A STUDY ON THE PHYSICAL AND MECHANICAL PROPERTIES OF ASPHALTIC CONCRETE INCORPORATING CRUMB RUBBER PRODUCED THROUGH DRY PROCESS

by

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To my parents

Sheikh Ali Mohamed Aden and Hawa Haji Hassan

For their love, support, and patience

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LIST OF ABBREVIATIONS

PDRM	Police Diraja Malaysia
AASHTO	American Association of State Highway and Transportation Officials
ACW14	Asphaltic Concrete Wearing Course
CRM	Crumb Rubber Modified Bitumen
SBS	Styrene-Butadiene-Styrene
DAMA	Drain Asphalt Modified Additive
PWD	Public Works Department
GRFT	German Rotating Flask Test
RTFOT	Rolling Thin Film Oven Test
PAV	Pressure Ageing Vessel
USA	United States of America
AAPA	Australian Asphalt Pavement Association
FTIR	Fourier Transform Infrared
LDADC	Lead Dithiocarbamate
HMA	Hot-Mix Asphalts
AAMAS	Asphalt Aggregate Mixture Analysis Systems

LIST OF PUBLICATIONS

JOURNAL

1. M.O. Hamzah, A.A. Mohamed and H. Ismail (2006). Laboratory Investigation of the Properties of a Newly Developed Crumb Rubber Modified Asphalt Mixtures. **Emirates Journal for Engineering Research**, Pp 67-72. Issue2006.
   http://www.engg.uaeu.ac.ae/ejer/issues/V11/iss2_11.htm

CONFERENCES

1. M.O Hamzah, Alk, T.C., A.A. Mohamed, and Kamaruddin, I., (2004). Prestasi konkrit asfalt Campuran Getah dengan bahan mentah**, Proceedings, Third National Conference in Civil Engineering.** Copthorne Orchid, Tanjung Bungah, 20-22 July,

2. A.A Mohamed, and Hamzah, M.O., (2004). Proposed Performance Related Mix Design for Road Pavements. **Malaysian Universities Transportation Research Forum Conference (MUTRFC).** Dec2004, Selangor

3. Meor Othman Hamzah and Abdullahi Ali Mohamed., (2005). Evaluation of Short and Long Term Ageing of Bituminous Mixtures Incorporating a New Bitumen Modifier. The 15th **International Road Federation World Meeting 2005, IRF, Bangkok, Thailand**, June 2005 (paper Bangkok)

4. A.A.Mohamed, M.O.Hamzah and H.Ismail, (2005). Evaluation of Physical Properties of Crumb Rubber Modified (CRABit) Asphalt Mixtures Proceeding of **Brunei International Conference on Engineering and Technology (BICET 2005),**
5. M.O. Hamzah, A.A. Mohamed and H. Ismail, (2005). Over View of Recycled Rubber Tire Powder for use in Asphalt Mixture. **Proceedings of South East Asia Conference on the Advancement of Scientific and Social Research (SEA-CASSR)**, 14-15 Dec Malaysia
6. A.A.Mohamed, M.O.Hamzah and H.Ismail (2006). Evaluation of Crumb Rubber Modified Bitumen through Comparison of Wet and Dry Mix Method. **Proceeding of 1st Civil Engineering Colloquium (CEC'06**). Engineering Campus, USM

KAJIAN CIRI-CIRI FIZIKAL DAN MEKANIKAL TERHADAP KONKRIT ASFALT MENGGABUNGKAN SERBUK GETAH BUANGAN YANG DIHASILKAN MELALUI PROSES KERING

ABSTRAK

Bitumen konvensional digunakan dengan meluas di kebanyakan negara di mana pada peringkat awal semasa kerja-kerja penghasilan, pembancuhan dan penggunaannya adalah agak sukar. Tahap kemampuan bitumen semasa hayat perkhidmatan mempunyai hubungkait yang rapat dengan ciri-ciri bitumen yang digunakan dalam konkrit asfalt. Kelemahan reologi bitumen konvensional ini menyebabkan peningkatan penggunaan pengubah polimer dalam meningkatkan ciri-ciri bitumen konvensional. Matlamat utama kajian ini adalah untuk menghasilkan suatu produk baru dikenali sebagai CRABit (CR30 dan CR50) yang terdiri dari serdak getah dan bahan tambah yang digunakan dalam campuran asfalt tumpat (ACW14). Kajian ini dibahagikan kepada dua fasa. Matlamat fasa pertama adalah untuk mengkaji ciri-ciri reologi produk baru tersebut dengan menggunakan campuran basah. Dalam kajian ini, ciri-ciri reologi tersebut diuji menggunakan reometer ricih dinamik. Dalam fasa kedua, campuran ACW14 mengandungi bitumen asas dan bitumen terubahsuai yang disediakan melalui campuran kering.

Kandungan bitumen campuran ACW14 menentukan cadangan rekabentuk campuran yang diadaptasi dari Kaedah Rekabentuk Leeds (LDM) yang diubahsuai dengan parameter-parameter lain. Ciri-ciri asas seperti modulus keanjalan, tegangan tak langsung, rayapan dan lesu telah diuji. Ciri-ciri ini ditentukan sebelum dan selepas kematangan spesimen untuk tujuan perbandingan. Ketuhar penuaan dengan ultra-ungu telah dibuat untuk penuaan jangka pendek dan jangka panjang bagi campuran bitumen asfalt. Keputusan menunjukkan bahawa penuaan mempengaruhi reologi bitumen dengan peningkatan modulus kompleks dan pengurangan sudut fasa. Sampel yang matang ditentukan oleh kekakuan yang tinggi dan kekenyalan berdasarkan

peningkatan modulus storan, G’. Keputusan juga menunjukkan peningkatan dari segi ciri-ciri kejuruteraan dan prestasi dengan pengubahsuaian. Sebagai contoh, campuran CR30 dan CR50 termampat mempunyai ketumpatan pukal yang rendah berbanding campuran 80/100. Campuran CR30 menunjukkan peningkatan sebanyak 35% dalam nilai Kestabilan Marshall (kekuatan). Nilai kekakuan rayapan campuran CR30 yang dikenakan beban selama 1 jam pada suhu 40°C memberikan nilai yang lebih tinggi dari campuran kawalan. Nilai-nilai modulus keanjalan campuran ubahsuai termampat didapati lebih tinggi dari campuran 80/100, manakala nilai-nilai kekuatan tegangan tak langsung (ITS) pula didapati terlalu tinggi.

Keputusan menunjukkan penuaan jangka panjang memberi kesan yang minimum terhadap campuran terubahsuai. Contohnya, nilai-nilai modulus keanjalan campuran 80/100 menunjukkan peningkatan sebanyak 64% selepas penuaan jangka panjang, manakala campuran terubahsuai menunjukkan peningkatan sebanyak 7% hingga 40%. Keputusan juga menunjukkan campuran 1% CR30 mempunyai hayat lesu yang tinggi berdasarkan analisis kajian perbandingan campuran 80/100. Sebagai kesimpulan, bahan tambah CR30 boleh dianggap sebagai pengubahsuai bitumen yang baik.

