap gradations and open gradations types of asphalt mixtures. However, the gap gradation is most commonly used to design CRM asphalt mixtures [22].

The literature review shows that a very limited and detailed research work has been conducted on the performance of dense graded CRM asphalt mixtures. In the current period, there are no sufficient reports and information about the mix design and usage of dense gradation with CRM asphalt mixture applications and its possible benefits.

In general, CRM asphalt pavements have been demonstrated to have lower maintenance costs, lower noise generation, higher skid resistance and better night-time visibility due to contrast in the pavement and stripping [20]. A number of researchers have said that the use of CRM asphalt can be useful to increase the fatigue life, reduce reflective cracking and low temperature cracking, and improve the tensile strength of CRM mixtures [14, 17, and 19].

Based on Caltrans [22], a summary of some advantages of using CRM asphalt mixtures for road pavement applications is given below:

- Enhanced moisture susceptibility.
- Better resistance to fatigue and reflection distress due to additional amount of binder in the CRM asphalt mixtures.
- Improved temperature susceptibility.
- Enhanced aging and oxidation resistance because of the additional amount of binder, thickness of the binder film, and anti oxidation properties of the crumb rubber.
- Enhanced resistance to rutting because of the improved viscosity.
- Reduced pavement maintenance costs.
- Reduced construction times due to thinner thickness.
- Reduced traffic noise and Improved safety.
- Better investments in power and natural incomes by using waste materials and not contributing to the stockpiles.

Recently, there are some researches and published papers on CRM asphalt mixtures. The main findings of these studies are discussed in the next paragraphs.

In 1990, H. AL-Abdul-Wahhab and Ghazi AL-Amri [31] studied the effects of using crumb rubber particles as modifier in asphalt mixture. The rubber contents were 10, 20, and 30 percent by weight of total binder. Their results showed that the Marshall Stability, Tensile Strength, Resilient Modulus, and Fatigue Life have improved with 10 percent rubber binder. However, they have concluded that mixtures mixes with rubber content above 10% show no enhancement in their properties as compared to mixtures with 10% content.

Chui-Te Chiu et al., (2006), studied the addition of the crumb rubber to Stone Matrix Asphalt (SMA). The performance of asphalt rubber SMA mixtures was investigated in their study. Two performance tests were performed: the moisture susceptibility test and rutting resistance test. They found that the asphalt rubber SMA mixtures were almost same as the conventional SMA mixtures in terms of durability properties. However, the wheel tracking tests results demonstrate that rutting resistance of asphalt rubber SMA mixtures was vastly improved compared with the conventional SMA mixtures [18].

Wong Cheuk Ching et al. (2006) investigated the influences of using various rubber sizes on the high temperature susceptibility. They have used a 10% content of crumb rubber by the wet processes including three rubber sizes (0.15, 0.30 and 0.60 mm). The results from their work showed that all rubber sizes have yielded an improved performance in terms of asphalt binders and mixtures at high temperatures. The results from the wheel tracking test showed that both used dense graded CRM asphalt mixtures in that study, leaded to an improvement in rutting resistance compared with the conventional asphalt mixtures. In addition, they found that the asphalt mixture produced with 0.15mm size had yielded the minimum rutting depths and showed the most excellent high temperature resistance compared with the other mixtures. They concluded that the modified mixtures by

0.15mm rubber sizes will produce the greatest influence on CRM asphalt mixture of dense gradation while the modified mixtures by 0.60mm rubber sizes will produce the greatest influence on CRM asphalt mixture of open gradation [15].

Feipeng Xiao et al. (2007) investigated the rutting resistance properties of the CRM asphalt mixtures having reclaimed asphalt pavement. Their work involved: two crumb rubber types, four rubber contents, and three crumb rubber sizes. Experiments were conducted to evaluate the tensile strength and rutting susceptibility of the distinctive mixtures by using an Asphalt Pavement Analyzer (APA). The results of the experiments demonstrated that, by and large, the utilization of RAP and crumb rubber in asphalt mixtures may altogether enhance the rutting resistance of these mixtures. They found that higher contents of RAP in the CRM asphalt mixtures increase the stiffness and ITS values which improve the stability of the mixture. This is also useful for enhancing rutting resistance of the mixtures. However, they found that the high rubber content in the mixtures decreases the ITS values and creep stiffness [19].

Permanent deformations (Rutting) is an important issue in asphalt pavements design. One of the methods being used to decrease the rutting in asphalt pavement is the modification of asphalt mixtures by crumb rubber. Liseane Fontes et al. (2009) compared the rutting characterization of CRM asphalt mixtures with gap and dense aggregate gradations with the unmodified dense gradation asphalt mixture using the Repeated Simple Shear Test and the wheel tracking test. His work showed that the CRM asphalt enhances considerably the rutting resistance. They said that the CRM asphalt with the most astounding softening point leads to CRM asphalt mixtures with improved resistance to rutting. Their results also showed that CRM asphalt mixtures have a better resistance to the rutting than conventional asphalt mixture with any the type of CRM asphalt or used aggregate gradation [13].

Baha Vural Kok et al. (2011), in their paper, compared the performance of CRM asphalt and SBS modified asphalt in asphalt mixtures using wet process by investigated the rutting, fatigue characteristics and resilient modulus of these mixtures. They were assessed by repeated creep test, indirect tensile fatigue test and indirect tensile resilient modulus test. They also aimed from their study to find out the suitable rubber content in mixtures that could display same performance to an SBS in mixtures in order to decrease the cost of asphalt mixture. The experimental results of their study showed a significant effect of using the crumb rubber for the modification of asphalt binder and asphalt mixtures. They found that, to get the same performance as with the use of SBS, the rubber content have to be used at higher content than SBS. The 8% crumb rubber content gave a better performance than the 2%, 3%, or 4% content of SBS. They also highlighted that the utilization of crumb rubber is favored over SBS modification because it may give huge expense sparing due to the high cost of SBS [14].

Fernando Moreno Navarro et al. (2012) investigated the influence of adding crumb rubber on the bearing capacity and cohesion of asphalt mixtures. They studied the resilient modulus and tensile strength of CRM asphalt mixtures. The used mixtures in their study were close graded mixtures. They found that the stability and the deformation resistance of the CRM asphalt mixtures were improved compared with those of the unmodified mixtures. They said that by adding crumb rubber to the asphalt mixtures will improve its resistance to traffic loads and therefore decrease the plastic deformations. However, their results also showed that adding crumb rubber somewhat decreased the tensile strength of the mixture. The results showed that crumb rubber enhanced the resilient modulus of asphalt mixtures. Finally, they concluded that using CRM asphalt is effective to enhance the long term performance of asphalt pavements. They also concluded that the CRM asphalt mixtures can increase the resilient modulus; so, it will decrease long term surface deformations [16].

Fatigue cracking of asphalt mixtures is considered as an example of the main damages in asphalt pavements which affect the pavement performance significantly. Hainian Wang et al. (2013), in their work, investigated the fatigue cracking properties of CRM asphalt mixture. They also studied the effect of gradation type, asphalt content, size and content of rubber on CRM asphalt mixtures' fatigue properties. In this research, gap gradation (SMAR-16) from Texas and a dense gradation (AC-16) were used for CRM asphalt mixtures. They found that content and size of the rubber highly affect CRM asphalt mixture's fatigue property. For mixtures, the maximum load and fatigue lives increase with an increase in the contents of crumb rubber from 15% to 20%. They said that 20% crumb rubber content could be optimum in terms of the anti-fatigue properties of CRM asphalt mixtures. Also, they added that using the small size of crumb rubber particles is better for the CRM mixture's fatigue property. However, the gap aggregate gradation produces mixtures with more improved performance compared to dense gradation for CRM asphalt mixtures [17].

It can be found that the ability of crumb rubber to enhance the asphalt mixture properties is may be affected on various factors including the type, size and content of crumb rubber particles in addition to the used aggregate gradation type in the CRM asphalt mixture. This research aims to investigate and identify the effect of using fine crumb rubber on a dense graded CRM asphalt mixture and to compare the potential basic performance properties of CRM modified and unmodified dense graded asphalt mixtures in the laboratory and to investigate the effects of different fine sizes (0.45, 0.30 and 0.15 mm) and contents (3%, 7%, 10%, and 15%) of Crumb Rubber Modifier (CRM) on performance characteristics of the local dense graded asphalt rubber mixtures.

Chapter 3

RESARCH METHODOLGY

To accomplish the objectives of this research, it includes seven main parts as shown in Fig. 3.1.

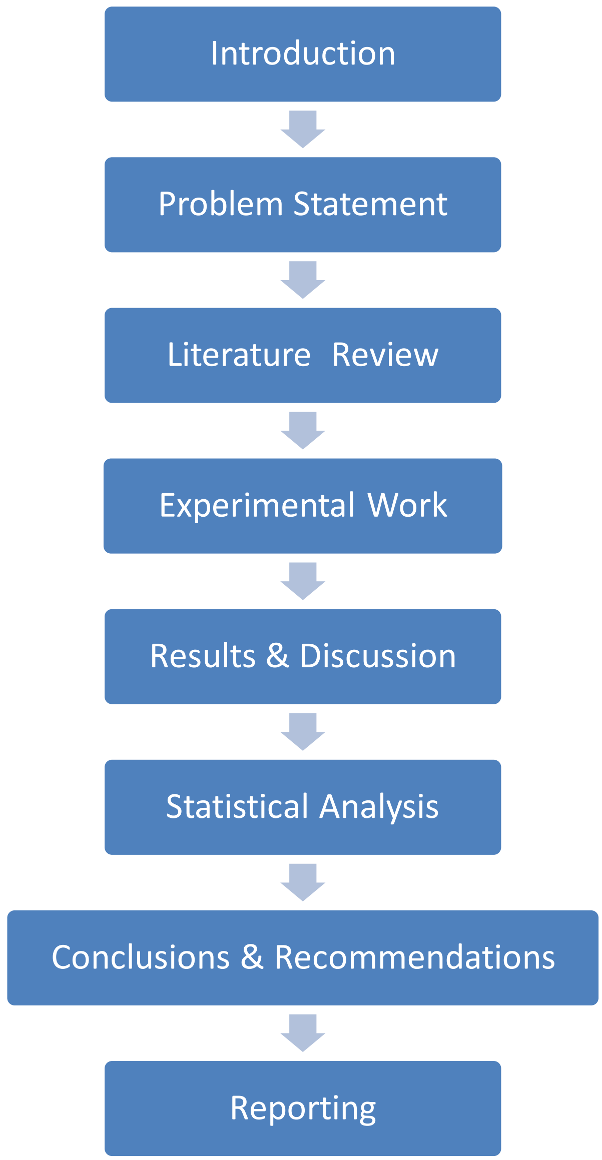

Figure 3.1 Flow chart of research methodology

3.1. Experimental Work

The experimental work of this research is divided into following parts:

1. Materials collection, preparation and characterization
2. Preparation and testing of CRM asphalts binders
3. Mix design and preparation of asphalt mixtures
4. Mixtures testing
5. Results and discussion
6. Statistical analysis
7. Conclusions and recommendations

Fig. 3.2 shows a flow chart of the experimental work of this research. The used materials including the base asphalt, aggregate and crumb rubber were obtained from the local market. The first stage of the lab work includes characterization of the used materials. The next stage is preparation and testing of the CRM asphalt binder's samples with the different combinations of rubber size and contents. Based on the binders testing results, the optimized CRM asphalt binders were selected for further testing of the mixtures. The final stage of the lab work includes the mix design, preparation and main testing of the asphalt mixtures. In this study, the Superpave mix design system is used to obtain the optimum binder contents for all asphalt mixtures. The following sections have discussed some of these stages in details.

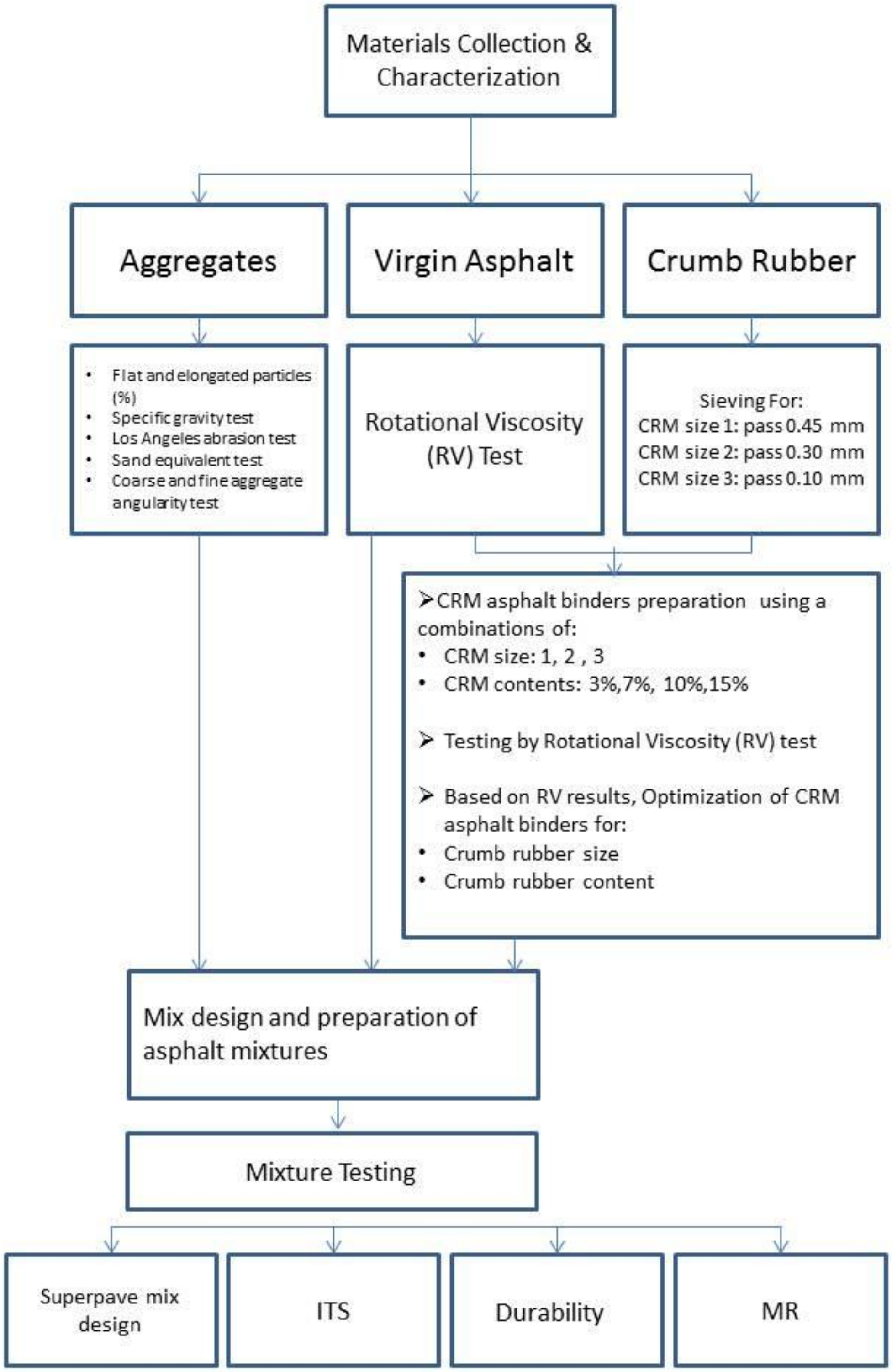

Figure 3.2 Flow chart of the experimental work

3.2. Materials Collection, Preparation and Characterization

3.2.1 Base Asphalt Binder

Only one source of local asphalt is used in this study as base asphalt. The used base asphalt binder in this study was obtained from Ras-Tanura refinery which is located in the eastern region of Saudi Arabia. The viscosity of the asphalt at 135°C is 564cP.

3.2.2 Crump Rubber

As discussed in chapter 2, crumb rubber properties are naturally variable due to tire type and grinding process. The literature review indicates that the ambient grinding process produces crumb rubber particles with rough edges that will have better interaction with asphalt binder than cryogenic due to the high surface area.

Only one type of crumb rubber was used in this research. It was obtained from Saudi Rubber Products Company (SARPCO) which is located in the second industrial city in Dammam in the eastern region of Saudi Arabia. They are using the ambient breaking method to cut old trucks' tires into crumb rubber. The physical shape of the crumb rubber is classically fine black powder.

In this research, three different gradations of fine particles size of crumb rubber are obtained from the collected rubber. Sieving is conducted to get the gradations of the three blends. The gradations (% passing) of the three blends are presented in Chapter 4.

The following particle sizes gradations of crumb rubber are used:

- CRM 1: crumb rubber particles passes sieve NO.40 (0.425mm).
- CRM 2: crumb rubber particles passes sieve NO.50 (0.300mm).
- CRM 3: crumb rubber particles passes sieve NO.100 (0.150mm).

