INVESTIGATIONS ON FIELD PERFORMANCE OF BITUMINOUS MIXES WITH MODIFIED BINDERS

FINAL REPORT OF THE R-85 RESEARCH PROJECT

Submitted to

MINISTRY OF ROAD TRANSPORT AND HIGHWAYS
GOVERNMENT OF INDIA

TRANSPORTATION ENGINEERING DIVISION
DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY MADRAS
CHENNAI – 600036.

2013

PREFACE

The Ministry of Road Transport and Highways (MORTH), Government of India sanctioned the Research Project – R-85 on 'Investigations on Field Performance of Bituminous Mixes with Modified Binders' to the Indian Institute of Technology Madras. The project envisages construction of 20 km of test track with Semi-dense Bituminous Concrete resurfacing with five different types of binders viz., VG-30, SBS modified binder, Crumb Rubber Modified Binder (CRMB), Natural Rubber Modified Binder (NRMB) and Waste Plastic Modified Binder (WPMB) and each of 4 km length under the Improvement of Riding Quality Programme of the MORTH.

The test tracks were constructed on NH-207 in Karnataka between km 84.000 to km 104.000, with the co-operation and support from the National Highways, Government of Karnataka and the office of the Regional Officer of the Ministry of Road Transport and Highways, Government of India, during 2010. The performance of the test track was periodically monitored and the results of the evaluation studies are presented in the report. Laboratory performance studies on different binders and the bituminous mixes with the five different modified binders were also conducted. The results of the laboratory and field performance data along with the life cycle cost analysis of the five different binders are presented in the report. The periodical field performance data were collected by the BMS College of Engineering, Bangalore and the Indian Road Survey Management Team from Chennai.

The co-operation and support extended by the Ministry of Road Transport and Highways, Government of India, the National Highways Department of the Government of Karnataka and the Industrial Consultancy and Sponsored Research of the Indian Institute of Technology Madras are gratefully acknowledged. The extensive laboratory and field studies were carried out by Dr.S.Anjan kumar and his dedicated and sincere hard works are thankfully acknowledged.

It is expected the findings of the research study will pave way for the selection of appropriate type of modified binder by the practicing engineers based on the relative performance results. Similar test tracks should be constructed in different regions of the country under varying traffic, climate and environmental conditions and the performance monitored so that, the relative performance of different binders may be evaluated under different traffic loads and climatic conditions. The report will be useful for researchers and practicing engineers in the country.

Chennai (A.VEERARAGAVAN)
25 March 2013 Principal Investigator

CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

1.1 BACKGROUND

Bituminous mixes are used widely for paving applications in India and worldwide. Currently, the road projects in India are taken up under Design, Build Operate and Transfer (DBOT) basis. The highway designer and the agency have to ensure satisfactory performance of the pavement during the design life to meet the contractual obligations. The selection of appropriate paving binders duly considering the climatic and loading conditions and the scientific design of the thicknesses of various pavement layers dictate the serviceability of the bituminous pavements during the design life. The mechanical properties of bituminous mixes depend to a large extent on the type, quality and quantity of binder used. Defects in flexible pavements such as rutting, crack initiation and propagation occur are not only due to traffic loads but also due to the thermal susceptibility of bituminous binders.

The materials that gain prominence in the area of improved pavement performance are modified bituminous binders. Modifiers in the form of polymers, natural rubber, fillers etc., are added to virgin bitumen in an attempt to improve its mechanical and thermodynamic properties. To understand the applicability and performance of these modified bituminous binders, traditional specifications based on measurements of viscosity, penetration, ductility, softening point and elastic recovery are generally not adequate. In order to relate the properties of the binder to the properties of the bituminous mixes and later to the field pavement performance, it is necessary to carry out investigations and understand the rheological behaviour of the bituminous mixes with modified bituminous binders. Investigations on the performance of bituminous mixes with different modified bituminous binders will provide the much needed information on the longevity of modified bituminous binders over conventional bitumen under different traffic, climate and environmental conditions.

1.2 NEED AND IMPORTANCE

From literature, it is found that modification of bitumen enhances the rheological and mechanical properties of viz., bitumen and mixes prepared using them. Modification of binders enhances the susceptibility of the bitumen to daily and seasonal temperature variations, improve adhesion and resistance to permanent deformation as well as fatigue

life of bituminous mixes. Various types of additives are used to modify the properties of the bitumen. Hence, there is a need to understand the fundamental properties and performance characteristics of these mixes with modified bituminous binders and compare the results with the properties of the bituminous mixes with unmodified bitumen.