A STUDY ON THE PHYSICAL AND MECHANICAL PROPERTIES OF ASPHALTIC CONCRETE INCORPORATING CRUMB RUBBER PRODUCED THROUGH DRY PROCESS

ABSTRACT

Conventional bitumen is widely used in most countries where it hardens at the early stages during handling, mixing and in service. The level of performance of service life has a close relationship with the properties of bitumen used in the asphaltic concrete. This rheological weakness of the conventional bitumen has generated an increasing interest in the use of polymer modifiers to enhance properties of conventional bitumen. The primary aim of this research is to develop a new product called CRABit (CR30 and CR50) that comprises of crumb rubber powder and additives for use in dense asphalt mixtures (ACW14). The study was divided into two phases. The goal of phase one was to test the rheological characteristics of the new product by using wet mix. The rheological properties of bitumen used in this study were tested by dynamic shear rheometer. Phase two, ACW14 mixture containing base and modified bitumen was prepared by dry mix. The bitumen content of ACW14 mixtures were determined a proposed mix design adopted from Leeds Design Method (LDM) with modified with other parameters. Fundamental properties such as, resilient modulus, indirect tensile, creep and fatigue were tested. For comparison, these properties were determined before and after ageing the specimen. A laboratory oven ageing with ultraviolet was fabricated ageing of short and long-term of bitumen asphalt mixtures. Results indicated that ageing influences bitumen rheology, by increasing complex modulus and decreasing phase angle. The aged samples are characterized by higher stiffness and elasticity, due to an increase of the storage modulus, G'. The results indicate an improvement on the engineering properties and the performance with the modification. For instance the compacted CR30, CR50 mix has lower bulk density than that of the 80/100 mix. CR30 mixes results in a 35% times increase in the Marshall Stability (strength) value. The value of creep stiffness of the CR30 mix after 1 hour

loading at 40°C is found to be higher than the control mix. The resilient modulus values of the modified compacted mix were found to be higher than that of the 80/100 mix, whereas the indirect tensile strength (ITS) values were found to be much higher.

The results indicate that the long term ageing has a minimal effect on modified mixtures. For instance, the resilient modulus values of 80/100 mixes has shown an increase of 64% after long term aged, while modified mixes indicated an increase of 7% to 40%. It is also noted from the results that 1%CR30 mixtures had the higher fatigue life based on the analysis of the study comparing to 80/100 mixes. It can be concluded that CR30 additives can be considered as an interesting modifier of the bitumen.

CHAPTER ONE
INTRODUCTION

1.1 Introduction

Countries around the world face challenges to maintain their existing road networks at the time of increasing traffic volume, higher axle loads and increased tire pressure. In Malaysia, most of the major road network is paved with dense graded asphalt. Mustafa and Sufian (1997) reported that bituminous surfacing in Malaysia failed mainly through cracking more critically some of the bituminous surfacing suffer from surface down cracking as early as four years after laying, much earlier than their normal design life of seven to ten years. An earlier study carried out by the Public Works Department (PWD) together with other research institutions concluded that the most common modes of pavement distress are cracking and rutting due to traffic loading and climatic factors such as temperature and moisture. Under the hot tropical sun, oxidative ageing of asphalt layers leads to the phenomenon of surface down crocodile cracking (Mustafa and Sufian, 1997). In 1987 and 2004, the Malaysian vehicle population was 3.6 and 13.9 million, respectively. Hence, over a period of 18 years the number of registered vehicles has more than doubled (PDRM, 2004). Figure 1.1 clearly depicts an increasing vehicle population, and this trend comes at the time when Malaysia gears toward an industry-based economy. The increase in the number of vehicles proportionally increases the percentage of scrap tires in the form of solid waste (Ahmed and Klundert, 1994). In addition funds allocated for road construction and upgrading have been increasing with each five-year development plan as shown in Figure 1.2.

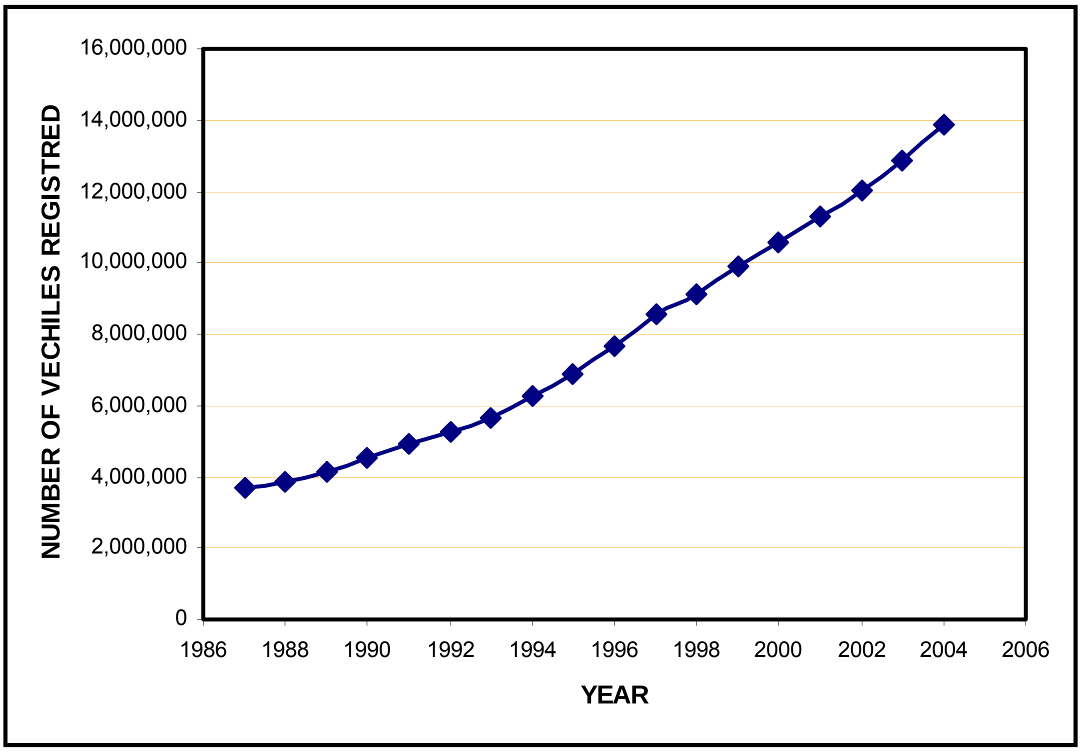

Figure 1.1: Trend in Motor Vehicle Registration
(Source: PDRM, 2004)

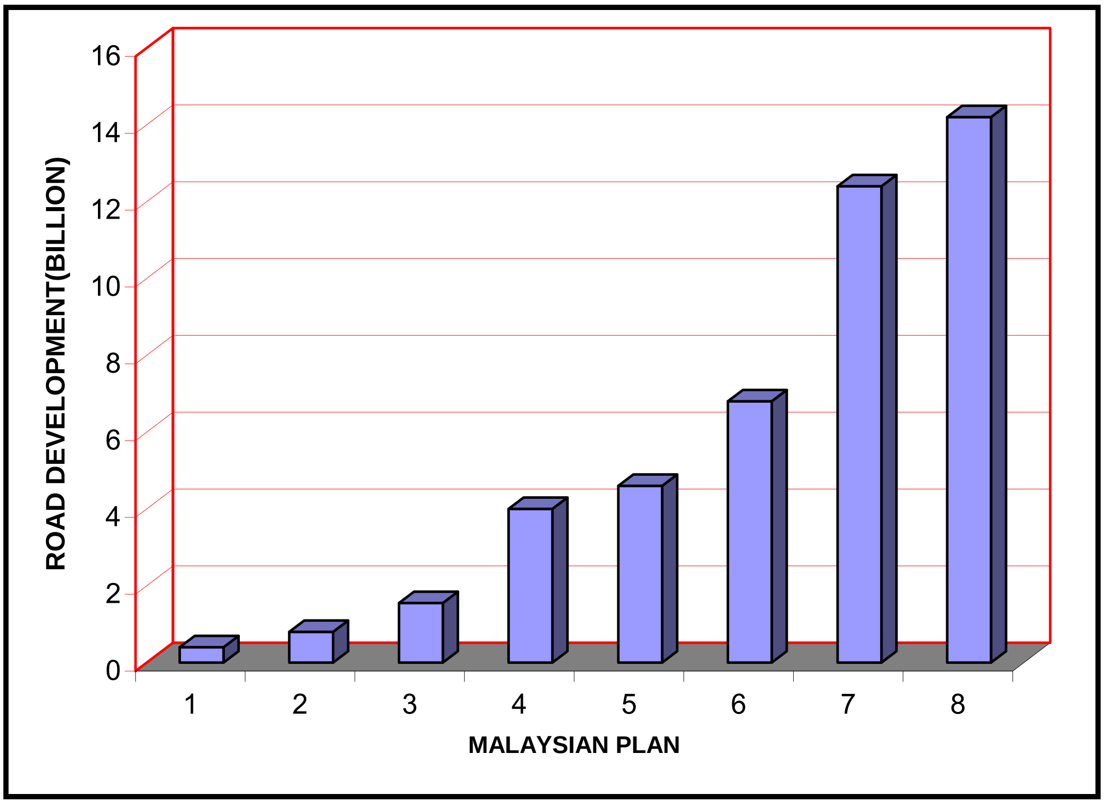

Figure 1.2: Road Development Allocation According to the Malaysian Plan
(Source: Razali, 2002)