3.2.3 Aggregates

The superpave mix design method requires a high quality of aggregates. In general, aggregates for HMA are required to be hard, tough, strong and durable. Local aggregate was used in the asphalt mixture. The mixtures in this study used the dense aggregate gradation. The most important properties of the aggregate were evaluated in the laboratory to make sure that it meets the current specifications of MOT in Saudi Arabia. The following tests have been conducted:

I. Los Angeles Abrasion Test

Aggregate must transmit the wheel loads to the underlying layers by its internal fraction and also be resistant to abrasion and polishing due to traffic. Also, the surface texture of the aggregates affects the workability and strength of the mixtures. A rough surface texture increases strength and requires additional asphalt binder. Voids in a compacted mass of rough texture aggregates are usually higher providing additional space for the asphalt binder.

Also, the asphalt binder forms stronger mechanical bonds with aggregates that have rough textures. The Los Angeles (L.A) abrasion test (ASTM C131) was applied to the aggregate to measure the toughness and the abrasion properties.

II. Soundness Test

Aggregates must be strong of breaking down or disintegration under the action of different weather conditions such as wetting and drying or freezing and thawing. This test (ASTM C88) gives an indication about durability properties of the used aggregates due to different weather conditions.

III. Coarse and Fine Aggregate Angularity Test

In compacted mixtures, the angular particles display better interlock and internal fraction and that results in greater mechanical stability than displayed by rounded ones. So, the used aggregate in hot asphalt mixtures must meet minimum crushed faces requirement for greater friction and interlocking. This test is conducted to check the angularity of the used aggregates (ASTM D5821).

IV. Flat and Elongated Particles (%)

Aggregates particles suitable for HMA should be cubical rather than flat, thin or elongated. This test has been conducted to evaluate the flat and elongated particles in the used aggregates (ASTM D4791). It is an important test for good performance of the mixtures.

V. Sand Equivalent Test

This test is used to determine the relative proportions of plastic fines and mineral dust from fracture in fine aggregates. If the amount of the clay in a mixture is high, a number of problems can result. For example, clay adhering to the aggregate may prevent a good bond between the asphalt binder and aggregates.

3.3. Preparation, Testing and Characterization of CRM Asphalt Binders

Different sizes and contents of fine crumb rubber are blended with base asphalt and tested to decide the suitable proportion of CRM asphalt binder to produce asphalt rubber that meets the requirements of ASTM D6114 specifications. The wet process used in this research to add the crumb rubber to the base asphalt. The CRM binders produced in the laboratory using different contents (3%, 7%, 10%, and 15%) by weight of base binder and three different CRM blends (CRM1, CRM2 and CRM3). Table 3.1 summarizes the 12 different combinations that are used in this research. Three samples are made for each combination for the CRM asphalt binder testing.

The preparation of the CRM asphalt binders in lab work of this research is same in each stage. First, 500g base asphalt binder is heated to 175°C, and then the rubber is added to the asphalt in a can and sealed with aluminum and kept in the oven at 190°C for 2 hours for the swelling of rubber particles. The process of blending the crumb rubber particles with the asphalt has been conducted in the laboratory by using a high shear blender at speed of 3000 RPH at a temperature of 180°C.

At the beginning, the optimum blending duration of the CRM asphalt blend is investigated using a rubber content of 7% for all the three CRM sizes. After conditioning in the oven (190°C) for 2 hours, they are blended at various durations (0, 15, and 30 minutes). This process is also done to investigate the effect of the blending duration on the viscosity and to find out the optimum blending duration to be used for further testing stages of this research. A blending temperature of 180°C is used which is considered sufficient based on the literature reviews. Moreover, it is a common temperature used to produce CRM binders in the applications of CRM asphalt mixtures. Based on the results, a suitable blending process is selected to be used in the investigation.

Table 3.1: Different Combination of CRM Asphalt Binders

CRM Size Type	**Rubber Content (%)**			
	3%	7%	10%	15%
Asphalt+ CRM 1	3 samples	3 samples	3 samples	3 samples
Asphalt+ CRM 2	3 samples	3 samples	3 samples	3 samples
Asphalt+ CRM 3	3 samples	3 samples	3 samples	3 samples

3.3.1 Rotational (Brookfield) Viscometer (RV) Test

Viscosity in general is the resistance of the material to flow and can be defined as the ratio of applied shear stress to rate of shear strain. It has some effect on the performance of HMA pavements. For example, at high construction temperatures, asphalt binders must be sufficiently fluid or workable to avoid pumping and mixing problems of HMA. As mentioned in Chapter 2, the viscosity of the CRM asphalt is may be affected by some factors related to the base asphalt, crumb rubber properties and production process. These factors mainly affect the interaction of the base materials.

The viscosity results can be used as a grading system of the asphalt binders. The lower number of centipoises, the less viscous the asphalt binder. The superpave binder specification limits the viscosity to 3000 centipoises (cP).

Rubber particle size and rubber content are main factors that may affect the CRM asphalt binder performance. Rotational Viscosity test is used to measure the viscosity of the virgin asphalt and CRM asphalt samples in order to grade the binders and to determine the effects of crumb rubber size and content variations on binder viscosity. In this research, the viscosities are obtained by using a Rotational (Brookfield) Viscometer (RV). Previous research works indicate that the viscosity test is the most suitable test to describe the flow characterizes of CRM asphalt binders.

In this research, the viscosities of CRM binders are tested using number 27 spindle at temperature of 135°C with a rotational speed of 20 rpm in the Rotational Viscometer. Both the base asphalt and these differently used CRM asphalt binders are subjected to a viscosity test at 135°C. Then, the results of the viscosity test are analyzed to find out the optimum CRM asphalt binders from the 12 used combinations based on crumb rubber size and content. The obtained optimum CRM asphalt binders are used for further testing of the CRM asphalt mixtures in this research.

3.4. Mix Design and Preparation of Asphalt Mixtures

There are many methods for designing asphalt mixtures. To overcome the deficiencies of the old methods, a new technology has emerged called the superpave mix design method. It is a new, comprehensive asphalt mix design and analysis system that is direct result of the Strategic Highway Research Program (SHRP). The main objective of this program is to develop a rational mix design method which relates the material characteristics of asphalt mixture to pavement performance. Also, the other objective of superpave mix design is to determine the best aggregate gradation to be used for Hot Mix Asphalt (HMA) and then to find the optimum asphalt content for the HMA based on superpave mix design method.

The superpave mix design is based on mixture volumetric properties at a specific level of compaction. The mixture compaction is applied by the Superpave Gyratory Compactor (SGC) which orients the aggregate particles in a way more similar to that observed under traffic. The resulting volumetric properties from the compaction process are used to select the optimum asphalt content. It is designed to produce samples in laboratory which simulate the field compacted mixtures.

In this part, mix designs of the control and CRM dense graded asphalt mixtures have been discussed. The superpave mix design method is chosen to design the used asphalt mixtures following the MOT/SHRP specifications for 12.5 mm top size Superpave Wearing Course (WC) layer. The optimum asphalt content obtained through Superpave mix design for the control and different CRM asphalt combinations is used to prepare compacted cylindrical asphalt concrete samples using gyratory compactors.

Based on the viscosity testing results, total of four CRM asphalt binders are selected for testing in the asphalt mixtures. These CRM asphalt binders include 2 types of CRM1 (3 and 7%) and two types of CRM2 (10 and 15%). In addition to that, plain asphalt mixture is added to control the asphalt mixture.

After defining proper aggregate and the optimum CRM asphalt binders, the next stage is to design and produce the control and CRM asphalt mixtures. The optimum binder content of the mixtures and all other design requirements are evaluated according to Hot

Asphalt Mix Design System of MOT of Saudi Arabia which is based on the Superpave mix design method [24].

The design of CRM asphalt mixture is divided into three parts: CRM asphalt selection, aggregate gradation design and optimum asphalt content determination. The first part is based on the results from the previous section. In this section, the focus is on the aggregate gradation design and optimum asphalt content determination.

In the design process, the used samples have a diameter of 6 in., two types of different asphalt mixtures are used in this research. The first mixture includes the control asphalt binder, while the other mixture includes the selected optimum CRM asphalt binders. A dense graded aggregate asphalt mixture, whose nominal maximum size of 12.50mm, is used for both mixtures. Based on the specifications, the proper gradation of the aggregates structure is found and evaluated according to MOT/SHRP requirements.

Furthermore, the N (ini), N (des), and N (max) values are 9, 125, and 205, respectively. These values are selected based on the desired traffic conditions of the research. Based on MOT/SHRP, the traffic designation class is a very heavy and ESALs of more than 30 million which is applicable for heavily trafficked highways [24]. The Optimum Asphalt Content (OAC) is defined as the amount to achieve 4% air voids according to the Superpave mix design method which minimizes rutting and pavement distress.

3.5. Mixtures Testing

The surface course is the top course of asphalt pavements and sometimes called the wearing course. It is constructed of dense gradation asphalt mixture which is subjected to a variety of traffic loads and different environmental conditions. The asphalt mixtures must be tested under these conditions to ensure the appropriate performance and to improve its properties by the available modifiers such as crumb rubber.

In this research, the fundamental engineering properties of the studied mixtures including the control mixture and the CRM asphalt mixture for its optimum asphalt content for each type of mixture are investigated in the laboratory to evaluate the overall quality of the used mixtures and to achieve the objectives of this research.

After the selection of design parameters, the required samples for the testing stage are compacted and prepared. To evaluate the main mixtures characteristics, four types of testing are conducted. The used tests are listed in Table 3.2.

The used samples in these tests have a diameter of 4 in. and height of 2.5 in. The same samples for each mixture type are used for the resilient modulus test and the indirect tensile strength tests since that the resilient modulus tests is non-destructive test. The following sections in this chapter explain these tests in details.

Table 3.2 List of the Mixtures Tests

Test Name	Function	Specification
Superpave	mix design method	AASHTO MP-2
The Indirect Tensile Strength	measure the tensile strength	ASTM D6931
Durability (Moisture Sensitivity)	measure the durability characteristics	AASHTO T-283
The Resilient Modulus	measure the resilient modulus	ASTM D-4123

3.5.1 Indirect Tensile Strength (ITS) Test

Theoretical structural design procedures for asphalt pavements are based generally on preventing two types of failures: fatigue failure (cracking) and permanent deformation (rutting). Fatigue cracking is controlled by limiting the tensile strain at the base of the asphalt mixture layer, while the permanent deformation (rutting) is controlled by limiting the compressive strain at the surface of the subgrade layer [30].

In a HMA, the mineral skeleton (aggregates) provides the compression strength, and the asphalt binder and mastic cohesion (adhesion binder/aggregates) provide the tensile strength of the asphalt mixtures [16]. The performance of asphalt mixture can be investigated by the Mohr–Coulomb failure theory. The asphalt mixture strength is based on cohesion and internal friction [19]. One of the main problems with CRM asphalt mixtures is small cohesion which associated to the interaction between the rubber particles and the binder [16].

The indirect tensile strength test is widely used for asphalt mixture design. It is an important characterization test for asphalt mixtures. It is mainly used to find out the tensile strength properties of the asphalt mixtures which are connected to the engineering characterizations of the asphalt pavements.

In this research, this test is used to measure the tensile strength of the used asphalt mixtures. The used samples in this test are 4 in. in diameter and 2.5 in. in height. The test is performed at 50 mm/min deformation rate and 25°C temperature in accordance with ASTM D6931 procedure. This test involves loading a cylindrical sample with static compressive loads along a diametrical plan through two opposite loading strips. These results in relatively uniform tensile stress applied vertically to the direction of the diametric plane of the applied load. This results in a splitting failure in general occurring along the vertical diametric plane.

During the test, the load and deformation at the failure point are recorded. The indirect tensile strength was calculated using the following equation:

$$ITS = \frac{2.P}{\pi.D.H} \qquad \textbf{(3.1)}$$

where:

ITS = indirect tensile strength expressed in (psi)

P = peak load expressed in pounds (Ib)

D = diameter of the sample in inch (in.)

H = thickness of the sample in inch (in.)

3.5.2 Durability Test

Durability characteristics of the asphalt mixtures are one of the most important features of the mixtures design. The durability is the ability of resisting the effects of the different environmental conditions with no major deterioration for a long period of time under the traffic loads [29].

This test is important to evaluate the moisture susceptibility or the deterioration of a HMA due to the effects of moisture which is also called stripping. It causes a loss of adhesion through the weakling of the bond between the aggregate surface and the asphalt binder which leads to loss of the cohesion of the mixtures and it may accelerate the developing of the distress such as rutting, cracking and raveling and therefore reduce the life of the asphalt pavement. The modification of asphalt mixtures is the most commonly used method in the improvement of the resistance to the moisture damage [25].

To evaluate the durability, a mixture is subjected to environmental conditions then the mixtures are tested using ITS test before and after the conditioning process. In this research, the moisture susceptibility (durability) is conducted according to the (AASHTO T283) procedure [22]. The used samples in this test are 4 in. in diameter and 2.5 in. in height. For each asphalt mixture type, six samples are prepared and compacted to an average air void content of 7.0%. Then, these samples are divided into two main groups of samples as required by the procedure. The first consists of dry samples (unconditioned samples) which are considered as the control samples and the second group consists of the wet samples (conditioned samples). In this test, the conditional process involves immersing the samples for 24 hours in the water at a temperature of 60°C, then immersing in water at 25°C for 2 hours before conducting the ITS test.

3.5.3 Resilient Modulus (Mr) Test

In actual field conditions when tires pass over a pavement structure, number of pulsating loads is suddenly applied to pavement layers. This repeated stress application induces distress that may affect the performance of the asphalt pavement. So, a good knowledge of the behavior of asphalt mixtures under repeated loads and different environmental conditions is desirable to determine the influence of the modification of asphalt pavement using crumb rubber materials.

The elastic modulus based on the recoverable strain under repeated loads is called the Resilient Modulus (Mr). It is one of the most significant characteristics of the performance of asphalt mixtures [14]. The resilient modulus is also a property that is directly related to the load carrying ability of the asphalt pavement [30]. Also, this test can measure the resilient modulus of mixtures under realistic variations of environmental conditions such as temperature and moisture.

The resilient modulus of asphalt mixtures is investigated by the diametric resilient modulus device which is considered as the most common method to measure the resilient modulus of asphalt mixtures [30]. It is basically a repetitive load test using the stress distribution principles of the indirect tensile test. In this test, the load is applied vertically along the diametric plane of samples every 1-3 seconds with 0.1 second duration and the resulting horizontal dynamic deformation across the horizontal dihedral plane of the sample is measured.

The used sample in the test is 4 in. in diameter and 2.5 in. in height. In this research, the test is conducted at a temperature of 25°C. Three different levels of dynamic loads are applied on the tested samples (95, 120 and 145 Ib) and the value of the static load was 5 psi. For each mixture type, 3 samples are tested with 2 diameter positions and readings are taken for a number of 3 repetitions.

3.6. Statistical Analysis

Statistical analysis has been performed on the obtained data by using the Minitab 16 software. These statistical analyses are important to investigate the results of this research and creating regression models that represent the studied variables (viscosity, tensile strength, durability and resilient modulus) and its correlation with different levels of the independent variables (crumb rubber size and contents). The models are useful to predict the various studied variables by selecting other unstudied levels of the independent variables in this research. Also, it is important to investigate the significance of the effect of these different factors on the basic mixtures characteristics.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Introduction

The results of laboratory tests are presented and discussed in three main parts according to the experimental program discussed in Chapter 3. The first part of this chapter includes the characteristics of raw material used in this study. The second part reports the asphalt binder testing results which include viscosity test results in addition to the main output of the statistical analysis. The third part shows the results of the asphalt mixtures testing which include the mixtures design, indirect tensile strength test, resilient modulus test and durability test in addition to the findings of the statistical analysis. Finally, a summary of the asphalt binders and mixtures testing results is provided at the end of each part.

4.2. Materials Characterization

4.2.1. Crumb Rubber

The gradations (% passing) of the three blends are listed in Table 4.1. The particle size distribution curves for the three CRM blends are shown in Fig. 4.1. The different properties of the crumb rubber provided by the supplier and particle size analysis data for each CRM blend are shown in Appendix A.

Table 4.1 Gradations (% passing) of the CRM Blends

Sieve Number (U.S)	Sieve Size (mm)	CRM1 Blend	CRM2 Blend	CRM3 Blend
40	0.425	100	-	-
50	0.300	65.45	100	-
60	0.250	45.81	86.09	-
80	0.180	26.53	46.69	-
100	0.150	17.43	27.15	100
120	0.125	11.97	16.89	74.27
140	0.100	7.24	8.94	41.75
170	0.088	3.97	3.96	23.79
200	0.075	1.93	1.98	10.68
270	0.053	0.48	0.6	2.91
Pan	-	0	0	0

The CRM1 blend has the largest particles sizes compared to CRM2 and CRM3. In this blend type, 35% of crumb rubber particles are between 0.425mm and 0.300mm. The CRM2 blend consists of medium size particles among the blends. 50% of this blend is passing the 0.300mm sieve size and retained on 0.180mm sieve size. The CRM3 blend consists of finest particles used in this research. 40% of these particles are passing sieve size of 0.100mm.