1.3 STUDY OBJECTIVES

The objective of the present investigation is to study the performance of semi-dense bituminous concrete mix with unmodified and different modified bituminous binders from a test track constructed on a National Highway, so as to compare their relative performance under actual traffic, climate and environmental conditions. The specific objectives of the research project are listed below:

- Laboratory evaluation of the properties of the various modified bituminous binders
- Laboratory tests on a typical bituminous mix using the various modifiers and study the properties of the mixes
- Study the laboratory rutting performance of the bituminous mixes and develop performance prediction models.
- Study the field performance of a thin bituminous overlay with different bituminous binders and develop performance prediction models for use in pavement design.
- Carry out life cycle cost analysis using different bituminous binders for application in pavement management.

1.4 SCOPE OF WORK

The scope of the project is predicting the life of the pavements overlaid with semi-dense bituminous concrete mix with different modified and unmodified binders. The rheological properties of the bituminous binders were characterized using dynamic shear rheometer. Aging of bitumen was simulated using rolling thin film oven and pressure aging vessel. Rutting resistance of bituminous mixes was determined using wheel tracker and by varying the temperature and bitumen type keeping the gradation and binder content constant. The effect of aging on rutting characteristics of bituminous mixes was investigated to understand the temperature susceptibility of modified and unmodified

bituminous binders. The report presents the investigations carried out on the performance of semi-dense bituminous concrete mixes laid with different modified binders on a selected test stretch on a National Highway and the observed field performance under actual traffic, climate and environmental conditions. The pavement performance prediction models and life cycle cost analysis are presented in the last chapter.

LITERATURE REVIEW

2.1 OVERVIEW

Repeated application of traffic loads causes structural damage to flexible pavements in the form of fatigue cracking of bitumen bound layer and rutting along wheel tracks. While fatigue failure is the result of flexural cracking of bitumen bound layer and rutting is the manifestation of permanent deformation in different layers of the pavement. The bituminous layer itself may display a significant amount of permanent deformation in hot climatic conditions (Palit et al, 2004). Permanent deformation or rutting in flexible pavements is a major distress mode and usually occurs as a result of a combination of densification and shear flow. It may be caused by the action of high stress at high temperatures on the surface of the pavement. Bitumen plays a major role in developing resistance against rutting of the mix. Development of modified bitumen to improve the overall performance of pavements has been the focus of several research efforts made over the past few decades. Use of modified binders for pavements is increased due to the need to design bituminous mixes to withstand higher wheel loads repetitions.

2.2 MODIFIED BINDERS

The primary aim of modification is to improve the temperature susceptibility of bitumen so that it has higher stiffness at high pavement temperatures and higher flexibility at lower pavement temperatures. Essentially modification is intended at improving the resistance of bituminous mixtures to permanent deformation at high pavement temperature without adversely affecting the low temperature properties. Hence modification of bitumen aims at manifesting the transitions of bitumen from a visco-elastic fluid to Newtonian fluid. Modifiers are blended directly with the bitumen or added to the bituminous mixture directly. An ideal bitumen modifier used in pavement construction should fulfill the following primary objectives:

- Stiffer mixtures at higher service temperatures to reduce rutting susceptibility.
- Softer mixtures at low service temperatures to minimize thermal cracking.
- Improved fatigue resistance of bituminous mixtures
- Enhanced resistance to stripping or moisture damage
- Increased resistance towards aging

2.2.1 Process of modification

Modified binders are normally produced in the bitumen production plant. In most of the cases, the modifier is blended with the base conventional bitumen at pre-defined percentages, temperature and stirring rate in a mixing tank for a minimum duration of time. In some cases, the modifiers are blended directly with the bituminous mix during its production on-site. Modification of bitumen results in complex interaction between the base bitumen and modifier. There are four possible distinct modes of interaction between bitumen and modifiers (Asphalt Academy, 2001):

- The modifier is present as a separate phase within the bitumen
- The bitumen is present as a separate phase in the modifier and the product will display the properties of the modifier rather than the bitumen.
- The modifier will form an interface with the bitumen giving greater elasticity due to changes in the mechanical structure of the material.
- The modifier will form a molecular bond with the bitumen giving greater elasticity and stiffness to the material.