1.2 Ageing Phenomenon of Bitumen and Asphaltic Concrete

The durability of asphaltic concrete is greatly influenced by the environmental changes during the year between hot and cold temperatures and between day and night. High temperatures can soften the bitumen and consequently reduce the stiffness of asphaltic concrete making the mix more susceptible to rutting. On the other hand, low temperature can increase the stiffness of bitumen and reduce the flexibility of the asphaltic concrete, hence, inducing fatigue failure. As a result, cracking of the pavement surface may develop which adversely affects the performance of the asphaltic concrete. Thus, high temperature stiffness and low temperature flexibility are important properties in bituminous mixtures respectively to avert rutting and cracking (Roberts *et al*., 1990).

Studies have been carried out for the last seven decades to better understand the factors that contribute to short and long term ageing. Hardening is primarily associated with loss of volatile components in bitumen during the mixing and construction phase and progressive oxidation of the in-placed material in field. The former is described as short term ageing while the latter is referred to as long term ageing. Both short and long term ageing cause an increase in viscosity of the bitumen and a consequent stiffening of the mixture. This may cause the mixture to become brittle and susceptible to disintegration and cracking (Roberts *et al*., 1990).

1.3 Background of the Study

Conventional bitumen is widely used in most countries where it hardens at the early stages during handling, mixing and in service. The level of performance of service life has a close relationship with the properties of bitumen used in the asphaltic concrete. This rheological weakness of the conventional bitumen has generated an increasing interest in the use of polymer modifiers to enhance the properties of conventional bitumen. Various elastomer and plastomer modifiers have been sought to address this problem. Modifiers vary in function and effectiveness, and development of modified bituminous material to improve the overall performance of pavements has been the focus of research for the past few decades. Use of discarded tires of vehicles in pavement construction was one of the steps taken in this direction. Disposal of waste tires is a serious environmental concern in many countries. Hence, usage of crumb rubber modified bitumen has the added environmental benefit of recycling scrap tires that would otherwise be stockpiled or land filled.

The problems addressed in this study were two fold. The first was based on the literature search in which it was found that, earlier studies were limited to studying the ageing process without improving the ageing resistance except only a few researchers (Martin, 1968; Haxo and White, 1979; Filippis, 1995; Oliver, 1995 and Ouyang *et al.*, 2005) who tried antioxidant compounds to improve the ageing resistance of bitumen. The second was the relative merits of the wet versus the dry methods are still being researched despite the fact that modified bitumen produced through either the wet or the dry process has demonstrated better properties compared to unmodified bitumen. Crumb rubber (CRM) modifier can be added to bituminous mixtures using both wet and dry processes, each leading to different properties. In the wet process, rubber and bitumen are mixed together at high temperatures. By contrast, in the dry process crumb rubber is added to the mineral aggregate before mixing with bitumen. In this case, the interaction of crumb rubber with the binder is considered relatively less and it can only be indirectly appreciated through the behaviour of the mixtures obtained.

Nevertheless, compared to the wet process the dry process has been a far less popular method for CRM asphalt production. This is due to problems regarding the compatibility of mixtures. However, according to Celauro *et al.,* (2004), the dry process is easier to run, while the wet process is more complicated but has the advantage of making it possible to exhibit quickly the rheological properties of the crumb rubber binder obtained. In this study, evaluation of mechanical properties was used to characterize the short and long term ageing of bitumen and bituminous mixtures containing crumb rubber modified with zinc dithiocarbamate. The bituminous mixtures were prepared through the dry process. Zinc dithiocarbamate was mainly used for their antioxidant properties and is commonly used as an efficient accelerator in manufacturing of rubber products. On the other hand, it can be used as a stabilizer in butyl rubber, and as an antioxidant to produce rubber-based adhesive. Attention was given to the important properties that primarily influence the performance of modified binders and mixes. The choice of crumb rubber was influenced by the fact that it had been claimed to perform better when added to the bitumen as a modifier (Isacsson and Lu 1999).

The Superpave procedures for bitumen testing have provided a beneficial framework for evaluating binders. However, Superpave standards are still relatively new and may yet be improved in some areas (Hoare and Hesp, 2000). A particular concern is the long-term ageing test, which takes place at pressures and temperatures well above road-ageing conditions. These temperature and pressure differences affect the mechanism of oxidation of the binder, which leads to physical properties that may be different from those obtained at road ageing conditions (Daniel *et al.*,1999).

AASHTO R30-02 (AASHTO, 2002) requires mixtures to be conditioned at 135^{o}C for 4 hours prior to compaction, for short-term ageing, and for long term ageing, at 85^{o}C for 120 hours in an oven. The conditioning procedure was designed to simulate the ageing that the compacted asphalt pavement undergoes during its 5-10 years of service life (Kandhal and Chakraborty, 1996). An alternative laboratory ageing oven with ultraviolet source was fabricated to evaluate short and long term ageing of bitumen and asphalt mixtures. The mixtures were evaluated by means of testing fundamental properties such as resilient modulus, indirect tensile, creep and fatigue. These properties were determined both, before and after ageing the specimen, for comparison.

1.4 Objectives

The primary aim of this research is to develop two new products called CR30 and CR50 that comprises of crumb rubber powder and additives for use in dense asphalt mixtures type ACW14 as specified in SPJ88 (JKR,1988). Both are collectively referred to as CRABit. The detailed objectives to attain this general aim can be outlined below:

1. To develop a new product known as CRABit (CR30 and CR50) which is a combination of crumb rubber powder and additives that would be used to facilitate mixing of aggregates and binder via dry process.
2. To study the rheological properties of CRABit (CR30 and CR50) modified binders mainly using the dynamic shear rheometer (DSR).
3. To establish the optimum binder content of ACW14 mixtures that incorporated CR30 and CR50 blended through the dry process.
4. To evaluate the effect of short and long term ageing of CR30 and CR50 modified mixtures and study the fundamental characteristics of the mixtures.

1.5 Scope of the Work

The scopes of the study focus mainly on the development of CRABit for improving bituminous mixes through dry process. The main compositions of CRABit include crumb rubber, antioxidant and accelerator formulated to improve bonding strength. Another two types of polymer-modified bitumen utilized for comparison are Drain Asphalt Modified Additive (DAMA) and on established modified bitumen SBS. DAMA is an additive, which was developed in Korea. The mix type used was ACW14 as specified as specified in SPJ88 (JKR, 1988).

1.6 Organization of the Thesis

The organization of this thesis is presented in the following manner:

1. Chapter one highlights the overview of the thesis, including background of the study and its objectives.
2. Chapter two presents a review of literature pertaining to investigations on the topics of bitumen additives and performance of modified bituminous mixtures. A brief review of test methods such as resilient modulus, creep, and indirect tensile and fatigue tests is also presented.
3. Chapter three describes the properties of aggregates, binders, fillers and modified bitumen and the experimental design used for this study
4. Chapter four presents results of rheological properties of a binder with a discussion on the data.
5. Chapter five presents the results of mix design with a discussion on the data.
6. Chapter six presents the results of short-term and long-term ageing of bituminous mixtures.
7. Chapter seven includes presentation of results of creep test carried out in this study.
8. Chapter eight includes presentation of results of fatigue carried out in this study.
9. Chapter nine explains the conclusions and the recommendations for future work.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Conventional bituminous materials performed their function satisfactorily in most of the pavements. However, existing highway systems have been dealing with increased traffic volume, higher axle load and tire pressure and extreme environmental impacts (Airey, 2002). The situation is evident for the last three decades, that the pavement has been facing more demands than before resulting in the need for an enhancement in the properties of bituminous materials. This chapter presents a brief review of literature on the topics related to bitumen additives, modified bituminous mixtures and mechanical characteristics of bitumen and mixtures.