The difference in sizes between the three blends is clearly noticeable. All the three blends are considered as fine particles sizes. None of the three blends has particles larger than 0.425mm size.

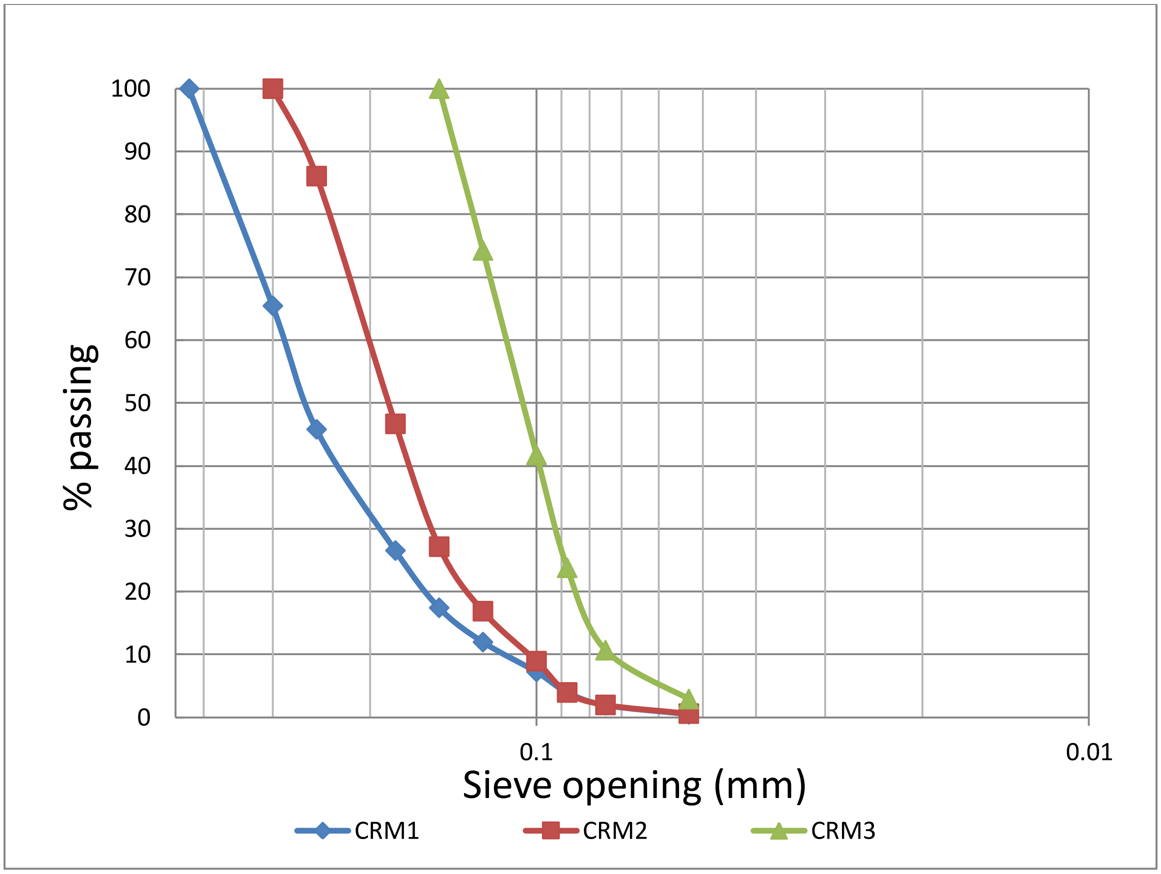

Figure 4.1 Particles size distribution curves

4.2.2. Aggregate

The results indicate that the quality of the used aggregate is very good and within the requirements of MOT/SHRP. Also, the results of the particle shape and surface texture are very good and within the requirements. The results of the coarse and fine aggregate testing are summarized in Table 4.2.

The results of the Los Angeles test show that the used aggregates are hard and tough. They have good resistance to abrasion and degradation. They have low dust content which is good to ensure the mixture durability by avoiding the problems of lack of sufficient asphalt. Also, the results of the soundness test show that the used aggregates are durable and have acceptable resistance under different weather conditions.

The angularity of the used aggregates is good for the mixtures strength due to the low amount of rounded aggregates which may reduce the shear strength and may lead to rutting problems. The high percentage of fractured faces in the used aggregates provides a good stability of the used mixtures. Also, the results of the flat and elongated particles test are acceptable. The low amount of the flat and elongated particles prevents the compaction problems since it may break down during the construction works and affects the mixture strength though low voids in the mineral aggregates (VMA) as a result to the breaking action.

Table 4.2 Aggregates Testing Results

Coarse Aggregates		
Test name	**Results**	**Specifications**
L.A. Abrasion (%)	29%	40%.Max
Soundness (%)	23%	25%.Max
Angularity (%)	98%	90%.Min (2 fractured faces or more)
Flat and elongated particles ratio (%)	0%	10%.Max (5:1 ratio)
Bulk specific gravity	2.57	-
Apparent specific gravity	2.77	-
Absorption (%)	2.50	-
Fine Aggregates		
Test name	**Results**	**Specifications**
Sand equivalent value	52%	40%.Min
Bulk specific gravity	2.47	-
Apparent specific gravity	2.74	-
Absorption (% Abs)	2.47	-
Combined Aggregates		
Bulk specific gravity	2.74	-
Apparent specific gravity	2.79	-
Absorption (% Abs)	2.50	-

Finally, the sand equivalent value is 52% which is above the minimum required value of (40%). This result indicates that the aggregates are clean and the clay content is acceptable which are very good results to avoid the stripping problems and ensure the good bond between the aggregates and the asphalt binder.

4.3. Asphalt Binders Testing

4.3.1. Viscosity of the Asphalt Binders

Viscosity is the property of resistance to flow (shearing force) in a fluid. In general, thick stiff fluids such as CRM asphalt binders have improved viscosity compared with conventional binders. The modification of asphalt binder by crumb rubber is used within a wide range of sizes and contents to improve asphalt pavement performance. The present research intends to study the influence of using fine crumb rubber particle size gradations on the performance of dense CRM asphalt mixtures. A total of 12 different combinations of CRM asphalt binders using three different fine gradations of crumb rubber (CRM1, CRM2 and CRM3) and 4 various contents (3, 7, 10, and 15%) are produced in the laboratory.

CRM asphalt binder's viscosity is based on a number of factors associated with the used raw materials and mixing procedure. In this research, the effect of blending duration, rubber size and rubber contents on the resulted viscosity of CRM asphalt binders are discussed in this section. Based on the results, the optimums CRM asphalt binders are selected for the asphalt mixtures testing. The results of the viscosity testing have been presented and discussed in the following three parts.

I. Blending Duration

As mentioned earlier in Chapter 2, it is important to find out the optimum blending duration for used materials. The needed condition of blending actually depends on the properties of the base materials. In this part, the viscosity test is used to verify viscosities as a function of different blending durations. The viscosity is checked at different times (0, 15 and 30 min) during the blending period. The results of the viscosities over these times are presented in Fig. 4.2.

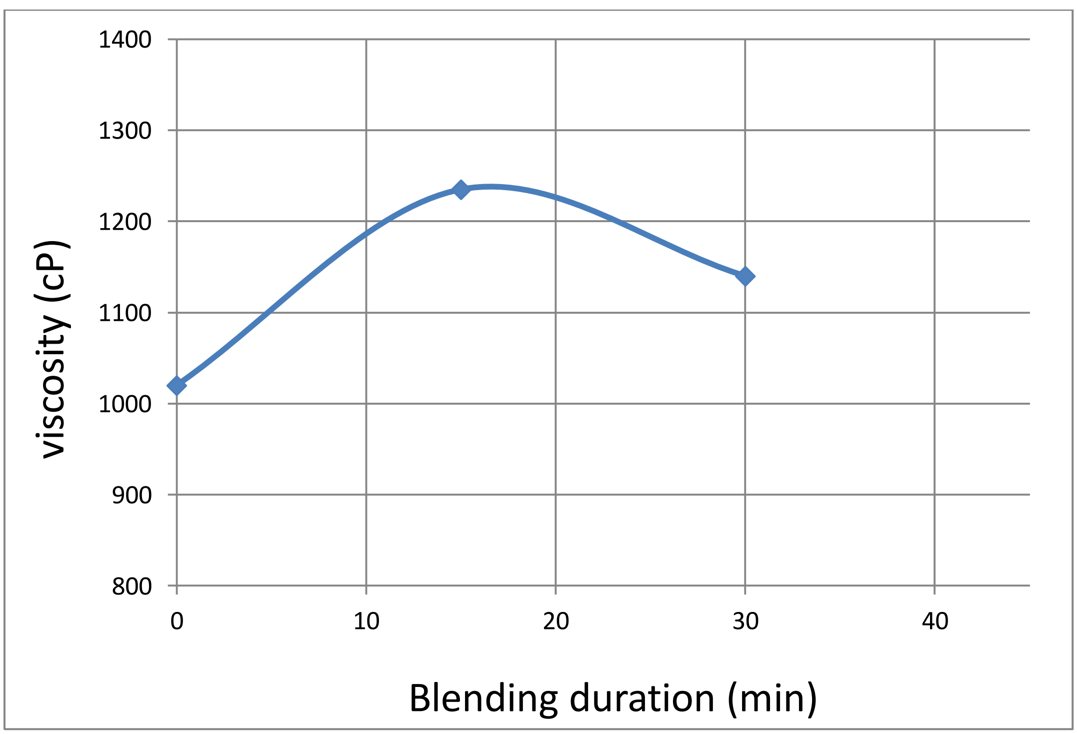

Figure 4.2 Viscosity vs. blending duration

Based on the used fine crumb rubber particles size, the expected optimum blending duration is 30 minutes as previous researches have reported. But, the use of high shear blender under high temperature (180°C) is very affective in decreasing the blending duration and increasing the quality of the blending. It is determined to use this blending duration for further testing of this research.

As shown in the Fig. 4.2 in the beginning, the viscosity is increasing to the maximum value which reflects the continuous swelling; after 15 minutes of blending, it starts to decrease due to degradation of the rubber particles.

This means that the viscosity reaches its maximum value at the saturation point of asphalt absorption and then starts losing the viscosity due to the breakdown of the particle components as a result of the increased blending duration. This behavior of the viscosity is from 0 to 30 minutes which is acceptable and also matching the literature reviews. In general, the fine rubber particles, with the large surface areas, need less blending duration compared to the coarse particles for a complete and faster swelling process. In fact, the large surface area of these fine particles increases the interaction areas of asphalt with the rubber.

II. Crumb Rubber Size

As mentioned in chapter 3, three different gradations of crumb rubber blend are used to investigate the influence of particle size on the resulted viscosity. The results of these viscosities (cP) are shown in Table.4.3.

Table 4.3 Viscosities of the CRM Asphalts (cP)

CRM Asphalt / CRM %	0%	3%	7%	10%	15%
CRM 1	564	975	1330	1600	2180
CRM 2	564	588	1163	2021	2914
CRM 3	564	622	1010	1481	2723

As expected, the results suggest that the crumb rubber size plays an important role that may affect the viscosity of the CRM binders. In fact, the size of the used crumb rubber affects mainly the interaction process with the asphalt. All CRM asphalt binders show higher viscosity values than the unmodified asphalt binder. The high viscosity is resulted from the fine particles with high surface area which absorbs more fractions from the asphalt binder and swell.

As shown in the Fig. 4.3, in general, the maximum viscosities with the lower contents are found with CRM1 type asphalt binders and with the higher contents are found with CRM2 type. The effects of the rubber size are more critical with high contents. The highest values are found with CRM2 type at 10% and 15% contents. The results show that the highest value of the resulted viscosities is 2914 cP which resulted with CRM2 asphalt binder when 15% of rubber added which improved by almost 415% as compared to the control asphalt. And, when 10% was added, the CRM2 resulted viscosity is 2021cP which has an improvement of 260%. At lower content 3% and 10%, the highest viscosities are 975 and 1330cP, respectively.

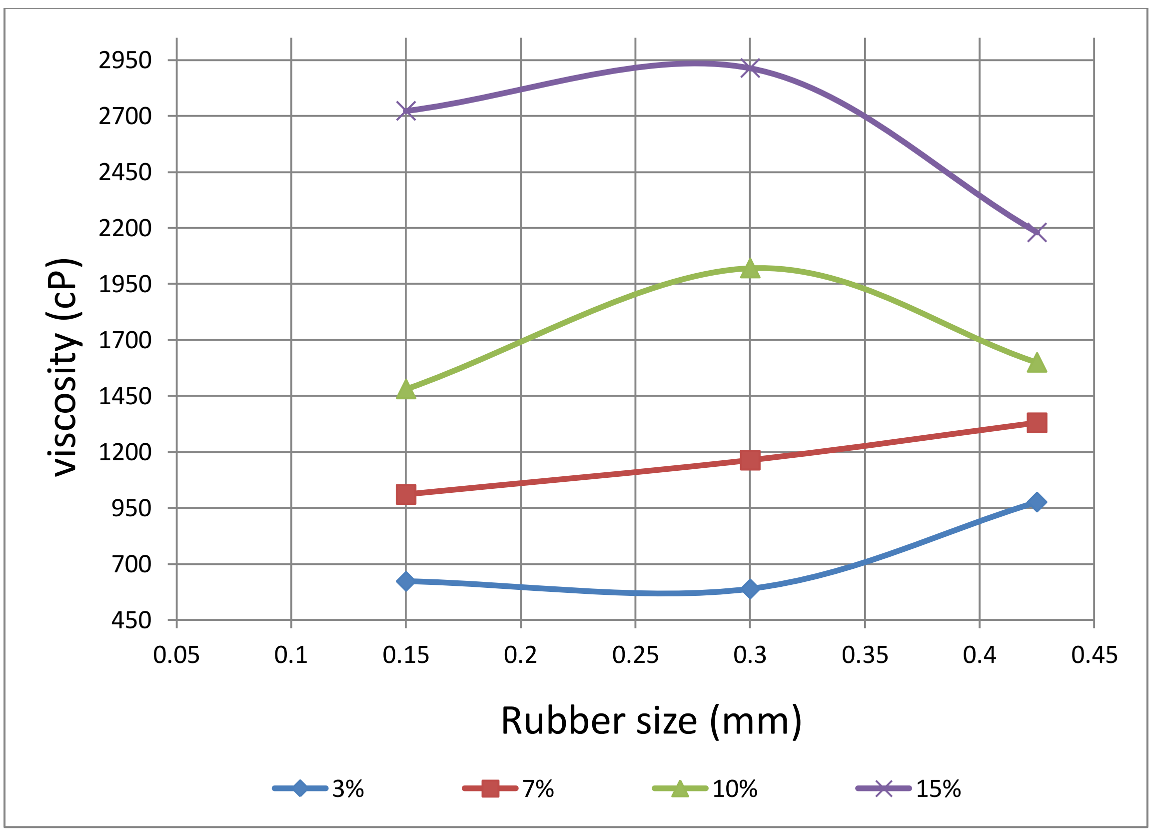

Figure 4.3 Viscosity vs. rubber size

As expected, these results confirm the findings in the literatures regarding the effect of the particles size. It is concluded that the size of the crumb rubber particle is a critical factor that affects the viscosity of the CRM asphalt binder. Based on the results of this research, the best CRM asphalt binder is CRM2 asphalt binder due to its highest viscosity values compared with the other two types. Also, these findings suggest that the effect of size is dependent on the used rubber content.

On the other hand, some of the researchers have specified that the improved viscosity of the CRM asphalt may involve physical and chemical parts. The physical part is about the viscosity improvement resulted from the inclusion of crumb rubber particles. A potential representation of this chemical interaction is studied by Holleran et al. (2000) which mentions that the light fractions of the asphalt and the crumb rubber interact to create a coated particle. Swelling process of the rubber particles is like those happens with the use of polymer modified asphalt [3]. The results of the viscosity test of this research reinforced this theory through the influences of the different crumb rubber properties on the resulted viscosities. The resulted differences of the viscosity because of the crumb rubber size reinforced that there is a chemical interaction going on between the asphalt and the rubber particles that affects the swelling and depolymerization process of the particles.

III. Crumb Rubber Content

In this part, the effect of the rubber content is investigated. Five different contents are used for each of the three CRM asphalt blends. The results of the viscosities (cP) are shown in Table 4.4.