2.2.2 Limitations of modification

The possible problems with modified binders are in the storage of the bitumen, mixing temperatures, and the duration of time the material is held at elevated temperatures before placing. The blending of bitumen and modifier, other than being proprietary information, is not an easy process and so modified bitumen is usually purchased in a ready blended form from the supplier. It is usually necessary for the modified bitumen to be held in a tank that is capable of being agitated in some way from production till actual use, as the polymers having different density to the bitumen tend to separate out, if kept in storage for prolonged periods. The additive can be destroyed by the temperature being too high during mixing, or by being held at elevated temperature for a long period of time after mixing. Even the bitumen storage time should be kept as short as possible to prevent deterioration of the additive (Drakos et al., 2005). Modified bitumen being a premium product, its utilization should be cost effective. In order to make the best use of modified binders, appropriated design and guidelines are needed. In most of the cases, appropriately designed flexible pavements with conventional bitumen perform well. However the situation which demands high performing materials has to be identified for

cost effective usage of modified binders. Thus, there is a need to develop warrants for the use of modified binders in the country.

2.2.3 Types of modifiers

Different types of additives are used as modifiers in bituminous mixtures, which can be classified in different forms. Table 1 shows a generic classification system that is used to define and classify modifiers in bituminous mixtures (IRC SP-53: 2010).

Table 1 Classifications of Bitumen Modifiers (IRC SP-53: 2010)

	Types of Modifier	**Example**
Synthetic Polymers	Plastomeric Thermoplastics	Polyethylene, Ethylene vinyl Acetate (EVA), Ethylene Butyl Acrylate (EBA)
	Elastomeric Thermoplastics	Styrene Butadiene Styrene (SBS) Styrene Isoprene Styrene (SIS) etc.
Synthetic rubber	Synthetic Rubber Latex	Styrene Butadiene Rubber (SBR) Latex Polychloroprene Latex etc.
Other rubber	Natural rubber	Latex or rubber produce
	Crumb rubber	Crumb rubber produced from discarded truck tyres further improved by additives

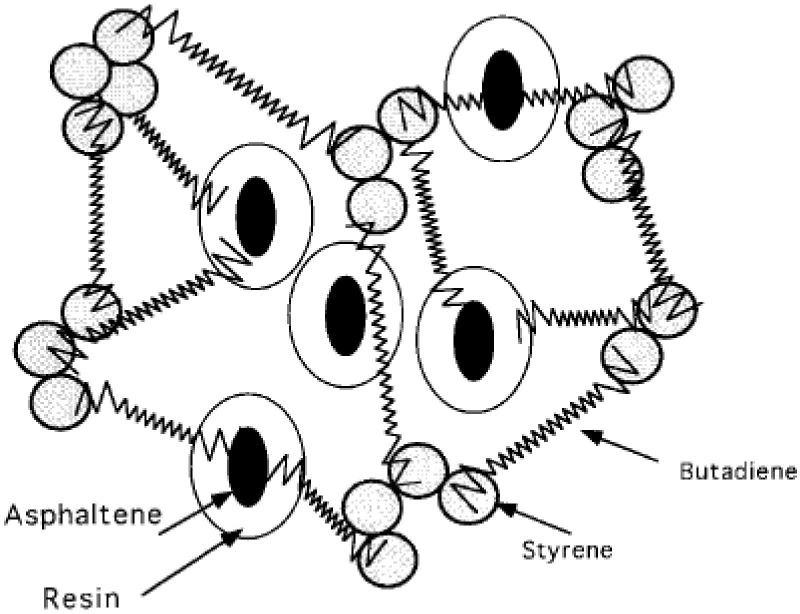
2.2.3.1 Polymer

A polymer is a very large molecule comprising hundreds or thousands of atoms formed by the successive linking of one or two, or occasionally more, types of small molecule into chain or network structures (Drakos et al., 2005). To achieve the goal of improving bitumen properties, a selected polymer should create a secondary network or new balance system within binders by molecular interactions or by reacting chemically with the bitumen. The formation of a functional modified bitumen system is based on the fine dispersion of polymer in bitumen for which the chemical composition of binders is important. The degree of modification depends on the polymer property, polymer content and properties of the base bitumen. Thermoplastics are characterized by softening on heating and hardening on cooling (Giavarini 2000). These materials, when mixed with

bitumen, associate at ambient temperatures and increase the viscosity and stiffness of bitumen at normal service temperatures. Polymers are capable of endowing physical and mechanical properties to bitumen, which could lead to better performance in pavement applications (Boutevien et al., 1989).