This chapter also reviews the research results dedicated to understanding the phenomenon of ageing and its relationship with rheological properties of bitumen and bitumen-aggregate mixtures. This would lead to a better knowledge on behaviour of bitumen when subjected to different thermal and mechanical conditions, both during construction and while in service. This phenomenon is depicted through the ageing index of bitumen and its chemical composition, as shown in Figure 2.1. The ageing index is defined as the ratio of the viscosity of recovered bitumen to the viscosity of original bitumen at 25°C. The variation in viscosity of the binders is small with respect to time, as is evident from Figure 2.1. When the asphaltene content increases, a gradual increase in viscosity is observed, although, only a slight change is observed in the saturates content (Read and Whiteoak, 2003).

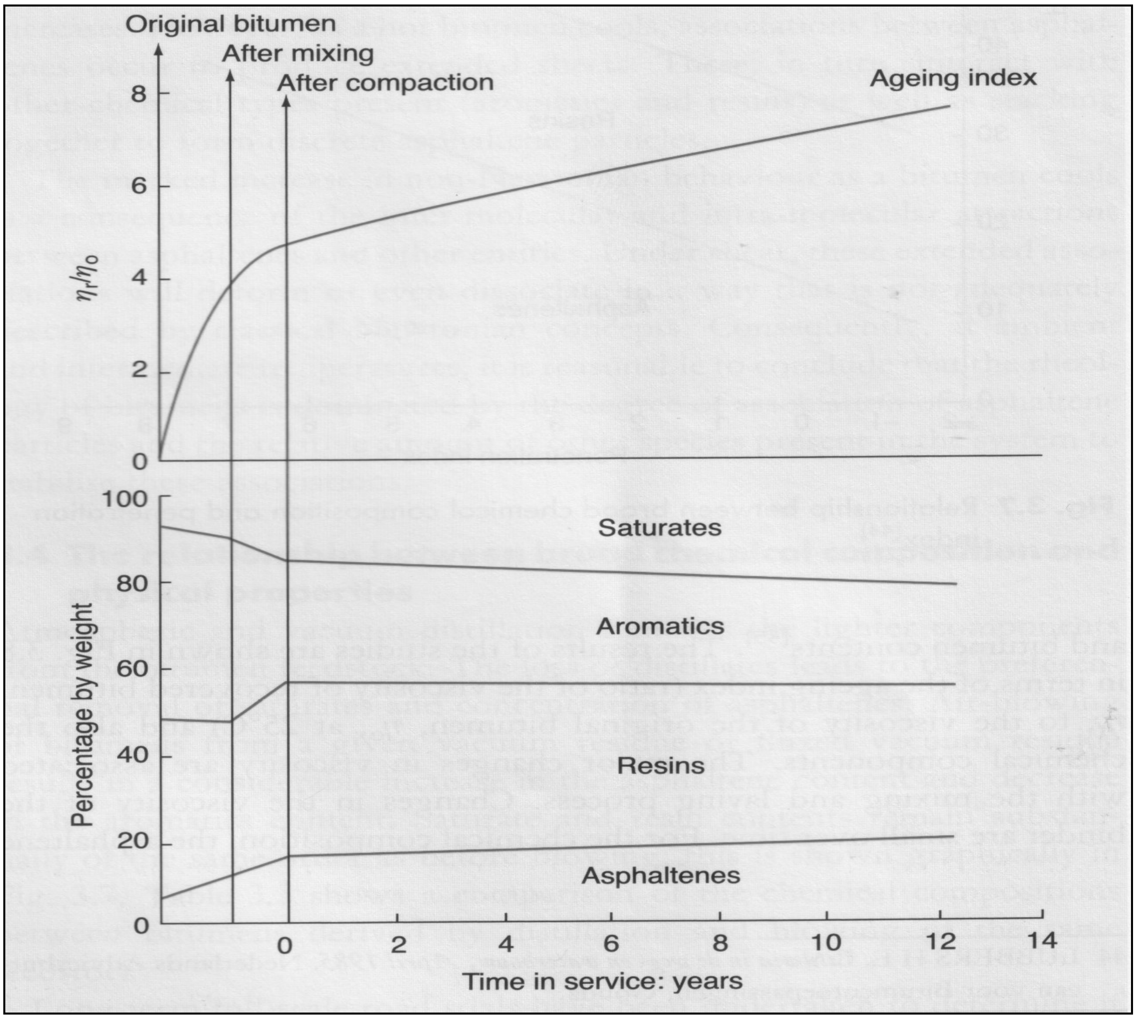

Figure 2.1: Changes of Bitumen Composition during Mixing, Laying and in Service (Source: Read and Whiteoak, 2003)

2.2 Historical Background of Binder Modification

Modification of bitumen is not a new phenomenon. As early as 1923, natural and synthetic polymer modifications of bitumen have been patented (Isacsson, and Lu, 1997; and Yildrim, 2005). During the 1930s, test projects were constructed in Europe (Yildrim, 2005). In the mid-1980s, the Europeans began developing newer polymers for use in bitumen modification, which were later used by the USA (Brule, 1996). During the same period, Australia also started using polymers in bituminous mixtures, which is evident from the current National Asphalt Specifications (AAPA, 2004). The idea of bitumen modification is also gaining acceptance in many developing countries, like

China, India, and Malaysia. Beside others, Mustafa and Sufian (1997) suggested the use of rubberized bitumen in road construction in Malaysia.

2.3 Modification of Bitumen by the Addition of Additives

Bitumen additive can be defined as a material added to the bitumen to improve the properties and performance of bitumen. An ideal additive should be able to decrease the temperature susceptibility, control age hardening and must be compatible with any type of bitumen (Yildirim, 2005). Numerous researchers are working in this area to evolve the most suitable additive that can improve overall performance of bitumen (Isacsson, and Lu 1999; Airey, 2002). Many investigations have been carried out using two main evaluation methods, firstly, testing bitumen either with or without additives, to determine its chemical, rheological, elastic and thermal properties as well as its sensitivity to heat and oxidation. Secondly, testing bituminous mix to determine its stability, water susceptibility, stiffness, tensile strength, fatigue resistance and creep resistance. A survey in 1997, conducted by Department of Transportation, USA, found that out of 50 states, forty seven states claimed to use modified binders in future. While, 35 Departments of Transport claimed that they would use modified binders in greater amount (Bahia *et al*., 1997). The same phenomenon happened in Austria in the mid 1990s, where the consumption of modified bitumen had reached up to 10% of total bitumen used in road construction (Lenk *et al*., 2004). An internal report of the Asphalt Institute identified 48 types of bitumen modifiers comprising of 13 polymers, 10 hydrocarbons, 6 mineral fillers, 6 antioxidants, 6 anti-stripping additives, 4 fibers, 2 extenders, and 1 oxidant (Bahia *et al*., 1997).

2.3.1 Crumb Rubber

Research on crumb rubber has been going on over the last three decades (Hossain *et al*., 1999). Crumb rubber is the recycled rubber obtained by mechanical shearing or grinding of scrap tires into small particles. There are two methods of blending reclaimed rubber with bitumen. A commonly used method is the wet process, in which reclaimed tire rubber powder of 10% to 30% by total weight is blended with bitumen at elevated temperature (Caltrans, 2003). The other method is referred to as the dry method, in which reclaimed tire rubber powder is added to the hot aggregate in quantities of 1% to 5% (Airey *et al.,* 2004). The characteristics of crumb rubber depend on the rubber type, asphalt composition, size of rubber crumbs as well as time and temperature of reaction. These factors have considerable effect on pavement performance (Abdelrahman and Carpenter, 1999; Raad *et al*., 2001; Kim *et al*., 2001).