Table 4.4 Viscosity Results of the CRM Asphalts

CRM % / CRM asphalt	CRM1	CRM2	CRM3
0%	564	564	564
3%	975	588	622
7%	1330	1163	1010
10%	1600	2021	1481
15%	2180	2914	2723

It is clearly observed that the rubber content is highly affecting the viscosity. As shown in Fig. 4.4, the results in this part indicate that, in general, the viscosity increases continually as the rubber content increases for any CRM type. Indeed, the effect of the rubber content on the viscosity became more significant as at the rubber content of 10% and 15%. The results show that the extent of the improvement of the viscosities due to the rubber content also depends on the size of the crumb rubber particles.

It is noted that for all of the used crumb rubber contents with the three CRM blends, none of the resulted viscosities exceeded the allowable maximum limit for CRM asphalt binders. The superpave asphalt requirements indicate that the asphalt viscosity should not exceed 3000cP at a temperature of 135°C. Exceeding this limit may result in pumping ability problems at the HMA plan. Rubber contents more than 15% may cause pumping problems, decrease the workability characterizes, consume more power and add more costs to the production of CRM asphalt binders.

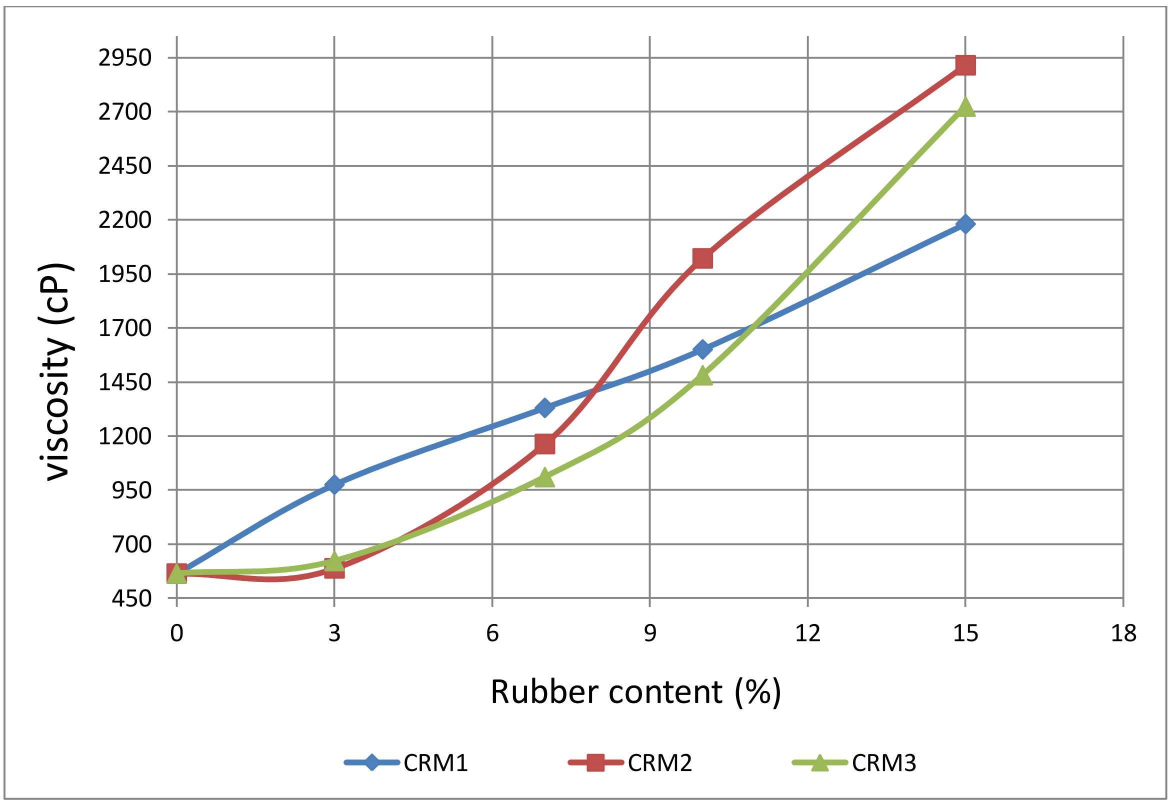

Figure 4.4 Viscosity vs. rubber content

As expected from the previous studies, the modification of the asphalt binder by crumb rubber increases the viscosity and that is very important to increase the thickness for better coating with aggregates in the asphalt mixtures. Moreover, it can be concluded that the increasing amount of crumb rubber in the asphalt binder lead to improvements of the viscosity with an increasing trend.

The improvement of viscosity values is basically due to the increase in content of rubber which mainly results from the increase of the absorption amount of the light fractions of the asphalt and increased crumb rubber swelling and as a result of the more rubber particles containing in the CRM asphalt. These findings of the viscosity testing with CRM asphalt give an indication about the significance effect of the crumb rubber modification especially at higher contents.

4.3.2. Optimum CRM Asphalts Binders

As a result of the great effects of these different factors of the crumb rubber properties which have been discussed above, it is very important step to find out the optimum CRM asphalt binders from the 12 used CRM asphalt binders for the production of CRM asphalt mixtures. These binders were selected based on the maximum obtained viscosity at each of the used rubber contents. Four CRM asphalt binders are selected to be added to the asphalt mixtures for the next stage of the research as previously explained. These binders are selected from two different types of CRM asphalt blends. Two binders are selected from CRM1 and two from CRM2. These binders are listed in the Table 4.5 with its corresponding viscosities.

Table 4.5 Optimum CRM Asphalt Binders

Binder No.	CRM Asphalt Blend	Rubber Content (%)	Viscosity (cP)
1	CRM 1	3	975
2	CRM 1	7	1330
3	CRM 2	10	2021
4	CRM 2	15	2914

As mentioned in the Fig. 4.5, the results show that the highest value of the resulted viscosities is 2914cP which is resulted from CRM2 asphalt binders with 15% of rubber. And when 10% is added, the CRM2 viscosity is 2021cP. At lower contents of 3% and 7%, the highest viscosities are 975cP and 1330cP, respectively resulted from CRM1. So, these selected CRM binders are used to achieve the objectives of the research regarding the performance of the asphalt mixtures.

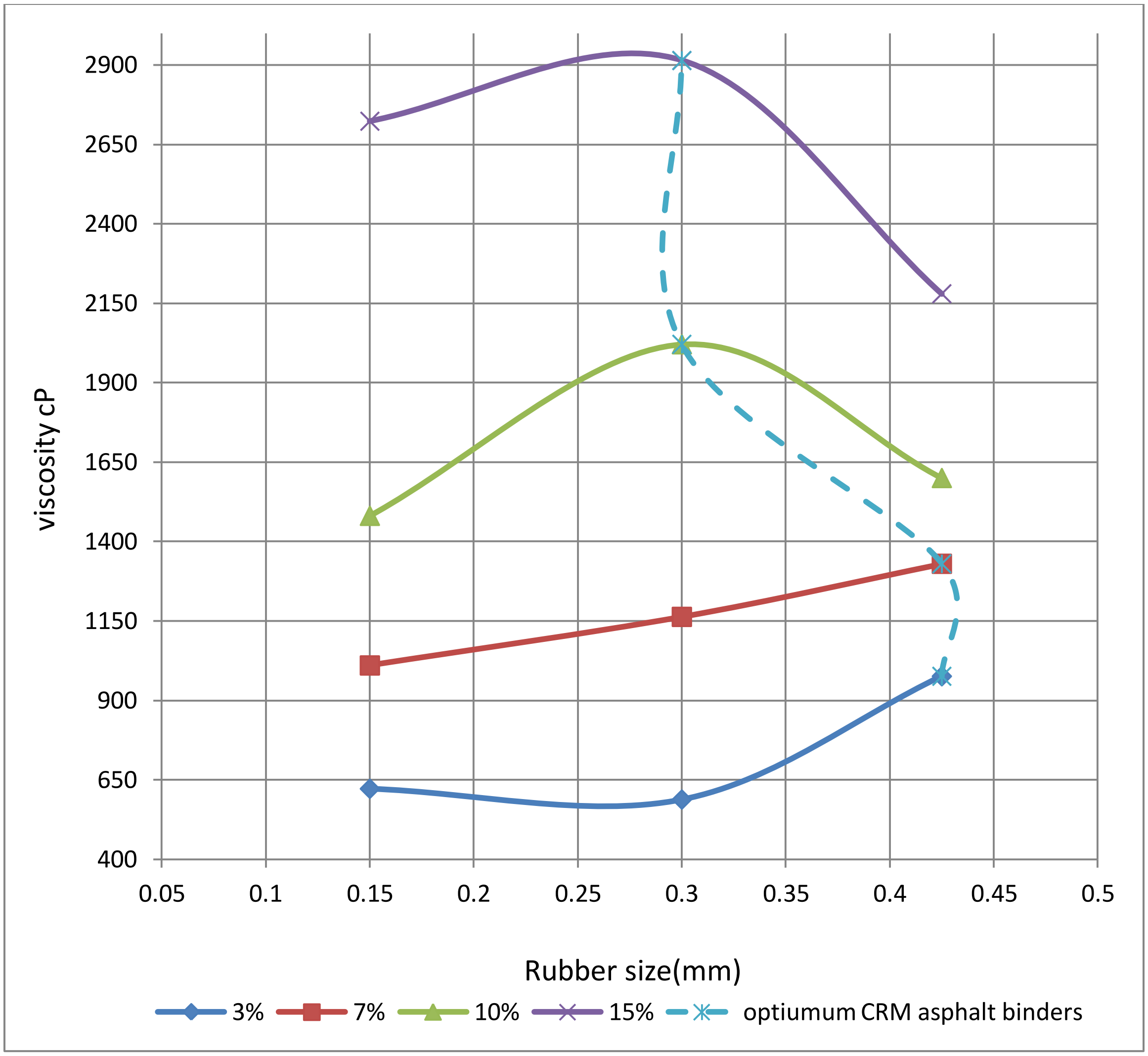

Figure 4.5 Optimum CRM asphalt curve

4.3.3. Statistical Analysis of the Asphalt Binder's Results

The statistical test, Analysis of Variances (ANOVA), is performed to see the effect of the crumb rubber size and contents on the viscosity of CRM asphalt. The analysis includes all results from viscosity test including the three used CRM asphalt types (CRM1, CRM2 and CRM3) and the different used contents (0, 3, 7, 10, and 15%).

Two-way ANOVA is performed on the obtained results of the viscosity test. The statistical results (at $\alpha=0.05$ level) indicate that only the crumb rubber content has a significant effect on viscosity of CRM asphalt which shows a p-value equal to 0.00. As expected, these findings indicate the high effect of this factor on the resulted viscosity. This result highly confirms the obtained conclusion from the discussion part of the effect of rubber content on the viscosity.

Results show that the crumb rubber size does not affect the viscosity of the CRM asphalt binders. The p-value for this factor is close to 0.57 which is very high value as compared to 0.05. Based on these findings, the three fine crumb rubber gradations used in this research are almost having the same effect on the resulted viscosity. This result does not match the findings from the discussion part of the effect of rubber size on the viscosity. The differences between the viscosities of the CRM asphalt binders are noticeable with each different rubber size.

Regression analysis is also performed on the viscosities results. A model is created for the prediction of viscosity as a function of the crumb rubber top size and rubber (%). Also, the regression analysis of the results indicates that the crumb rubber content is highly correlated with viscosity of the CRM asphalt unlike the crumb rubber size which is not correlated with the resulted viscosity. Tables 4.6 to 4.8 show the analysis results of the viscosity model.

The regression Analysis shows the following:

The regression equation is:

Viscosity = 435 – 24.9 (Top Size) + 138 (Rubber content)   (4.1)

Table 4.6 Viscosity Model Summary

Std. Error of the Estimate	**R Square**	**Adjusted R Square**
270.84	91%	90%

Table 4.7 Regression Coefficients of the Viscosity Model

Predictor	**Coefficient**	**SE Coefficients**	**T**	**P**
Constant	434.9	207.2	2.10	0.058
Size	-24.90	85.65	-0.29	0.776
Content	138.30	13.31	10.39	0.000

Table 4.8 Analysis of Variance for the Viscosity Model

Source	**DF**	**Sum of Squares**	**Mean Square**	**F**	**P**
Regression	2	7925230	3962615	54.03	0.000
Residual Error	12	880246	73354	-	-
Total	14	8805477	-	-	-

4.4. Summary of the Asphalt Binder's Results

Viscosity at mixing and construction temperature is an important property as it shows asphalt's ability for pumping, coating the aggregate in HMA mixture, and placing and compacting. The different properties of the crumb rubber and asphalt may produce different modified binders' properties as a result of its effects on the interaction process between the base materials. Generally, the addition of crumb rubber materiel improves the asphalt binder performance. However, there are some factors that should be kept under consideration while using the crumb rubber as a modifier to the asphalt binders. The results of the experimental work of the asphalt binder testing obtained from this research show the following important points:

- The modification of asphalt binder by crumb rubber significantly improves the viscosity at high a temperature which leads to a better stability of asphalt pavements and reduces susceptibility to permanent deformation. It will also improve the workability during construction.
- The size of the crumb rubber, rubber content, and blending conditions of CRM asphalt have an effect on viscosity of asphalt binder.
- The viscosity test of the CRM asphalt binders is a critical indicator that may reflect the clear influences of those factors on the interaction process between the base materials.
- The best CRM asphalt binder was CRM2 asphalt binder due to its highest viscosity values compared with the other two types. These findings suggest that the effect of size depends on the used rubber content.

- The resulted differences of the viscosity due to the crumb rubber size and rubber content reinforced that there is a chemical interaction going on between the asphalt and the rubber particles that affects the swelling and depolymerization process of the particles.
- Unlike the crumb rubber size factor, the statistical results show that the rubber content is highly a significant factor in terms of defining the viscosity of CRM asphalt.

4.5. Asphalt Mixtures Testing

This part includes the results of the mix design and engineering testing of used asphalt mixtures. Superpave mix design method is used to design and determine the Optimum Asphalt Content (OAC) of the control and CRM asphalt mixtures. The performances of mixtures are evaluated based on their main engineering properties which are used to study the influence of adding crumb rubber as a modifier to the asphalt mixtures using the different CRM asphalt binders selected previously. In this research, the studied CRM asphalt mixtures are made using the optimum CRM asphalt binders resulted from the binder testing results. Based on the viscosity testing results, total of four CRM asphalt binders are selected for testing in the asphalt mixtures. These CRM asphalt binders include two types of CRM1 (3 and 7%) and two types of CRM2 (10 and 15%). In addition, plain asphalt mixture is also used and decided to be the control asphalt mixture. The results of this part have been presented and discussed in the next sections.

4.5.1. Superpave Mix Design

The CRM Asphalt mixtures and the control asphalt mixture are produced using dense gradation with a 12.5mm nominal maximum aggregate size. The use of dense gradation in the CRM asphalt mixtures is due to the use of fine crumb rubber gradations used in this research in addition to the desired objectives. The mixing temperature is set at 180°C and the compacting temperature at 150°C. These temperatures are selected based upon past experience reported in the literature review. The Optimum Asphalt Content (OAC) of the used mixtures is evaluated according to the Superpave mix design method which is the most widely applied method for the designing of the asphalt mixtures in Saudi Arabia. Fig. 4.6 illustrates the 0.45 power chart of the 12.5 mm mixture gradation curve used for all the types of mixtures studied in this research. As it can be observed, the gradation curve is within the required control points. The distribution of particle sizes is expressed as a percentage of the total weight as shown in Table 4.9.