2.2.3.1.1 Styrene Butadiene Styrene (SBS) polymer

Among elastomeric materials, styrene-butadiene-styrene block copolymers (SBS) have attracted most attention for bitumen modification. These copolymers combine both elastic and thermoplastic properties, and therefore are commonly called elastomeric thermoplastics. SBS copolymers consist of styrene-butadiene-styrene tri-block chains, and have a two-phase morphology, showing spherical domains formed by the polystyrene blocks within a matrix of poly-butadiene (Figure 1). These hard block domains act as physical cross-links in forming the elastomeric network (Drakos et al., 2005).



Figure

Figure 1 Three dimensional network of SBS modified bitumen (Rozeveld et al. 1997)

In addition, they behave as well dispersed, fine-particle reinforcing filler in promoting high tensile strength and modulus. The thermoplastic nature of SBS copolymers at elevated temperatures and their ability to provide a continuous network on cooling are the reasons for their great attractiveness as bitumen modifiers. SBS absorbs the maltenes in the bitumen, swells and, at higher dosage levels, forms a continuous molecular network in the bitumen phase which makes up a major fraction of the bitumen by volume (Asphalt

academy, 2001). When a SBS copolymer is added to hot bitumen, it absorbs maltenes from the bitumen and swells by up to nine times its initial volume. At suitable SBS concentrations a continuous polymer network can be formed throughout the bitumen. This, in turn, significantly modifies temperature susceptibility and visco-elastic behaviour of conventional base bitumen.

2.2.3.2 Crumb rubber

It is the recycled rubber product obtained through scraping of automotive pneumatic tyres. The crumb rubber has to be processed by mechanical means and should be substantially free from ground fabric, steel and other contaminants including moisture for use as a bitumen modifier. When introduced to the hot bitumen, the rubber swells, through absorption of the aromatic fractions of the bitumen. As a result of the high blending temperature, some of the rubber dissolves in the bitumen and some is de-vulcanized.

2.2.3.3 Natural rubber

Natural rubber latex consists of polymerised isoprene monomers which increase the elasticity of the bitumen. However, the natural rubber latex is more sensitive to heat and is therefore mainly used in the modification of cold bituminous binders. Natural rubber used as a modifier often has problem of compatibility (Yildrim, 2007). It increases the bitumen's viscosity, lowers the penetration and increases the softening point.

2.2.3.3.1 Waste plastics

In order to track the pavement industry towards sustainable construction practices, waste plastics are used in bituminous mixes. Waste plastic essentially is obtained through service industries and house hold wastes used for package purposes. Majority of its constituents are high and low density polyethylene. The polyethylene has been examined (Boutevien et al., 1989) as bitumen modifier which increases the viscosity and stiffness of bitumen at normal service temperatures. The use of waste plastic as bitumen modifier was encouraged in India and other parts of the world to reduce environmental pollution and also for utilization of waste materials in pavement construction to account for preservation of natural resources.

2.2.4 Effect of modification on rheology of bitumen

Rheology is the study of flow and deformation of materials. The viscoelastic like response of bitumen is substantially influenced by the time and temperature. In case of modified bitumen, the rheology of the material depends on the type, size and content of the modifier. Nicholas et al. (1989) showed that the modification of bitumen with ethylene co-polymers enhances resistance to creep at high temperatures without loss of low temperature stress relaxation properties when compared to conventional binders. According to Collins et al. (1991), the complex modulus (G^*) increases and phase angle (δ) decreases with increase in polymer concentration. Hence, with increasing polymer concentration, the bitumen will be more resistant to deformation and exhibit enhanced elastic recoil. This was especially found to be true at concentrations exceeding the critical network concentration. Investigations carried out by Goodrich(1992) showed that measurements of the visco-elastic properties of the bitumen over a range of possible road temperature could be well correlated with the behaviour of the bitumen. Separating the viscous and the elastic character of the binders as a function of temperature and dynamic shear rate establishes the fundamental basis for predicting the behaviour of binders in low temperature creep, fatigue and high temperature creep. Polymer modification was found to be effective in improving the rheological properties and reducing temperature susceptibility (Anderson (1992), Dubabe et al. (1995)). It was found that the polymer modifiers separate out from the base bitumen, if stored at elevated temperature, which places a handling and storage limitations of polymer modification (Dubabe et al. (1995).