The effects of rubber concentration on the properties of bitumen were studied by many researchers (Bahia and Davies, 1994; King *et al*., 1993; Mahrez and Rehan, 2003). Mahrez and Rehan (2003) carried out experiments to study the effects of three different rubber concentrations (3%, 9%, and 15%). According to this study, after rolling thin film oven test (RTFOT), the unmodified bitumen showed an improvement of about 1.5 times in G* value, and in the case of rubberized bitumen, the samples with 3% and 9% rubber showed an increase of about 2.5 times and the sample with 15% of rubber showed an increase of about 1.5 times compared to their original unaged values. After pressure ageing vessel (PAV) test, the G* of unmodified bitumen increased by about 2 times its unaged values and by about 2 to 3 times in case of rubberized bitumen. McGennis, (1995), on the basis of his experiments both in laboratory and field, claimed that bitumen containing fine meshed rubber is very viscous. Both the wet and dry methods were used and the results were reported to be satisfactory. However, care must be exercised when designing crumb rubber mix, because crumb rubber takes time to disperse in bitumen. Zanzotto and Kennepohl (1996) discussed devulcanization and depolymerization of rubber in the presence of bitumen and application of temperature and shear, while, Billiter *et al*., (1997) found that extending the blending time from 1 hr and increasing the blending temperature from 177°C and above significantly reduced the high-temperature viscosity. Another research on concentration of rubber below 12% showed that the binder viscosity declines with time and stabilizes approximately between 45 and 60 minutes of mixing as shown in Figure 2.2 (Lougheed and Papagiannakis, 1996). However, for a binder made of 18% crumb rubber, the viscosity initially declines but increases after approximately 45 minutes, as shown in Figure 2.3.

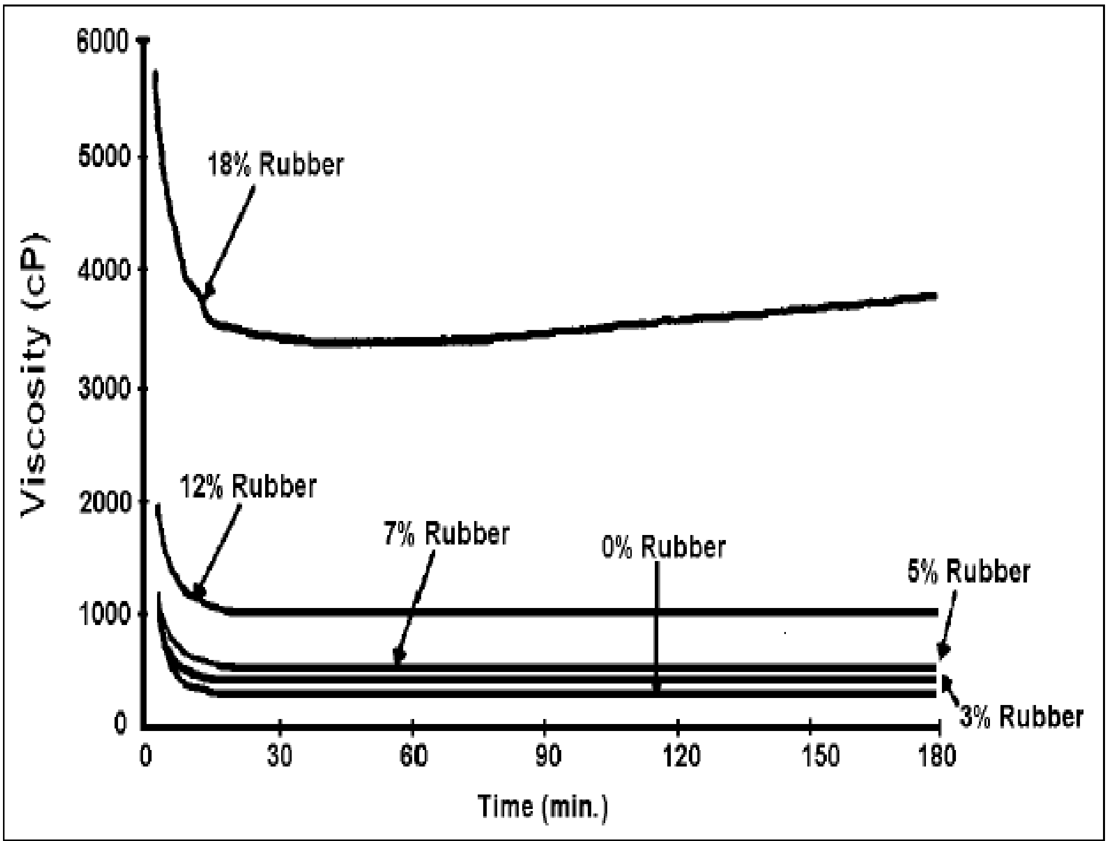

Figure 2.2 Viscosity and Mixing (interaction) time for Various CRMs
(Source: Lougheed and Papagiannakis, 1996)

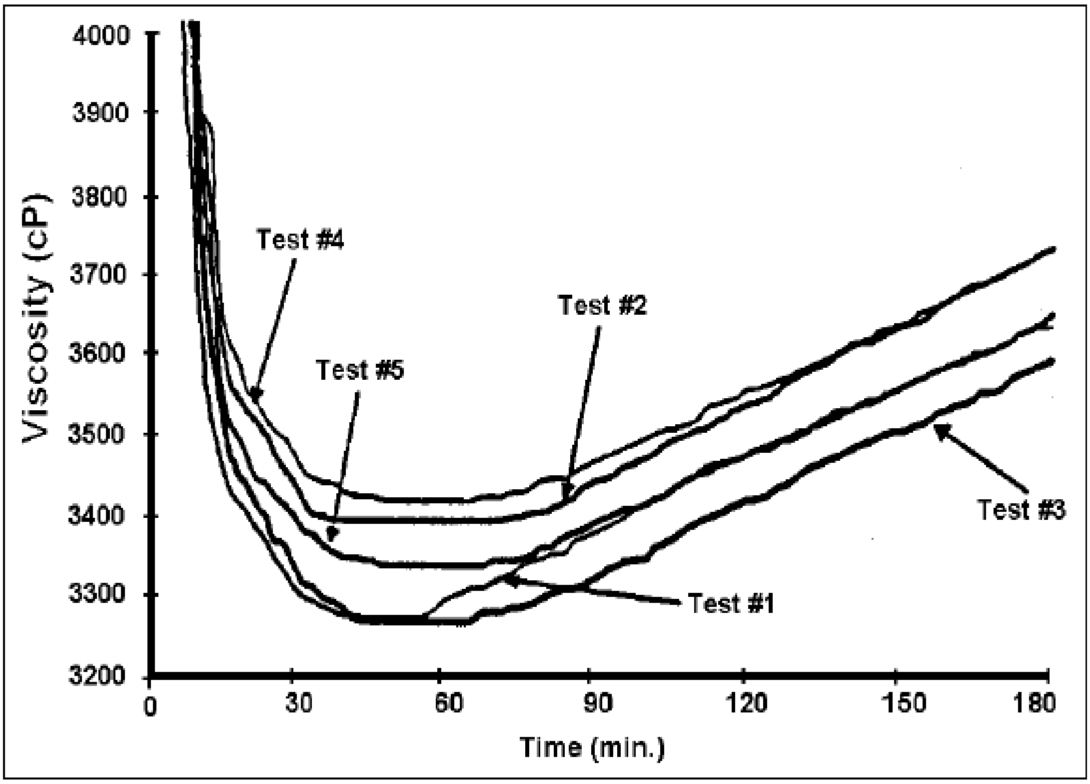

Figure 2.3: Viscosity and time Measurement for 18% CRM binder
(Source: Lougheed and Papagiannakis, 1996)