Table 4.9 The distribution of Particle Sizes

Sieve Size (mm)	Passing (%)
19	100
12.50	95.2
9.5	81.8
4.75	44
2.36	31.4
1.18	22.1
0.6	16.1
0.3	11.3
0.15	7.9
0.075	5.2

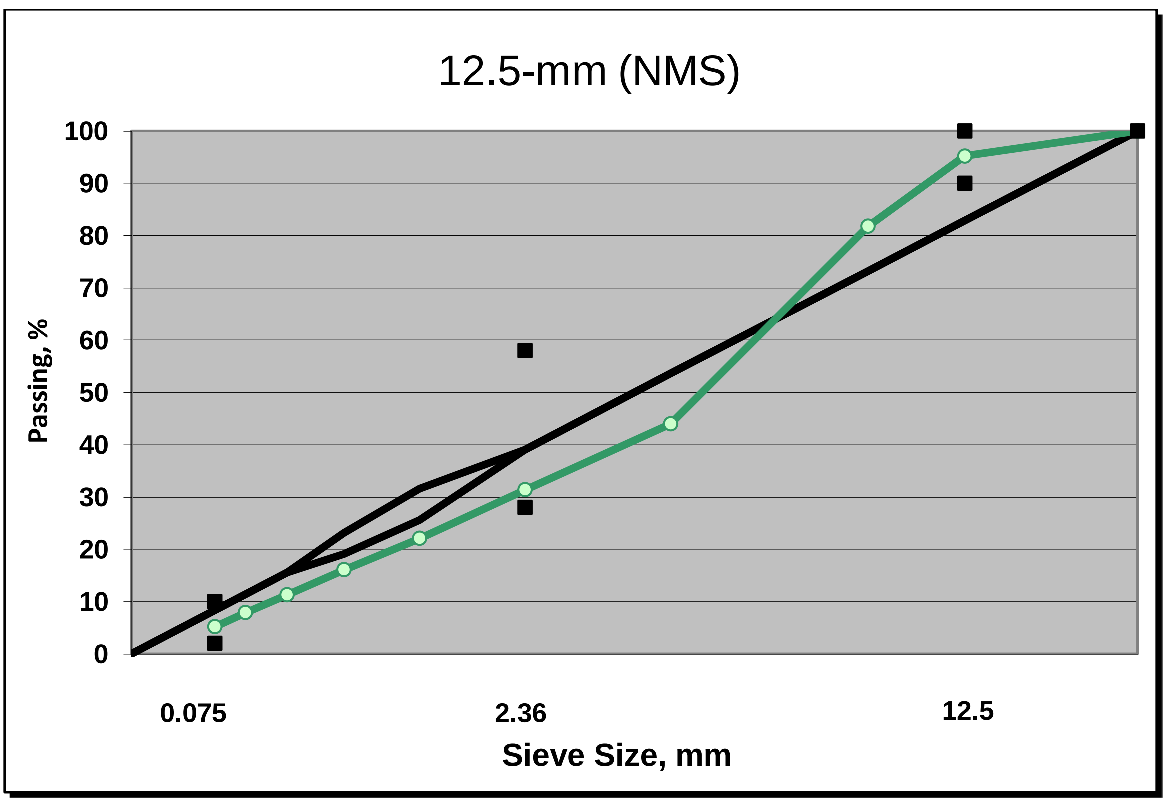

Figure 4.6 The 0.45 power chart of the mixture gradation curve

4.5.2. Optimum Asphalt Contents

The quantity which is needed to get 4.0% air voids at a specified number of design gyrations is called optimum asphalt content (OAC). The volumetric properties of the mixture should be obtained in this stage to determine the OAC for the used mixtures after the determination of suitable aggregates gradation.

Based on the obtained results from the mixtures design process, it is found that the OAC for control asphalt and CRM asphalt mixtures are 4.20% and 4.70%, respectively. As we can observe, the required amount of asphalt is increased with the CRM asphalt mixture. Because of the little variations between the results of the CRM asphalt binders, it is decided to use the same OAC for all the types of CRM asphalt mixtures.

4.5.3. The Indirect Tensile Strength (ITS)

After determining the optimum asphalt contents, the indirect tensile strength test is conducted. All of the types of mixtures are tested using their optimum CRM asphalt binders. Five types of asphalt mixtures are tested including two types of CRM1 (3 and 7%) and two types of CRM2 (10 and 15 %) in addition to the control asphalt mixtures. According to the procedure, three samples of each mixture type are prepared and tested.

The results of the indirect tensile strength are shown in the Table 4.10. In general, the addition of crumb rubber into the mixtures slightly improves the tensile strength as compared to the control mixture. The CRM asphalt mixtures exhibit almost higher indirect tensile strength values than the control asphalt mixtures especially with CRM1 asphalt mixtures. The ITS values of tested samples obtained from this research ranged from 660 psi to 684 psi. As shown in the table, slight differences are found between the ITS values of the tested CRM asphalt mixtures. These findings indicted that, in general, the effect of the different used sizes or contents is not significance.

The maximum value for indirect tensile strength is obtained with CRM1 with 3% of rubber content as shown in Fig. 4.7. In this case, the value of the ITS has been increased by only 3.5% as compared to the unmodified mixture. In case of 7% content, the ITS value reduced by 2% compared with 3% content.

Table 4.10 Indirect Tensile Strength Results

Asphalt Binder	Peak Load (Ib)			ITS (psi)			Avg. ITS (psi)
	1	2	3	1	2	3	
Control (0%)	9780	10880	10450	623	693	665	660
CRM1 (3%)	10850	10565	10730	691	673	684	684
CRM1 (7%)	10715	10420	10550	682	663	672	673
CRM2 (10%)	10388	10265	10480	663	654	668	663
CRM2 (15%)	10615	10150	10260	676	646	653	661

On the other hand, the minimum value of ITS values of the CRM asphalt mixtures is found with CRM2 using 15% content which shows almost no improvement as compared with control asphalt mixture. The influence of the rubber content on the tensile strength values with CRM2 shows the same performance as CRM1. The higher rubber contents of 10 and 15% do not affect the ITS value.

As can be observed from these results, the CRM1 mixtures with its coarser particles with 3% and 7% contents gives better results than CRM2 even with its higher contents (10% and 15%). In general, the values obtained from mixtures with CRM2 show almost no improvement as compared to the control mixtures. So, the influence of the rubber on the ITS values are hardly noticeable with CRM2 types unlike the mixtures with CRM1 which obtain better results.

The Indirect Tensile Strength (IDS) test is very useful in deciding the performance of dense asphalt mixtures which mainly depend on the mixture`s cohesion. From the obtained results of the ITS test of this research, it can be concluded that the crumb rubber almost had no influence on the tensile strength property of the dense asphalt mixtures as it was expected through the literature reviews. The crumb rubber particles do not improve the bond between the aggregates and the asphalt binder. Based on the ITS results, the optimum CRM asphalt binder is found to be CRM1 with 3% content.

Some of the studies have shown the efficiency of the crumb rubber materials in improving the tensile strength of the asphalt mixtures [14, 17, 19 and 31]. However, some of them do not confirm that and conclude that the crumb rubber may reduce the tensile strength [16 and 21]. They say that it may be caused by the poor interaction between the asphalt binder and the rubber particles. These findings, in addition to the results of this research, indicate that the CRM asphalt mixture properties affect its tensile strength property. These may be related to the crumb rubber properties like size or content or may be related to the used aggregates gradation type. In general, the poor improvement of the ITS may be related to cohesion problems resulted from adhesion between the fine crumb rubber particles and the asphalt binder which may have affected the blending with the aggregate. A probable justification for this problem may be solved by increasing the amount of asphalt binder in the CRM asphalt mixtures, but in this research, this is not possible.

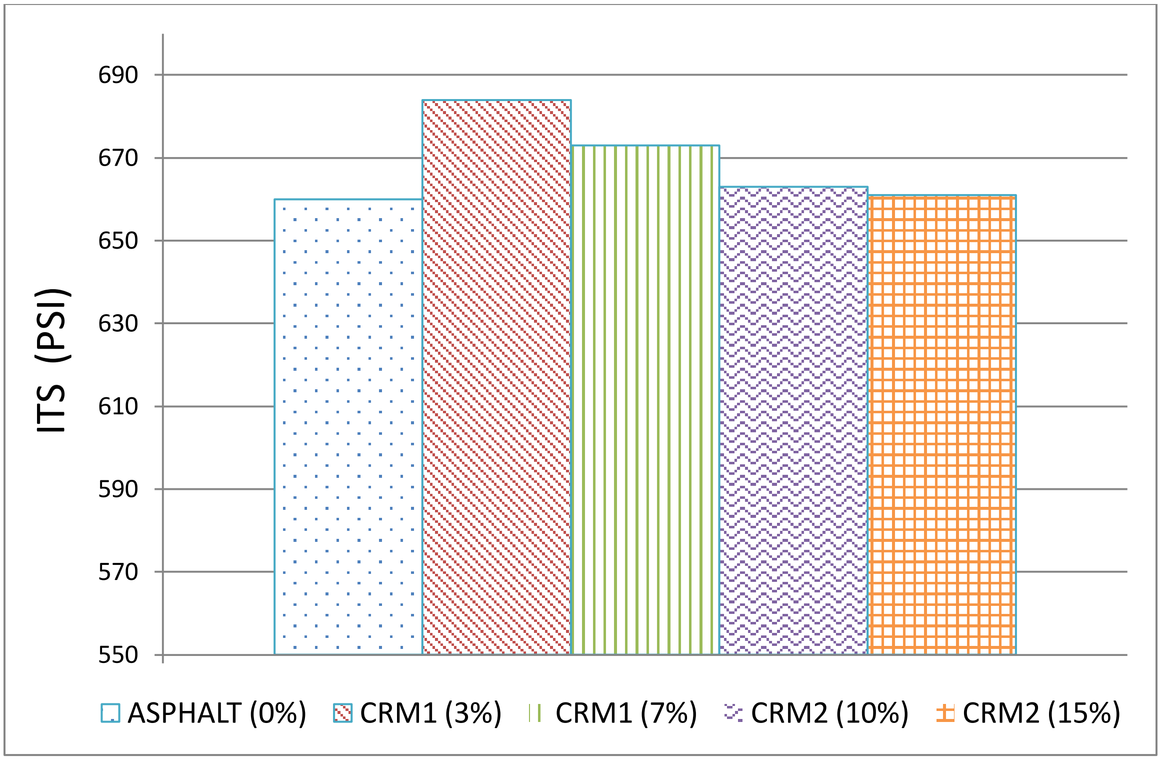

Figure 4.7 Indirect tensile strength of the CRM asphalt mixtures

4.5.4. Durability

The durability test is performed using the Tensile Strength Ratio (TSR) which is applied to investigate durability of samples and to evaluate the influence of the crumb rubber on the asphalt mixtures. It should be noted that the increased TSR values lead to better durability properties, and therefore improve resistance of asphalt mixtures of moisture influence. Normal specification requires a TSR value of 80% or more. In this test, five types of asphalt mixtures are tested including two types of CRM1 (3 and 7%) and two types of CRM2 (10 and 15 %) in addition to the control asphalt mixtures. A total of six samples have been prepared for each mixtures type. Three are used as dry samples and the other three as wet samples.

The wet samples of the used mixtures after the conditioning process is tested in the ITS test and their ITS values are found. The complete results of the ITS values of the wet samples are shown in Appendix B. Using the results obtained from the ITS test of the dry samples presented in section 5.1.5, the TSR values are calculated using the following formula:

TSR = ITS (Wet) / ITS (Dry) (4.2)

Where:

TSR: tensile strength ratio (%)

ITS (Wet): indirect tensile strength (psi) for the dry samples

ITS (Dry): indirect tensile strength (psi) for the wet samples

The results of TSR values are shown in Table 4.11 for all the tested samples. The TSR value for the control samples is determined to be 74%. The typical TSR values of the CRM asphalt mixtures ranges from 83% to 96%. These results show that all CRM asphalt mixtures exceed the minimum requirement of 80%.

Table 4.11 Tensile Strength Rations

Asphalt Binder	TSR (%)			Avg. TSR (%)
	1	2	3	
Control (0%)	77	71	74	74
CRM1 (3%)	83	82	83	83
CRM1 (7%)	89	88	94	90
CRM2 (10%)	96	97	95	96
CRM2 (15%)	78	86	87	84

From Fig. 4.8, the maximum TSR value between the CRM asphalt mixtures is found with CRM2 of 10% content. In this case, 23% improvement is gained as compared to the control mixture. None of the CRM asphalt mixtures had a TSR value less than the control mixtures. The minimum TSR value of the CRM asphalt mixtures is found with CRM1 when 3% of rubber is added. In this case, TSR value is 83% which is improved by 11% as compared to the control mixture.

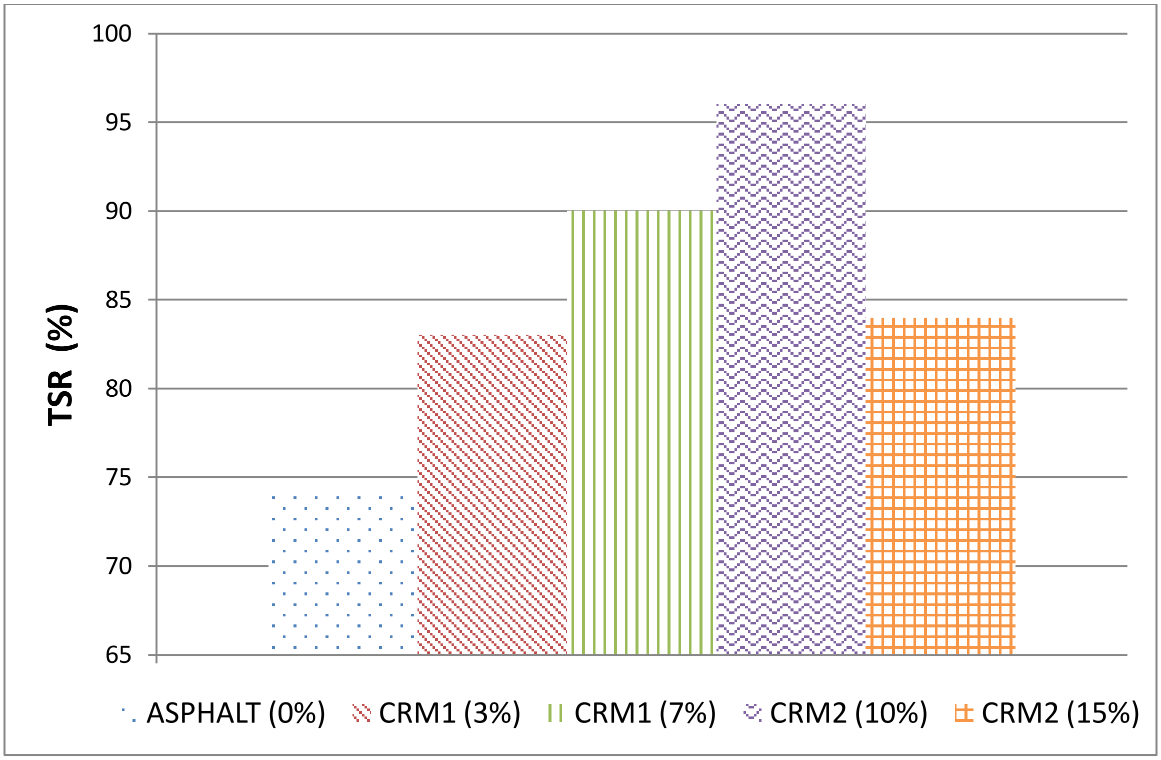

Figure 4.8 Tensile strength ratios of the mixtures

From Fig. 4.8, it can be noticed that the mixtures of CRM1 with 3% content and CRM2 with 15% content show almost the same TSR values. These small differences between the CRM1 and CRM2 values may indicate that the size of the rubber is not an important factor in defining the durability of the CRM asphalt mixtures.

As we can see in the figure, increasing the rubber content from 3% to 10% has increased the TSR value from 83% to 96% without considering the slight effect of the rubber size. After that, when 15% content is used, the TSR value decreases to 84%. These findings indicate that the crumb rubber content has a major function in defining the durability properties of the CRM asphalt mixtures.

The resistance of moisture effects in the asphalt pavements is one of the main problems that need to be improved. From the obtained results, it can be concluded that the addition of crumb rubber into the asphalt mixtures increase the TSR values of the control asphalt mixtures. These findings of this test have confirmed the literature reviews [16 and 22] regarding the effectiveness of crumb rubber particles in improving of the durability properties of the asphalt mixtures. So, the CRM asphalt mixtures have a high resistance to the effects of environmental conditions, such as water, ageing and temperature differences. In addition, the modification of asphalt binder by crumb rubber particles leads to a better adhesion by stronger bonds between the aggregates surface and the asphalt binder and that can delay the deterioration of the pavement distress for longer time and therefore increase the life of the asphalt pavement and reduce the pavement maintenance costs.

The results of the test also indicate that the differences between the fine crumb rubber sizes have no significance effect on the durability properties. However, the results indicate the high significance effect of the rubber content on the durability properties of the asphalt mixtures. In terms of durability properties, the optimum rubber content between the used CRM asphalt mixtures was found to be 10% content. However, increasing the rubber content over 10% will decrease the TSR value, and therefore decrease the moisture resistance of the asphalt mixtures.

4.5.5. The Resilient Modulus (Mr)

Resilient modulus tested by the indirect tensile form represents the elastic properties of asphalt mixtures under repeated load effectively. It should be noticed that the high value of resilient modulus point to that at known applied stress will result in a low strain in the mixture, but will not indicate that the mixture will have high strength. The resilient modulus of the different asphalt mixtures are measured in this test. Five types of asphalt mixtures are tested including two types of CRM1 (3 and 7%) and two types of CRM2 (10 and 15%) in addition to the control asphalt mixtures. Three different levels of dynamic loading were applied on the tested samples (95, 120 and 145 Ib). For each mixture type, 3 samples are tested with 2 diameter positions and readings are taken for a number of 3 repetitions. The results of the resilient modulus are discussed in the following paragraphs.