Rubber modification exhibit shear-thickening and shear-thinning behaviour depending on the shear rate subjected (Zaman et al. (1995). The authors concluded that addition of rubber, showed improved elasticity and creep resistance thereby enhancing the low temperature properties. Viscosity of rubber modified bitumen increases due to aromatic oil absorption and rubber particle swelling (Lougheed and Papagiannakis (1996). Also Lu and Isacsson in 1996 observed that modification of bitumen with SBS polymer reduces the temperature susceptibility and its frequency dependency varies with the content and the interaction between polymer and base bitumen (Figure 2).

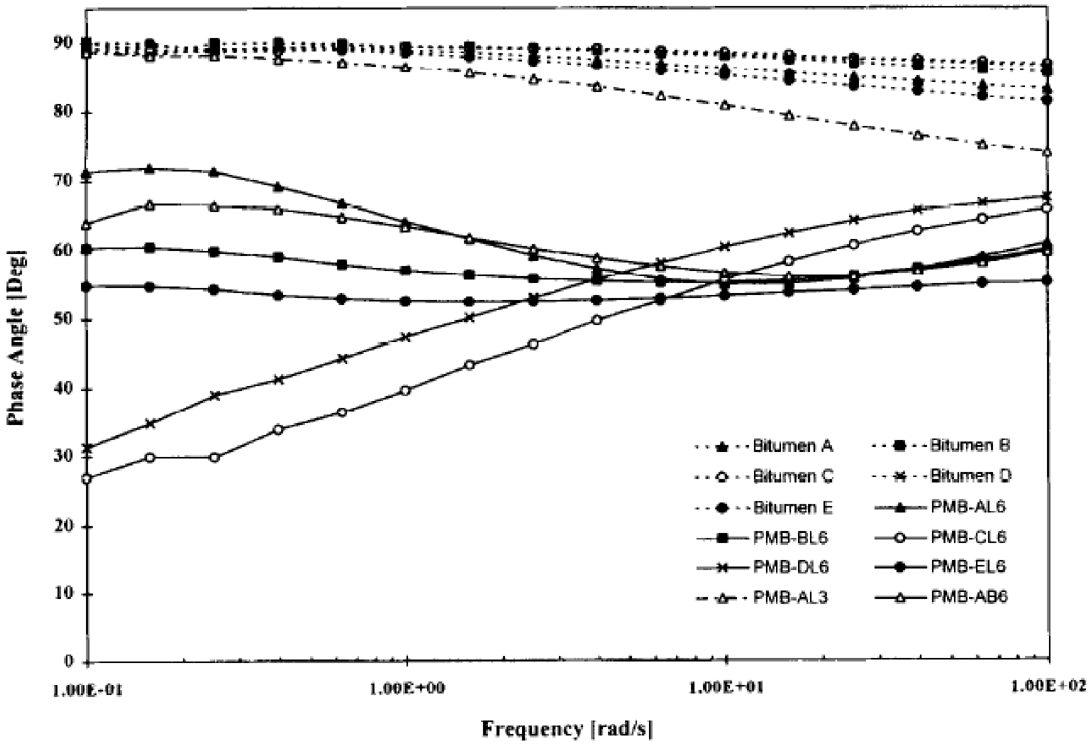


Figure 2 Frequency dependence of modified binders (Lu and Isaccson 1996)

Kim et al. (2000) reported that the concentration and size of crumb rubber has a significant role on the viscosity of the modified binder. They concluded that keeping the rubber modified bitumen agitated during storage can reduce phase separation significantly.