According to Oliver (1982), the elastic recovery increases with a decrease in crumb rubber particle size. A reduction in size from 1.18 mm to 0.300 mm produced more than 50% increase in elastic recovery at 0.5 hour digestion time. Similarly, an investigation to observe the effect of crumb rubber particle size on the stability of asphaltic concrete was performed by Khedeywi *et al*., (1993). Four different concentrations and three different crumb rubber particle sizes were used. It was concluded that stability of asphaltic concrete mixtures decreases as the crumb rubber concentration in bitumen of 20% and particle size of 0.300mm to 0.075 decreases. Palit *et al., (*2004) conducted a study to determine the effect of crumb rubber of 0.6 mm particle size on the performance of crumb-rubber-modified asphalt mixes. According to the study, crumb-rubber-modified mixes not only have improved fatigue and permanent deformation characteristics but also have a potential, as shown in Figure 2.4. There is a 100% increase in fatigue life, as observed from laboratory fatigue test results. While modified mixes displayed slower buildup of irrecoverable deformation compared to other mixes. The rate of permanent deformation found to be the slowest in the case of mixes containing 30CR10 binder having superpave aggregate gradation as shown in Figure 2.5. Troy *et al*., (1996) conducted a research on crumb rubber pavements using Hveem mix design method and concluded that the Hveem compaction is inadequate for mixtures containing crumb rubber binders.

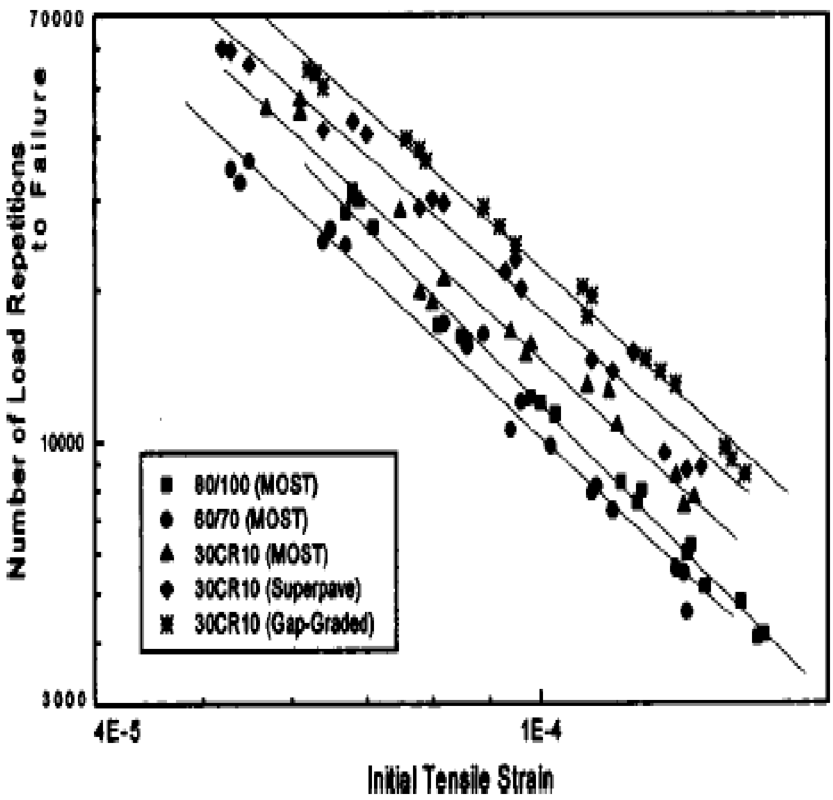

Figure 2.4: Variation of Fatigue life with Initial Tensile Strain for Different Mixes
(Source: Palit *et al*., 2004)

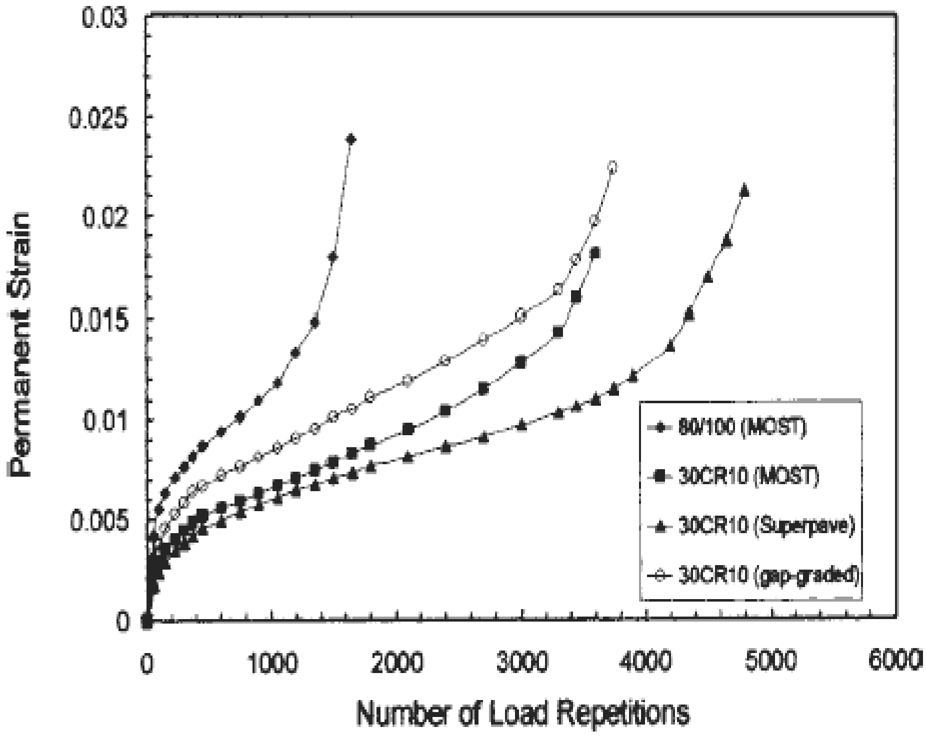

Figure 2.5: Variation of Accumulated Permanent Strain with Number of Load Repetitions (Source: Palit *et al*., 2004)

2.3.2 Styrene - Butadiene - Styrene

Styrene–butadiene styrene (SBS) is one of the most commonly used asphalt modifiers for paving applications (Airey, 2003). SBS is a block copolymer that increases the elasticity of bitumen. Many researchers (Collins *et al*., 1991; Isacsson and Lu, 1995 and Diehl, 2000) mentioned the benefits of SBS at low temperatures. At low temperature, the flexibility is increased, which helps in better resistance to fatigue and cracking. Thermoplastic elastomers derive their strength and elasticity from physical cross linking of the molecules into a three dimensional networks as shown in Figure 2.6.