The average values of the resilient modulus obtained from for all the applied levels of the dynamic loads with each mixture type are shown in Table 4.12. Generally, the addition of crumb rubber to the asphalt mixtures increases the value resilient modulus as compared to the control mixture. The typical average values of Mr range from 767Ksi to 1037Ksi. The resilient modulus of the control asphalt mixture is found to be 767Ksi. All the CRM asphalt mixtures have Mr Value higher than the control asphalt mixture. The complete results of resilient modulus for each type of the tested mixtures and its variations with different used loading conditions are presented in Appendix C.

Table 4.12 Average Resilient Modulus Values of the Mixtures

Binder Type	OAC (%)	Resilient Modulus (ksi)
Control asphalt (0%)	4.20	767
CRM 1 (3%)	4.70	832
CRM 1 (7%)	4.70	1037
CRM 2 (10%)	4.70	955
CRM 2 (15%)	4.70	837

The maximum resilient modulus value is obtained with CRM1 of 7% rubber content. In this case, an improvement of 26% is obtained as compared to the control mixture. From the CRM asphalt mixtures, the mixture with CRM1 with 3% rubber content has the minimum MR value which increases by only 8% as compared to the control mixture.

As we can observe from Fig. 4.9, the optimum CRM asphalt mixture in terms of resilient modulus is found with CRM1 with 7% rubber content. Also, the effect of rubber size on the Mr value is not clear. Indeed, the values of CRM1 with 3% rubber content with its coarser particles and CRM2 with 15% rubber content are almost the same. This result may give small indication about the insignificant effect of rubber size. However, we can conclude that this obtained data of the used binder cannot be used to evaluate the real effect of the rubber size on the resilient modulus.

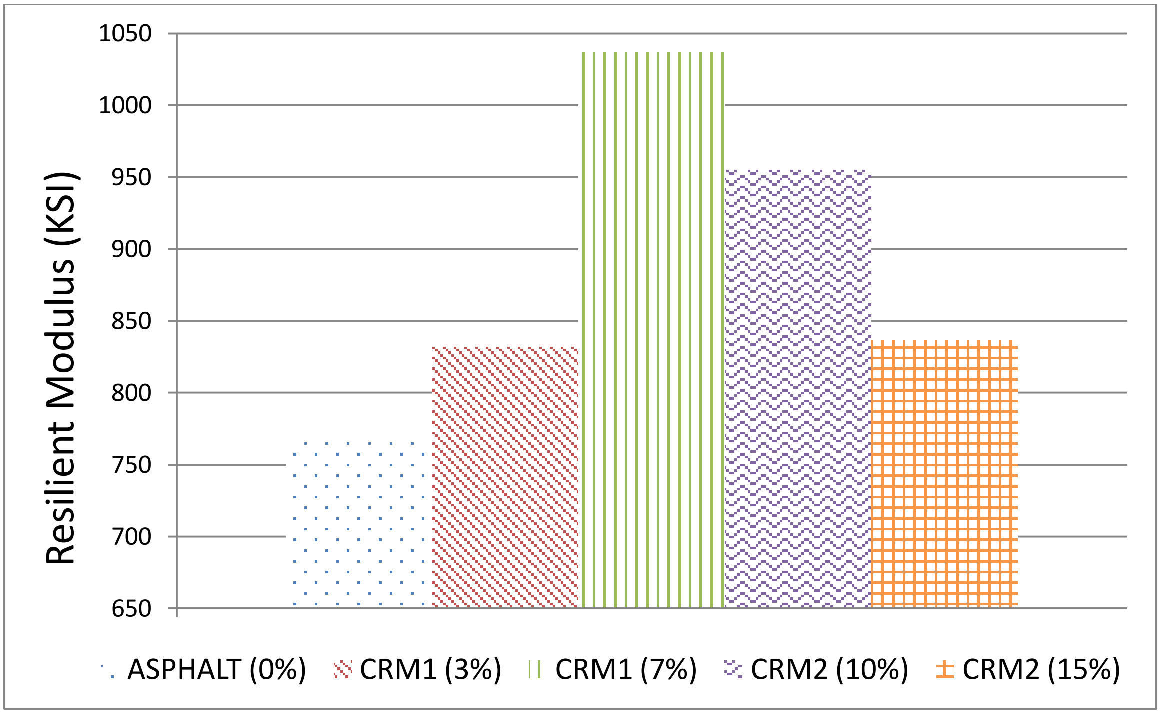

Figure 4.9 Average resilient modulus of the mixtures

On the other hand, if we ignore the rubber size influence, we can notice the significant influence of the rubber content on the resilient modulus value. The value of Mr increases from 0% content until it reaches its maximum value at 7% content; then, it reduces at 10 and 15% rubber contents. These results indicate that the higher contents of rubber do not improve the resilient modulus values of CRM asphalt mixtures.

Figs. 4.10 to 4.12 represent the average resilient modulus values of all the tested types of mixtures for each different dynamic loading condition individually (95, 120 and 145 Ib), respectively. These different loading conditions are applied to evaluate the influence crumb rubber under these different loads on the resilient modulus values. In general, from these results we can conclude that the different applied dynamic loading have no significant influence on the resilient modulus values. However, the same performance of average results of different loadings is found under each loading condition. The obtained resilient modulus of the different tested asphalt mixtures always shows the same trend under any types of loading. The highest and lowest Mr values of the mixtures are found at different levels of the applied loadings. These little variations of the resilient modulus results under different loading conditions do not show the significant effect of the loading conditions on the resilient modulus properties.

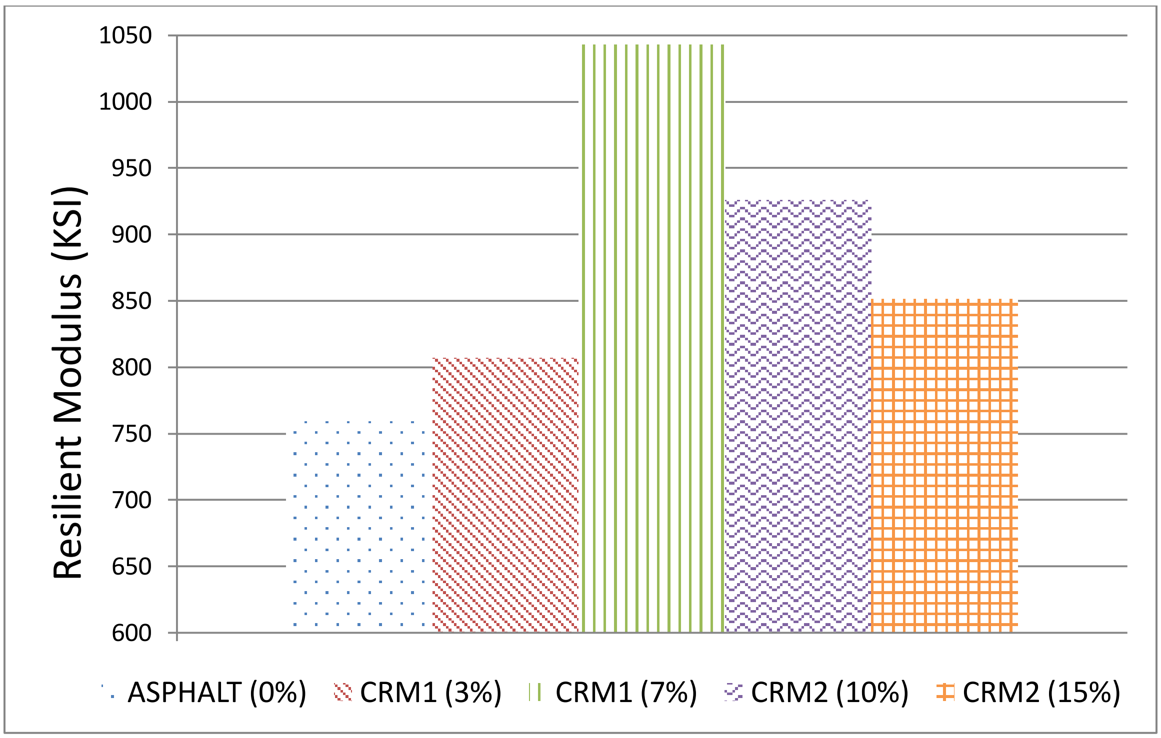

Figure 4.10 Average Resilient modulus of the mixtures at loading of 95 Ib

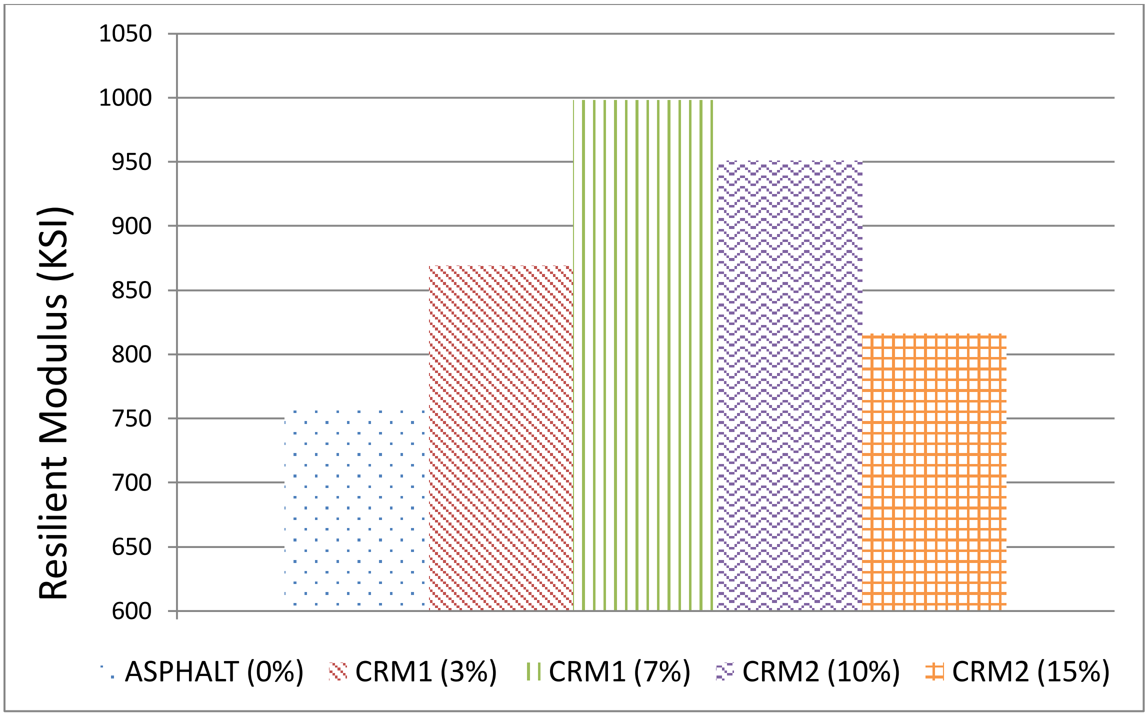

Figure 4.11 Average Resilient modulus of the mixtures at loading of 120 Ib

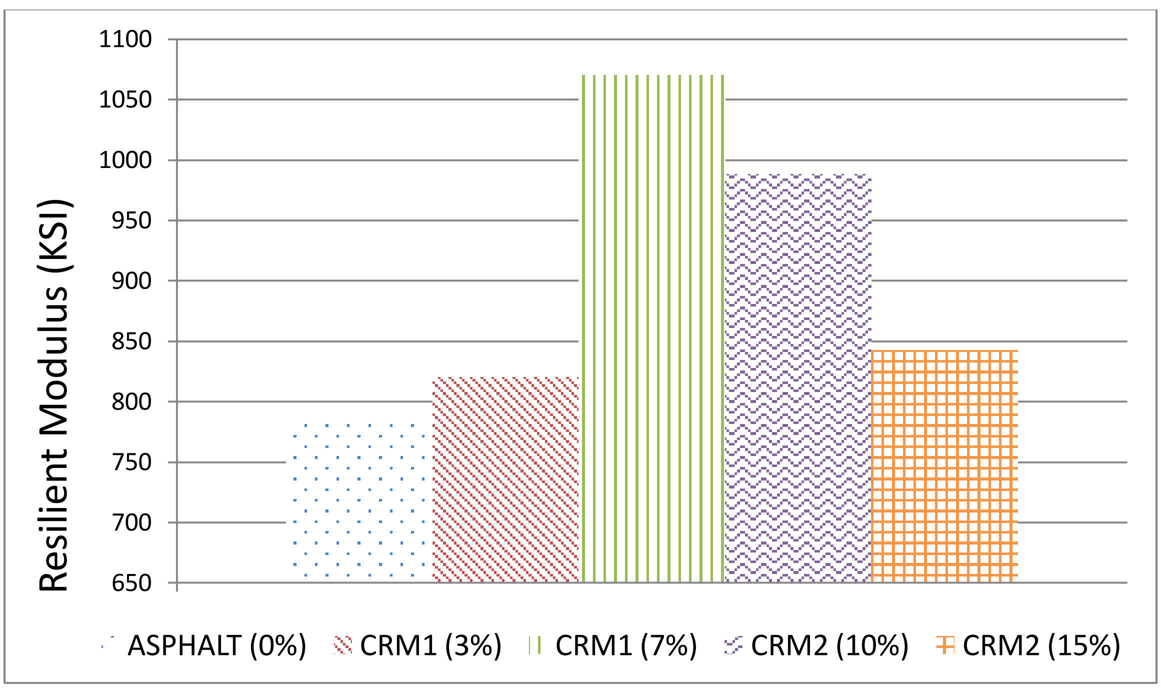

Figure 4.12 Average Resilient modulus of the mixtures at loading of 145 Ib

It can be observed from Fig. 4.13, the differences between the tested types are the almost the same for all the applying loading conditions. The CRM1 with 7% content with any loading condition has the highest resilient modulus while the control asphalt mixtures are always the minimum as compared to the other mixtures. From all the values, the maximum value is observed under a loading of 145 Ib with CRM1 (7%). The minimum value is observed with the control asphalt mixture under a dynamic load of 95 Ib. The tables of average resilient modulus values of all the tested types of mixtures are shown in Appendix C for each different dynamic loading condition individually (95, 120 and 145 Ib).

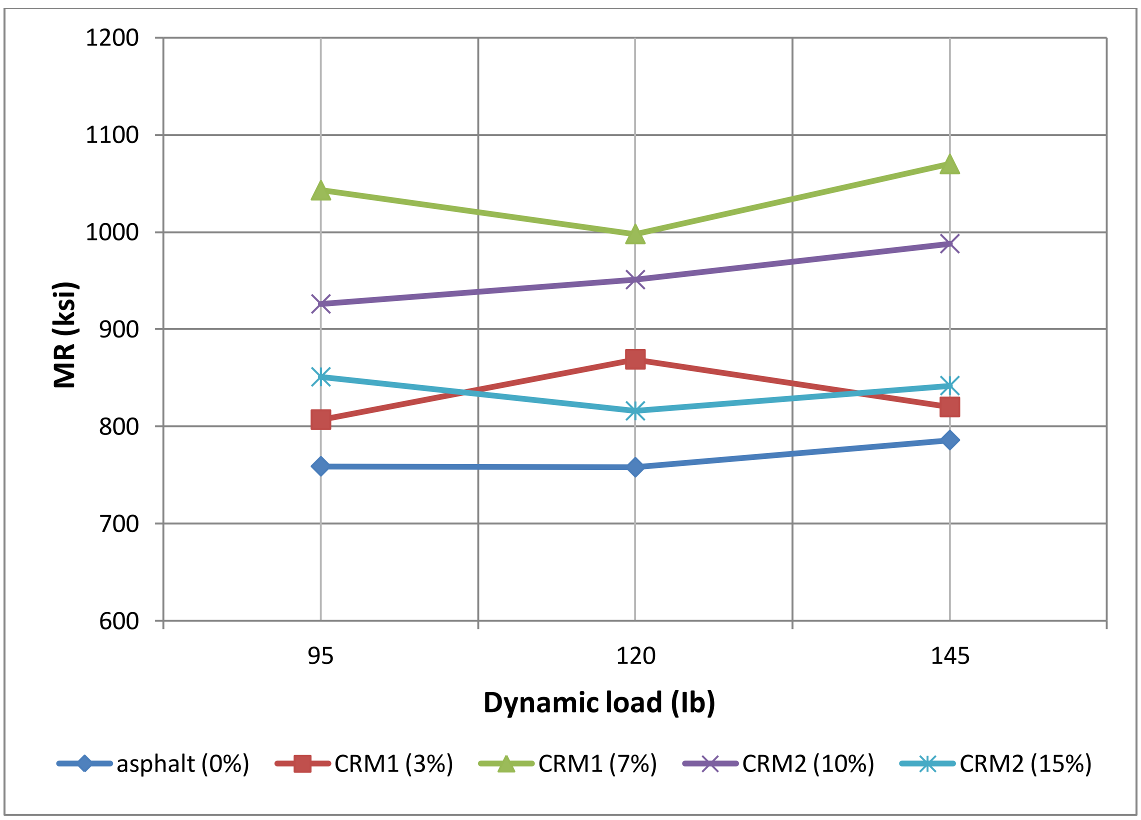

Figure 4.13 Average resilient modulus vs. Different dynamic loads

The resilient modulus test is useful test to investigate the behavior of CRM asphalt mixtures under repeated loads. The resilient modulus test shows a good indication of the effectiveness of the crumb rubber to asphalt mixtures under varying loading conditions. As expected from the literature review [14, 15, 16, 21 and 31], the results show that the CRM asphalt mixtures have better resilient modulus values than that of the unmodified asphalt mixtures. These obtained results conclude that the use of CRM asphalt in asphalt pavements considerably enhance the resistance to rutting. In fact, this improvement is directly related to mixture resistance to plastic deformations since a mixture with improved resilient modulus have better bearing capacity. Therefore, these types of mixtures are less influenced by the traffic loads and experience less deformation under traffic loads. As a result to this, it delays the appearance of surface deformations. So, the modification of asphalt binder by crumb rubber is effective to enhance the performance of asphalt pavements. In addition to all of that, the improvement of resilient modulus may be useful to construct asphalt pavement layers with less thickness in a cost effective manner.

4.5.6. Statistical Analysis of the Asphalt Mixtures Testing Results

The Statistical test, Analysis of Variances (ANOVA), has been performed to evaluate the influence of the size and content factors on the tested engineering properties of the used asphalt mixtures. These properties include the tensile strength, durability and resilient modulus properties. As discussed earlier, it should be noted that the studied CRM asphalt mixtures are made using the only optimum CRM asphalt binders resulted from the binder testing results. Four CRM asphalt binders are selected for testing in the asphalt mixtures. These CRM asphalt binders include two types of CRM1 (3 and 7%) and two types of CRM2 (10 and 15 %) in addition to plain asphalt mixture which is added to control the asphalt mixture.

In general, for all of the tested mixtures properties, the regression analysis of results at α=0.05 indicate that only the crumb rubber content is considered as a major influence on durability and resilient modulus properties of the CRM asphalt mixtures. As expected, these findings point to the high influence on the rubber content factor on the mixtures performance in terms of these two properties. However, the results indicate that the rubber content factor is not the important factor of the tensile strength properties of the mixtures. In this case, the results show a p-value higher than 0.05. These results confirm the obtained conclusion regarding the effect of rubber content on resulted properties.

The results also show that the crumb rubber size does not affect any of the different tested properties of the CRM asphalt mixtures. The p-values for this factor are always higher than 0.05. Based on these findings, the three fine crumb rubber gradations used in this research are almost having the same influence on the resulted performance of the CRM asphalt mixtures.

Based on the above findings, it is found that the size of the rubber is not correlated with any of the properties. Also, the crumb rubber is only correlated with durability and resilient modulus properties. Therefore, regression analyses are repeated and performed on the CRM asphalt mixtures' durability and resilient modulus properties. Models are created for the prediction of these properties as a function of the crumb rubber content.

The regression analysis of the results indicates that the crumb rubber content is highly correlated with durability and resilient modulus properties of the CRM asphalt mixtures. The following parts show that these models for durability and resilient modulus results, respectively. Tables 4.13 to 4.18 show the analysis of the models results.

I. Durability Model:

The regression equation is:

(Durability) = 77.7 + 0.977 (Content) (4.3)

Table 4.13 Durability Model Summary

Std. Error of the Estimate	R Square	Adjusted R Square
6.83741	40.7%	36.9%

Table 4.14 Regression Coefficients of the Durability Model

Predictor	Coefficient	SE Coefficients	T	P
Constant	77.743	2.358	32.96	0.000
Content	0.9773	0.2952	3.31	0.004

Table 4.15 Analysis of Variance for the Durability Model

Source	DF	Sum of Squares	Mean Square	F	P
Regression	1	512.44	512.44	10.96	0.004
Residual Error	16	748.00	46.75	-	-
Total	17	1260.44	-	-	-

II. The Resilient Modulus:

The regression equation is:

(Resilient modulus) = 816 + 8.62 (Content) (4.4)

Table 4.16 Resilient Modulus Model Summary

Std. Error of the Estimate	R Square	Adjusted R Square
94.9098	21.8%	16.9%

Table 4.17 Regression Coefficients of the Resilient Modulus Model

Predictor	Coefficient	SE Coefficients	T	P
Constant	815.65	32.76	24.91	0.000
Content	8.622	4.098	2.10	0.052

Table 4.18 Analysis of Variance for the Resilient Modulus Model

Source	DF	Sum of Squares	Mean Square	F	P
Regression	1	39885	39885	4.43	0.052
Residual Error	16	144126	9008	-	-
Total	17	184011	-	-	-

4.6. Summary of the Asphalt Mixtures Results

The performance of CRM asphalt mixtures is evaluated in terms of their main engineering properties which are used to determine the influence of the modification of asphalt mixtures by fine crumb rubber particles. Five types of asphalt mixtures are tested including two types of CRM1 (3 and 7%) and two types of CRM2 (10 and 15%) in addition to the control asphalt mixtures. The following points summarize the main points obtained from the experimental results of the asphalt mixtures results of the research:

- The CRM Asphalt mixtures and the control asphalt mixture are produced using dense gradation with a 12.5mm nominal maximum aggregate size.
- The optimum asphalt contents for control asphalt and CRM asphalt mixtures are 4.20% and 4.70%, respectively.
- The CRM asphalt binders modified by the fine crumb rubber particles used in this research are suited for dense graded asphalt mixtures. The voids space is enough to accommodate sufficient asphalt binder content that can enhance the performance of dense graded mixtures.
- The testing results show that the crumb rubber modification has no influence on the indirect tensile strength property of the dense asphalt mixtures.
- The durability test results indicate the high significance influence of the rubber in improving the moisture susceptibility properties of the asphalt mixtures.
- In terms of durability properties, the optimum rubber content between the used CRM asphalt mixtures is found to be 10%. Increasing the rubber content over 10% tends to decrease the moisture resistance of the asphalt mixtures.

- The results from the resilient modulus test show a good indication of the effectiveness of the crumb rubber to asphalt mixtures under varying loading conditions. The CRM asphalt mixtures are less susceptible to traffic loads and experience less deformation under traffic loads.
- In terms of resilient modulus properties, the optimum CRM asphalt mixture is found to be the CRM1 with 7% content. Also, smaller contents of crumb rubber cause the resilient modulus to increase much better than the larger contents.
- The obtained results of the different tests conclude that the differences between the fine crumb rubber sizes used in this research have no influence on the CRM asphalt mixtures properties, but, the rubber content has significance influence.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The production of crumb rubber asphalt modifiers particles obtained from used tires is an appropriate application to the removal problems of these wasted tires. It can be an excellent additive material that improves the properties of the conventional asphalts mixtures. In general, the lab testing results of this research show the effectiveness of the usage of crumb rubber particles as modifiers of asphalt mixtures.

5.1.1. CRM Asphalt Binders

CRM asphalt binder is a type of modified asphalt using a crumb rubber produced from waste tires. The influence of the crumb rubber size and content on the interaction process with the base asphalt is studied by the viscosity test using different combinations of particles sizes and contents. According to the results of binder testing, the following conclusions are made:

- The viscosity is not only indicating the performance of the CRM asphalt at high temperature but, it can also be a critical indicator of the effects of different crumb rubber properties on the interaction process between the base materials.

- The results of this research confirm that the viscosity of the CRM asphalt mainly depends on the crumb rubber content, rubber size, curing conditions, and mixing conditions.
- The modification of the asphalt by adding crumb rubber significantly enhances the binder viscosity and that is important to increase the thickness of binder film and better coating of aggregates, and therefore improving the stability of the asphalt mixtures for a better rutting resistance at a high temperature.
- Regardless of the CRM type, the higher crumb rubber content leads to higher viscosity as a result of increase in the absorption of the light fractions by the crumb rubber. Also, with increased rubber content, the viscosity improvements show an increasing trend.
- Instead the crumb rubber size, the statistical results show that the rubber content has an important influence on viscosity of CRM asphalt.

5.1.2. CRM Asphalt Mixtures

This research focuses to study and recognize the influence of using fine crumb rubber on a dense graded CRM asphalt mixture and to compare the potential basic performance characteristics of mixtures in the laboratory. Some fundamental engineering properties of the studied mixtures are also investigated in the laboratory for its optimum asphalt content. As results to findings of this research, a better understanding of the performance of CRM pavements is obtained. In general, the modification of asphalt mixtures by crumb rubber not only solves the problem of the removal of waste tires, but it is also an efficient way of enhancing performance of asphalt mixtures. Based on the results of mixtures testing, the following conclusions are made:

- The CRM asphalt binders modified by the fine crumb rubber particles used in this research are effective for the dense graded asphalt mixtures. The voids space is enough to accommodate sufficient asphalt binder content that can enhance performance of dense graded mixtures.
- The testing results show that the crumb rubber has no influence on the indirect tensile strength property of the dense asphalt mixtures. The crumb rubber particles do not improve the bond between the aggregates and the binder.
- The results indicate that the modification of asphalt binder by crumb rubber particles highly improve the moisture susceptibility performance. However, increasing the rubber content over 10% tend to decrease the moisture resistance of the asphalt mixtures.
- The modification of asphalt mixtures using crumb rubber increases the resilient modulus properties, and therefore it has a better resistance to rutting.
- Unlike the rubber size, the obtained results of the different tests conclude that the rubber content has significant influence on the CRM asphalt mixtures properties.
- The improvement of the asphalt mixture due to the crumb rubber modification is a cost attractive mean to delay the appearances of various distresses and increase the service life of the asphalt pavement.

5.2. Recommendations

The following recommendations are highly important for further studies in terms of CRM asphalt binder and mixtures performance.

5.2.1. CRM Asphalt Binders

- The origin of the crude oil, refining methods, and the amounts of the chemical fractions will cause these variations in properties of the base asphalt. So, further studies are needed with other asphalt sources to investigate the influence of the asphalt properties on the CRM asphalt.
- In order to make more general conclusions about the influence of the crumb rubber properties and production process on the interaction process, it is recommended to test more crumb rubber sizes and contents with different curing and mixing conditions.

5.2.2. CRM Asphalt Mixtures

- Different properties of dense mixture gradation should be investigated to have a complete idea about its effectiveness with the crumb rubber.
- The performance of CRM mixtures should be investigated under different types of tests to obtain a complete idea about the performance of dense CRM asphalt mixture.
- The present research used laboratory simulation testing of the characteristics of the asphalt mixtures. Field observations are needed to supply better comparisons under actual field conditions.

- Economic analysis of crumb rubber modified asphalt pavement should be performed to determine the life-cycle costs including construction, maintenance and other costs, and comparing them with those of pavements having other modified or conventional asphalt mixtures.

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APPENDICES

APPENDIX A

Crumb Rubber Properties

Chemical and Physical Properties of the Crumb Rubber

Saudi Rubber Products Co.
A Subsidiary of Rashid S. Al-Rashid Group

الشركة السعودية لمنتجات المطاط
احدى شركات مجموعة راشد سعد الراشد

Sarpco's Crumb Rubber

Chemical and Physical Properties of Sarpco's crumb rubber:

Appearance and Odor:	*Black granules*
Specific Gravity:	*1.14 +/- 0.03*
Auto-Ignition Temperature:	*700°F*
Flashpoint (COC):	*475°F*
Stability:	*Stable*
Solubility in Water:	*Nil*
Wt. % Volatile:	*< 1% primarily water*
Hazardous Polymerization : (PVC) Poly Vinyl Chloride	*None*

Sarpco's crumb rubber Composition:

PRINCIPLE COMPONENTS	PERCENTAGE
Reprocessed Rubber (NR-SBR)	40 – 45 %
Carbon Black	27 – 33 %
Zinc Oxide	2 – 3 %
Sulfur	1.5 – 2.5 %
Stearic Acid	1 – 2 %
Process Oil	10- 20 %

APPENDIX B

Durability Test Results

Table B. 1 Indirect Tensile Strength Values of the Wet Samples

Asphalt binder	**Deformation (in)**			**Peak load (Ib)**			**ITS (psi)**			**Avg. ITS (psi)**
	1	2	3	1	2	3	1	2	3	
Control (0%)	0.24	0.26	0.25	7450	7725	7670	475	492	488	485
CRM1 (3%)	0.30	0.24	0.28	9040	8635	8930	576	550	569	565
CRM1 (7%)	0.23	0.24	0.26	9600	9250	9885	612	589	630	610
CRM2 (10%)	0.22	0.21	0.23	9950	9970	10005	633	635	637	635
CRM2 (15%)	0.24	0.30	0.31	8235	8700	8885	525	554	566	548

APPENDIX C

Resilient Modulus Test Results

Table C. 1 Complete Results of Control Asphalt (0%)

Sample No.	Position No.	Dynamic load (Ib)	Tensile strain (micro-strain)			Resilient modulus (ksi)		
			1	2	3	1	2	3
1	1	95	15.2	13.8	16.5	805	809	733
		120	20	20	22	810	800	730
		145	11.50	24.5	15.5	820	784	865
	2	95	18	18	17.8	723	739	731
		120	22.5	21.4	21	705	753	720
		145	26	28.50	27	725	795	720
2	1	95	14.80	16.50	14	779	800	794
		120	23	19	20	745	790	815
		145	23	23	18	835	825	780
	2	95	19.50	17.20	19	745	720	728
		120	22	24	21	795	722	713
		145	24	25.50	26	750	737	790

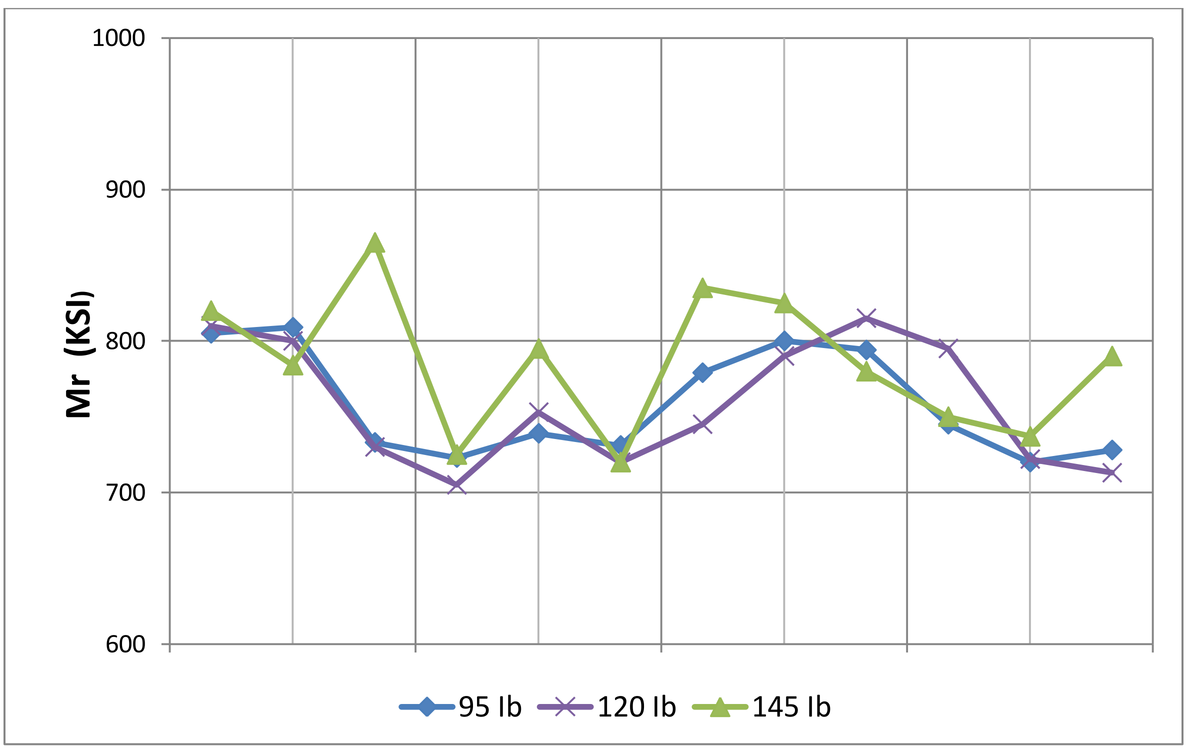

Figure C. 1 Variations of the resilient modulus results of control asphalt

Table C. 2 Complete Results of CRM1 Asphalt (3%)