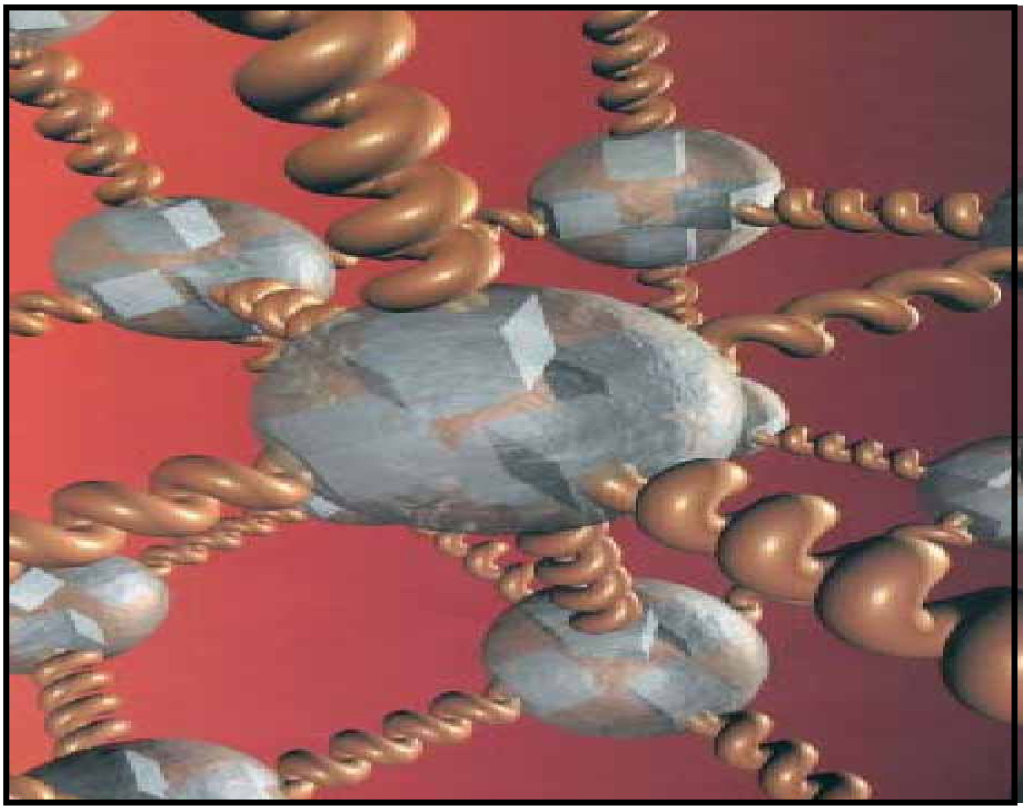

Figure: 2.6: Schematic Structure of Thermoplastic Elastomers at Ambient Temperature (Source: Read and Whiteoak, 2003)

The behavior of SBS modified bitumen at elevated temperatures and their ability to provide a continuous network are the reasons for their suitability and demand as bitumen modifiers (Read and Whiteoak, 2003). Isacsson and Lu, (1995) reported that SBS improves resistance to flow at high temperature without making the binder extra stiff at low temperature. Chen *et al*., (2002), studied the morphology and engineering properties of SBS binders using transmission electron microscopy, rotational viscometer, and dynamic shear rheometer. The morphology of polymer-modified bitumen was described by the SBS concentration and the presence of microstructure of the copolymer. When the SBS concentration increases, the copolymer gradually becomes the dominant phase, and the transition is followed by a change in complex modulus of SBS-modified asphalt as shown in Figure 2.7.

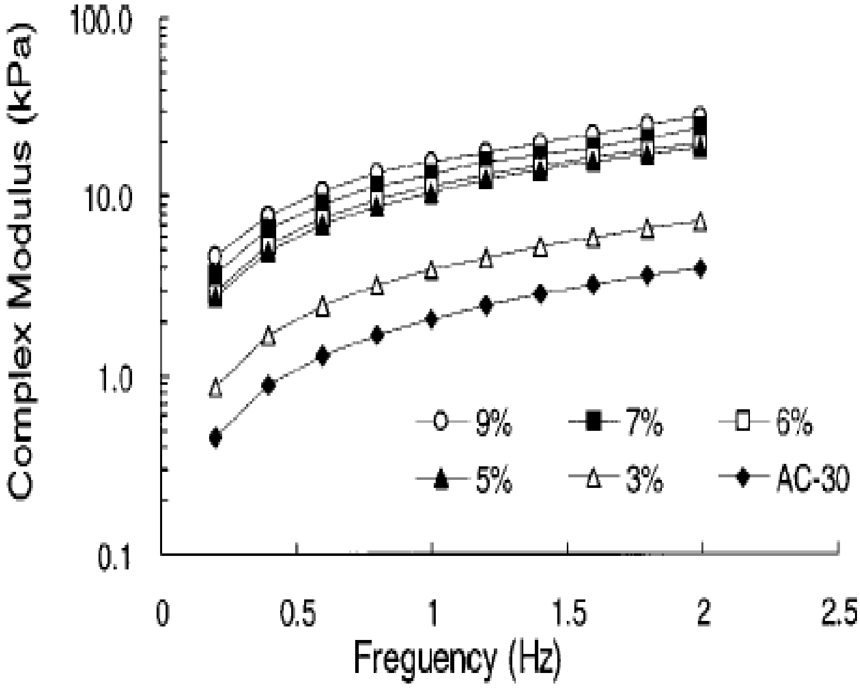

Figure 2.7 Complex Modulus of Styrene-Butadiene-Styrene-Modified Bitumen At 60°C (Source: Chen, et al., 2002)

The effects on ageing on polymer-modified bitumen have been previously studied using both the rolling and thin film oven test (RTFOT). Gahvari (1997) found that after RTFOT aged of SBS, an increasing complex modulus when compared with the un-aged SBS binders, indicating the degradation of polymer with oxidation. Cortizo *et al*., (2004) studied SBS-modified bitumen under different ageing conditions. The results of both the normalized test and the rotational viscosities test showed the effect of degradation. However, Ouyang *et al*., (2005) evaluated the ageing properties of base and SBS-modified bitumen using Fourier Transform Infrared (FTIR) spectroscopy. They found that an increase in the values of viscosity and softening point and decrease in the penetration and ductility in both bitumen.

2.3.3 Zinc Antioxidant

Zinc dithiocarbamate, besides being used as antioxidant, is also used as an efficient accelerator in manufacturing of rubber products. It can be used as stabilizer in butyl rubber, and as antioxidant to produce rubber-based adhesive. The addition of antioxidants to bitumen has been shown to be effective in retarding the rate of bitumen hardening (Oliver, 1995).

Martin, (1968) studied 33 antioxidants belonging to four major classifications and identified a better chemical classification known as peroxide decomposers. Martin, (1971) also examined the effect of 12 selected antioxidants on oxidative hardening in eight asphalt cement samples. Asphalt cement films were exposed in air at 300 psi (2070 kPa) pressure and to solar radiation. The changes in the asphalt cement were determined by sliding plate viscometer. Researchers studied the effect of lead and zinc antioxidants on bitumen hardening. LDADC (Lead dithiocarbamate) was found to be effective in reducing the rate of hardening (Haxo and White, 1979).

2.4 Descriptions of Surface Distress Mechanisms

There are many reports that provide mechanisms of distress of different Hot-Mix Asphalts (HMA). According to Robert *et al.*, (1996) distress is the condition of the pavement structure that reduces serviceability. Distress manifestations are the visible consequences of various distress mechanisms, which usually lead to the reduction of the serviceability. Distresses are expected to occur due to environmental effects and repeated traffic loads. There may be numerous causes of surface distresses. Therefore, it is important to properly ascertain the main cause before any action. Brown *et al.*, (2001) identified distress models that included both load-associated cracking and non-load associated cracking. Some of these distresses are distortion, shoving, rutting, slippage, disintegration, and skid. A brief description of the failure mechanism of each distress is provided below. HMA is subjected to a variety of distresses like other paving materials.

2.4.1 Permanent Deformation

Permanent deformation results from the accumulation of small amount of unrecoverable strain as a result of repeated loads applied to the pavement. Rutting can occur as a result of problematic subgrade, unbound base course, or HMA. Brown *et al.,* (2001) reported that permanent deformation in HMA is caused by consolidation and or lateral movement of the HMA under traffic. Shear failure (lateral movement) of the HMA courses generally occurs in the top 100 mm of the pavement surface. However, it can run deeper if proper materials are not used. Eisenmann and Hilmer (1987) also found that rutting is caused mainly by deformation flow rather than volume change. Sousa (1994) claimed that after the initial densification, the permanent deformation of the bituminous mixture occurs due to shear loads which occur close to the surface of the pavement, in the area that confines the contact area between the tire and the pavement. These efforts increase without the occurrence of volume variations in the bituminous mixture and they are the main mechanisms of rutting development during the design life period of the pavement. Investigations have been carried out on incorporating polymer modified bitumen to improve the performance of bituminous composites (Zoorob and Suparma, 2000). This included bitumen modification using SBS or EVA or SBR (natural and ground tire rubber) in various concentrations. Most of the results obtained from laboratory and full-scale trials demonstrate varying improvement in the performance of these modified bituminous mixes in terms of increased resistance to permanent deformation.