Sample No.	Position No.	Dynamic load (Ib)	Tensile strain (micro-strain)			Resilient modulus (ksi)		
			1	2	3	1	2	3
1	1	95	16	14.7	13.2	748	799	828
		120	17.50	20	20.4	873	783	777
		145	24	20.5	22.6	748	774	816
	2	95	11.7	15.5	15.4	948	828	838
		120	18	20	19	930	843	915
		145	24	24	24	843	850	853
2	1	95	16	17	15	805	771	800
		120	14.50	18	19	907	820	893
		145	18	24	24	942	707	725
	2	95	15.5	16.5	15	793	747	775
		120	15.4	15.7	16.2	913	900	878
		145	19.3	19	19	860	866	860

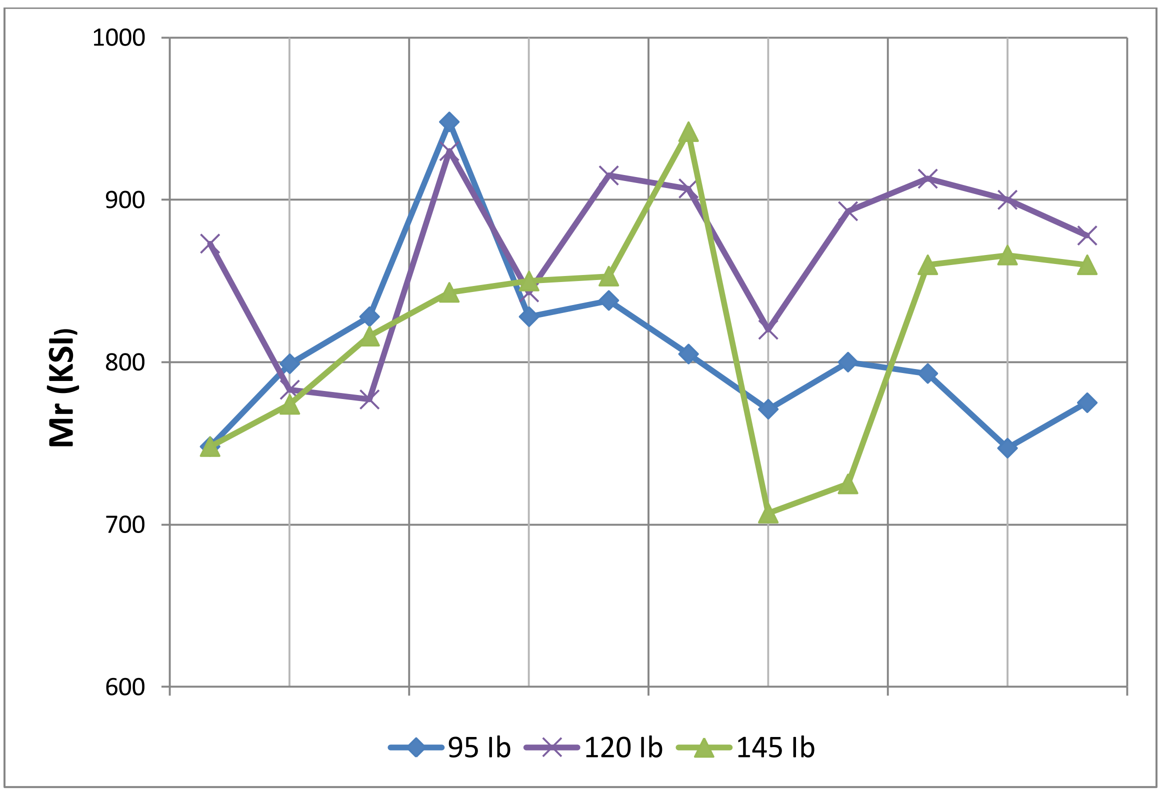

Figure C. 2 Variations of the resilient modulus results of CRM1 asphalt (3%)

Table C. 3 Complete Results of CRM1 Asphalt (7%)

Sample No.	Position No.	Dynamic load (Ib)	Tensile strain (micro-strain)			Resilient modulus (ksi)		
			1	2	3	1	2	3
1	1	95	11	10.6	10.4	1000	1045	1052
		120	15	15	14.6	957	940	985
		145	17.4	17	17	982	1009	1000
	2	95	13.5	12	12	904	923	906
		120	16	16	15	961	960	1020
		145	17	19.5	19.6	1085	950	948
2	1	95	10	9.50	11	1130	1200	1169
		120	12	11	12	1055	1121	997
		145	12.50	13	12	1091	1042	1125
	2	95	13	12.50	12	990	1011	1182
		120	15	15	16	986	954	1047
		145	14	12	14.50	1205	1227	1173

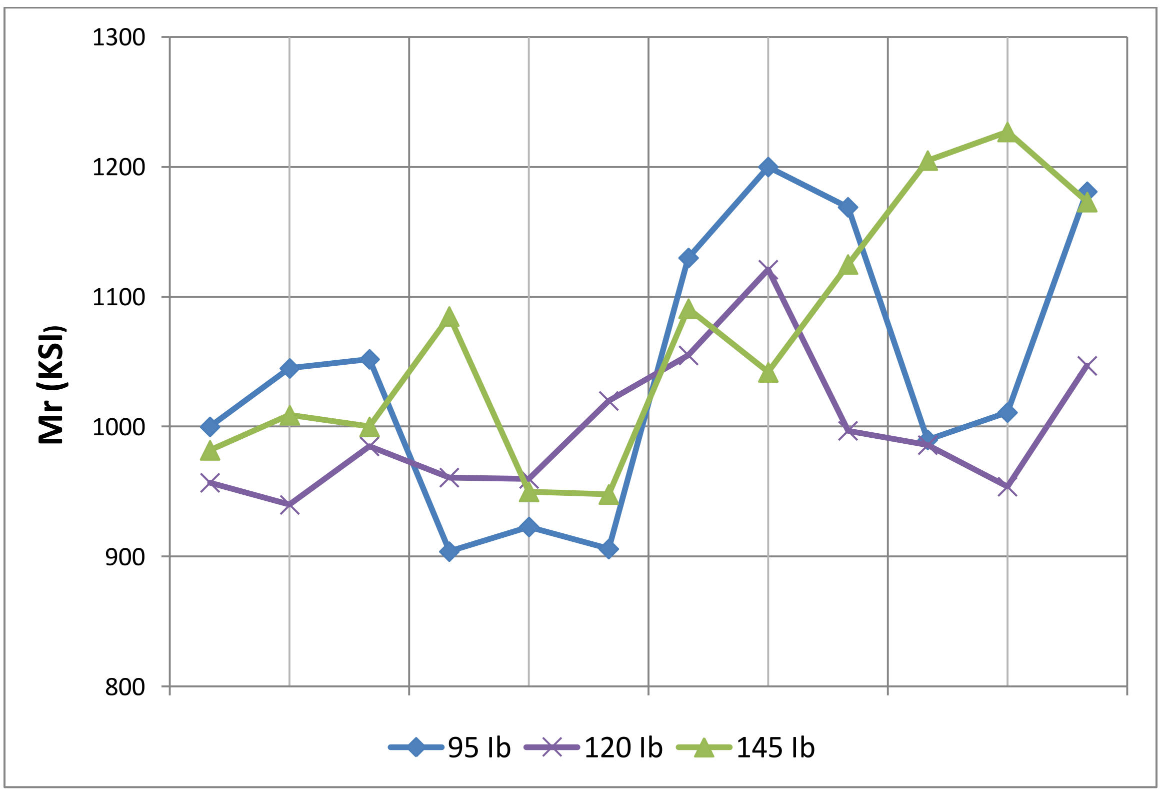

Figure C. 3 Variations of the resilient modulus results of CRM1 asphalt (7%)

Table C. 4 Complete Results of CRM2 Asphalt (10%)

Sample No.	Position No.	Dynamic load (Ib)	Tensile strain (micro-strain)			Resilient modulus (ksi)		
			1	2	3	1	2	3
1	1	95	14	14	15	960	969	978
		120	13	11	13	905	1000	1040
		145	12	12	14	1000	1010	950
	2	95	15	15	13	890	926	962
		120	12	14	12	995	920	1005
		145	11	11	13	1023	1050	1013
2	1	95	16	15	15	890	924	940
		120	16	14	15	900	995	913
		145	13	13	14	1022	967	889
	2	95	16	15	16	860	879	935
		120	14	15	16	910	925	898
		145	12	14	14	1032	955	941

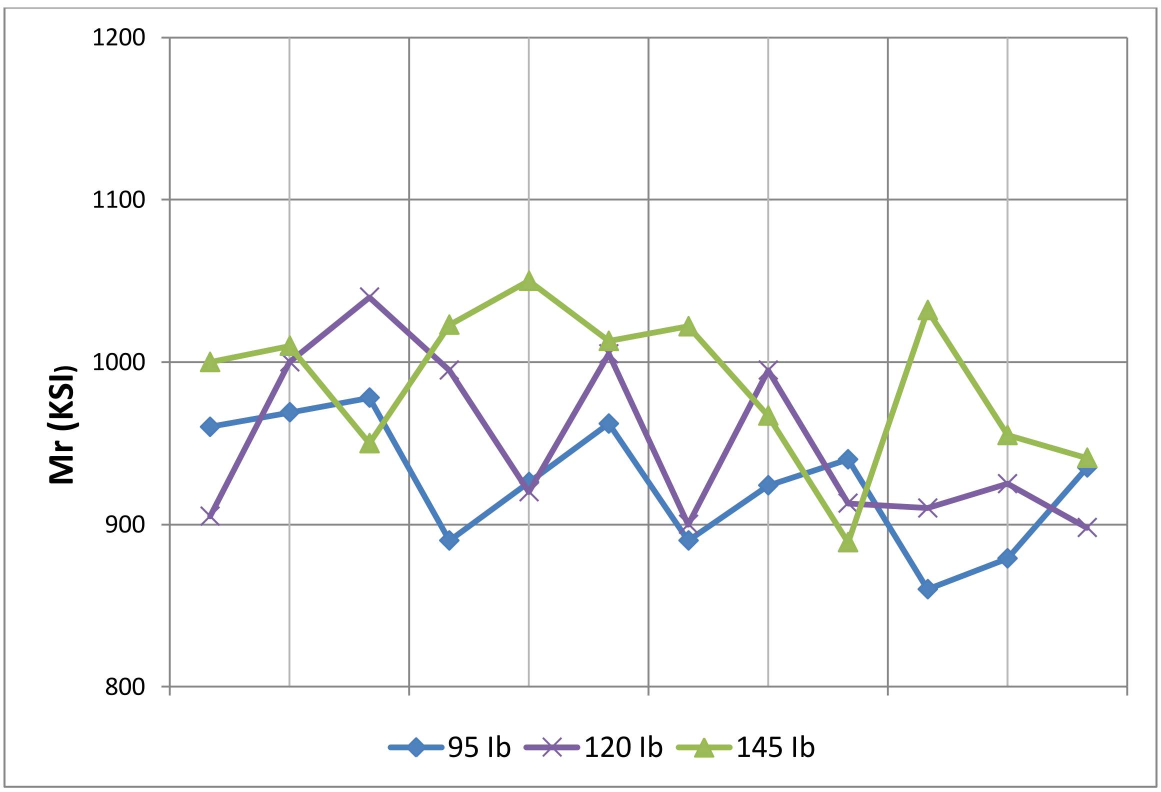

Figure C. 4 Variations of the resilient modulus results of CRM2 asphalt (10%)

Table C. 5 Complete results of CRM2 asphalt (15%)

Sample No.	Position No.	Dynamic load (Ib)	Tensile strain (micro-strain)			Resilient modulus (ksi)		
			1	2	3	1	2	3
1	1	95	13	13	13	978	957	952
		120	16	18	17	963	869	937
		145	22.5	20	21	825	952	885
	2	95	16	15	16	780	833	847
		120	17.50	16	15	740	823	873
		145	16	15	14	862	894	939
2	1	95	15	14	14	800	872	907
		120	21	21	22	733	803	770
		145	21	23	25	927	834	800
	2	95	16	16	16	763	760	765
		120	22	22	22	772	752	760
		145	26	25	26	732	730	723

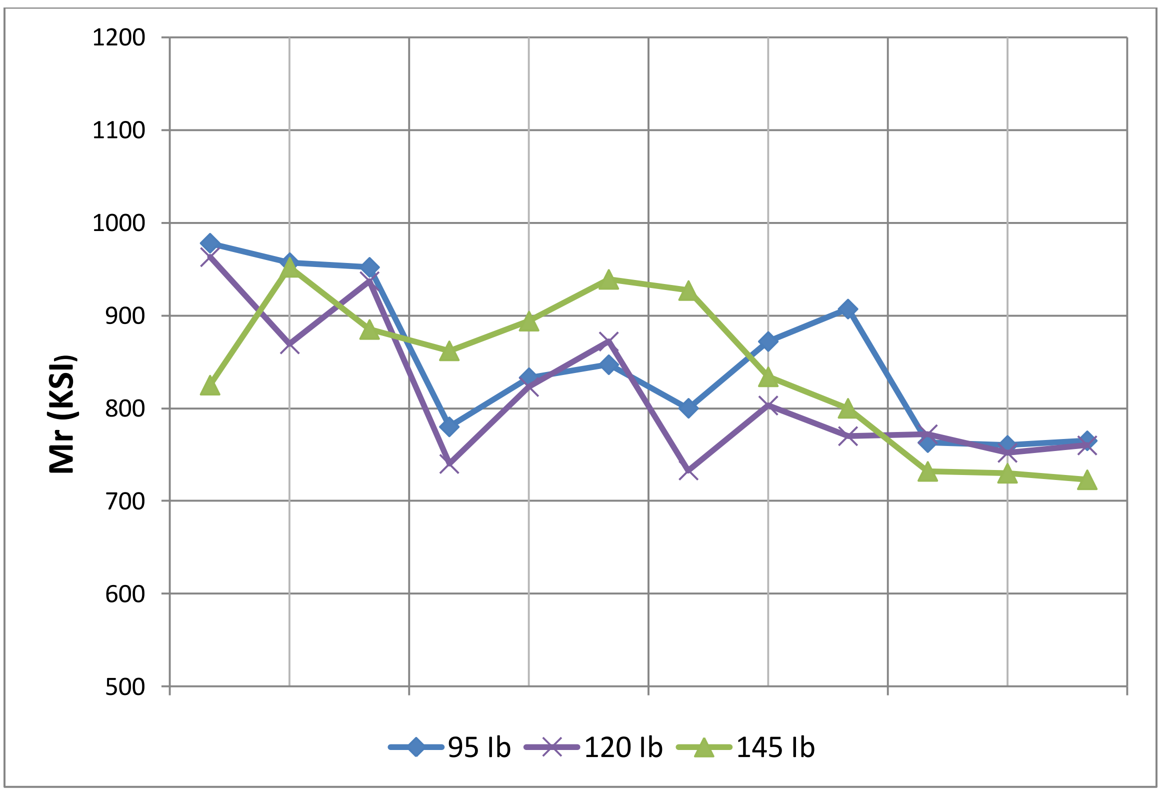

Figure C. 5 Variations of the resilient modulus results of CRM2 asphalt (15%)

Table C. 6 Average Resilient Modulus Values at Dynamic Load of 95 Ib

Binder type	OAC (%)	Resilient Modulus (ksi)	Standard deviation
Control asphalt (0%)	4.20	759	35.36
CRM 1 (3%)	4.80	807	53.45
CRM 1 (7%)	4.80	1043	106.10
CRM 2 (10%)	4.80	926	38.66
CRM 2 (15%)	4.80	851	81.21

Table C. 7 Average Resilient Modulus Values at Dynamic Load of 120 Ib

Binder type	OAC (%)	Resilient Modulus (ksi)	Standard deviation
Control asphalt (0%)	4.20	758	41.18
CRM 1 (3%)	4.80	869	52.03
CRM 1 (7%)	4.80	998	53.40
CRM 2 (10%)	4.80	951	51.69
CRM 2 (15%)	4.80	816	77.74

Table C. 8 Average Resilient Modulus Values at Dynamic Load of 145 Ib

Binder type	OAC (%)	Resilient Modulus (ksi)	Standard deviation
Control asphalt (0%)	4.20	786	45.95
CRM 1 (3%)	4.80	820	68.64
CRM 1 (7%)	4.80	1070	97
CRM 2 (10%)	4.80	988	47.09
CRM 2 (15%)	4.80	842	82.35

VITAE

Name: Mohammed Khalied Al-Turki

Nationality: Saudi

Date of Birth: 24 December 1988

Email: moe_kt@hotmail.com

Telephone number: +966-506824375

Address: Jubail University College, Jubail Industrial City, Saudi Arabia

Academic Career:

Mohammed Al-Turki was born on December 24, 1988 in Saudi Arabia. He obtained his Bachelor's Degree in Civil Engineering from Jubail University College, Saudi Arabia in May 2011. After that, he worked as Teaching Assistant at the same university till September 2012. He joined the Master's Program in the Civil & Environmental Engineering Department at King Fahd University of Petroleum and Minerals (KFUPM) in August 2012.