An experimental program consisting of resilient modulus and creep-rebound testing was conducted to determine the effects of maximum aggregate size on the stiffness and resistance to permanent deformation of bituminous concrete mixtures (Newtson and Turner, 1993). Three aggregates (two pit-run alluvial deposits and one crushed limestone) of three top sizes (19.1 mm, 25.4 mm, and 31.8 mm) were investigated. Stiffness and resistance to permanent deformation were found to decrease with increasing maximum size when alluvial aggregates were used, but was found to increase when crushed limestone was used.

2.4.2 Fatigue Cracking

Fatigue cracking of flexible pavements is thought to be caused by the horizontal tensile strain at the bottom of the HMA layer. The failure criterion relates the allowable number of load repetitions and the tensile strain. The cracking initiates at the bottom of the HMA where the tensile strain is highest under the wheel load. The cracks propagate initially as one or more longitudinal parallel cracks. After repeated heavy traffic loading, the cracks become interconnected in a manner that resembles the skin of an alligator. Laboratory fatigue tests are performed on small HMA beam specimens. Due to the difference in geometry and loading conditions; especially rest period between the laboratory and the field, the allowable number of repetitions for actual pavements is greater than that obtained from laboratory tests. Therefore, the failure criterion may require incorporating a shift factor to account for the difference.

Fatigue cracking is generally considered to be more of a structural problem than just a material problem. It is usually caused by a number of pavement factors that have to occur simultaneously. Obviously, repeated heavy loads must be present. Poor subgrade drainage, resulting in a soft, high deflection pavement, is the principal cause of fatigue cracking. Improperly designed and / or poorly constructed pavement layers also contribute to fatigue cracking. It has been reported that fatigue cracks initiate from the bottom and migrate toward the surface (McGennis, 1994: Mustafa and Sufian, 1997). These cracks occur because of the high tensile strain at the bottom of the HMA. However, Brown *et al.*, (2001) observed fatigue cracks to start at the surface and migrate downwards. The surface cracking starts due to tensile strains in the surface of the HMA. Generally, it is believed that for thin pavements the fatigue cracking typically starts at the bottom of the HMA while, for thick pavements it starts at the HMA surface. Typically, fatigue cracking is not caused by the lack of control of HMA properties; however, these properties would certainly have a secondary effect (Brown *et al.,* 2001).

2.5 Durability and Rheological Properties of Bitumen

The life of a road surface material is affected by environmental factors such as temperature, air and water. The main components of road surface material mixture are coarse and fine aggregate, mineral filler and a relatively small amount of bitumen. This small amount of bitumen has a significant impact on the material performance. Bitumen, in common, is affected by the presence of oxygen, ultraviolet radiation, and temperature. These external factors cause it to harden and affect the durability (Roberts *at al*., 1990).

Anderson *et al.*, (1994) reported that empirical property tests such as penetration, ductility and ring and ball temperature cannot provide accurate measures of the changes in property due to ageing. In fact, for the last two decades bitumen ageing has been explained by the rheological parameters expressed by complex modulus (G*) and phase angle (δ) as a function of frequency and temperature or both.

2.6 Determination of the Stiffness Modulus of Bitumen

The most unique behavior of bituminous materials is the dependence on their mechanical response on time of loading and temperature. In order to predict the engineering performance of a material, it is necessary to understand its stress–strain behavior. Deshpande and Cebon (2000) mentioned that some researchers (Nijboer, 1948; Goetz and Chen, 1950) attempted to modify bitumen using soil. These approaches assumed rate-independent plastic behavior for the mixes. However, in the 1950s a viscoelastic description of the behavior of bitumen became popular. The most common approach was that by van der Poel (1954) who introduced the use of ‘‘stiffness’’ to describe the mechanical behavior of pure bitumen as a function of temperature and loading time. Van der Poel (1955) also extended the stiffness concept to experimentally map the dynamic behavior of various bituminous mixes for small strains where the linear behavior is dominant. Van der Poel (1955) assumed that the stiffness of the mix is a function only of the stiffness of the bitumen and the volume fraction of the aggregate. Subsequently, Heukelom and Herrin (1964) proposed the following relationship for predicting the stiffness of bituminous mixtures.

$$\frac{Smix}{Sbit} = \left[1 + \frac{2.5}{P}\frac{Cv}{(1 - Cv)}\right]^{p} \qquad (2.1)$$

Where S_{mix} = stiffness of the mix

S_{bit} = stiffness of bitumen,

Cv = volume concentration of the aggregate defined by,

$$Cv = \frac{Volume\ of\ Aggregates}{Volume\ of\ (aggregates + bitumen)} \qquad (2.2)$$

The above equations were derived from empirical fits to data from static and dynamic tests on well-compacted mixes having about 3% air voids and *Cv* values ranging from 0.7 to 0.9. Recently, Brown et al. (1992) modified the 2.1 to 2.3 to

$$\frac{Smix}{Sbit}\left[1 + \frac{257.5 - 2.5VMA}{p(VMA - 3)}\right]^{p} \qquad (2.3)$$

Where

VMA = percentage of voids in mixed aggregate and

P = same function of S_{bit} Equation 2.4 is valid for VMA values from 12 to 30% and $S_{bit} \geq 5$ MPa.

The most widely adopted empirical method uses penetration index (PI) and penetration-viscosity number (PVN). The PI was originally developed in 1936. About two decades later, Van der Poel (1954) developed a nomograph for predicting the stiffness of bitumen using routine test data. Van der Poel recognized the time and temperature effects that were inherent in the calculation of the PI but found that, in most of the cases, the time dependence and the rheological type of the bitumen were the dominant factors.

After a decade this nomograph was later updated and revised to accommodate penetration and viscosity measurements. However, the following shortcomings were observed in this nomograph:

1. Out of all the 50 bitumen samples tested, the majority were conventional bitumen (Van der Poel, 1955).
2. Most of the modifier binders have PI value that falls outside the range of nomograph, so it is difficult to predict the stiffness modulus of modified bitumen.
3. The nomograph will correspond only to the bitumen used in the original investigation, which is conventional bitumen (Davies, 1993).

Because of poor reliability of these monographs and non-applicability to modified bitumen, a more direct method to measure stiffness was required.

2.6.1 Dynamic Shear Modulus

The Strategic Highway Research Program (SHRP) originally conceived the idea of characterizing bitumen using rheological properties, in response to a perception from within the highway industry that quality of paving-grade bitumen had in many instances deteriorated to an unacceptable level. Because of this perception, the primary objective of the bitumen related section of SHRP was to develop performance-based specifications for bitumen and bituminous mixtures (Mihai *et al.*, 2000). In particular, the complex modulus (G*) is a major indicator of the mechanical behavior and performance. In the case of viscoelastic materials such as, bitumen, a tensile stress, σ applied at a loading time t = 0, causes a strain, ε_t which increases not proportionally with loading time. The stiffness modulus, S_t is defined as the ratio of the applied stress to the resulting strain.

Therefore, dynamic (oscillatory) shear rheometer was developed, which is considered to be the best technique to explain the uniqueness of the behavior of bitumen. In the shear mode under dynamic testing, G* and δ were measured. G* represents the total resistance to deformation, while δ, the phase angle, represents the magnitude of deformation. These parameters were useful for this study because they were used to predict pavement performance such as rutting (G*/sinδ) and fatigue (G*sinδ). The elastic modulus and shear modulus are related as shown in equation 2.4:

$$E = 2\,(1 + \mu)\,G^* \tag{2.4}$$

E = Elastic stiffness modulus

μ = Poisons ratio

G* = Complex Modulus

The value of Poisons ratio μ depends on the compressibility of the material and may be assumed to be 0.5 for pure bitumen, while less than 0.5 for bituminous mixtures. Thus,

$$E = 3\,G^* \tag{2.5}$$