Yousefi et al. (2000) studied the effect of modification of binders using recycled polyethylene (RPE). Results from the thermo mechanical analysis showed that modified binders with RPE can provide high performance binders whereas, the problem of the stability of the RPE suspensions in bitumen medium remains unsolved. According to Gopal et al. (2002) increasing the crumb rubber content decreased the creep stiffness, and improves thermal cracking resistance of rubber modified binders. However it was also observed that some combinations of crumb rubber size and content can neither improve nor jeopardize the low temperature properties of the bitumen.Wang et al. (2002) showed that for compatibility between base bitumen and polymer modifiers, both complex shear modulus and phase angle should be taken into account. Also the improved toughness and tenacity of base bitumen depends on the type and amount of polymer.

Isochronal plots developed by Elseifi et al. (2003) indicated that polymer modification is effective in increasing rutting resistance at high temperature and fatigue resistance at intermediate temperatures. Also Kumar et al., in 2004 showed that there is an improvement in physical properties and temperature susceptibility of SBS modified bitumen as compared to neat bitumen.

2.2.5 Effect of modification on morphology of bitumen

Kraus, (1982) found that modification of bitumen with polymer exhibits multiphase morphology and the rheological behaviour of polymer modified bitumen could be the result of multiphase morphology. According to Brule et al. (1988), the longer time of agitation of the bitumen polymer blend results in finer microstructure. The finer the microstructure, greater will be the deformability in case of bitumen with a polymer network. Binders with a coarse microstructure are not deformable at low temperature. Loeber et al. **(1995)** showed that the presence of polymer in bitumen results in the development of aggregates of asphaltenes in a smooth matrix which is probably made of polymer and oil. Similarly Rozeveld et al. (1997) showed that the micro-structural network of bitumen (Figure 3) could provide a useful indication of the state of asphaltene dispersion or aggregation, which is therefore expected to provide insight into the rheological properties as well as the failure mechanism of bituminous mixtures.

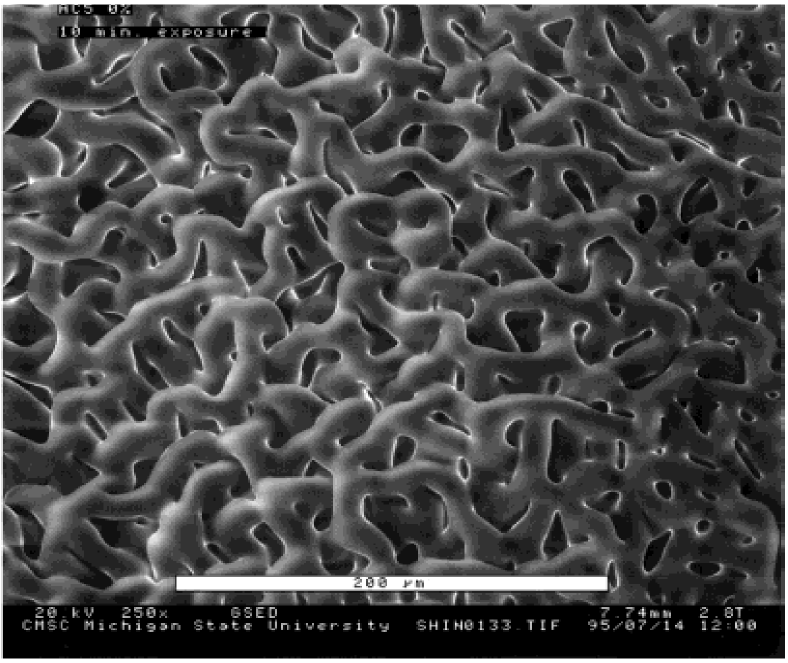


Figure 3 Microstructure of bitumen (Rozeveld et al. 1997)

Abdelrahman and Carpenter (1999) carried out morphological studies on crumb rubber modified binders. The authors found that swelling and degradation are the two possible interactions that will result through modification of bitumen with crumb rubber. This interactions result in a liquid phase and swollen particles forming a unique structure, thereby, responsible for the flow behaviour of crumb rubber modified bitumen. Chen et al. (2002) found that the optimum SBS content can be determined based on the formation of the critical network between bitumen and polymer (Figure 4). Formation of this network between base bitumen and polymer due to modification results in increased complex modulus. Yousefi (2002) showed that morphology of rubber modified binders shows continuous and dispersed phase depending on the rubber type and the oil fraction in the base bitumen. Yousefi (2002) also found that rubber modification increases the high temperature properties but becomes brittle at low temperatures which may be due to swallowing of oil fraction and carbon black present in the rubber.

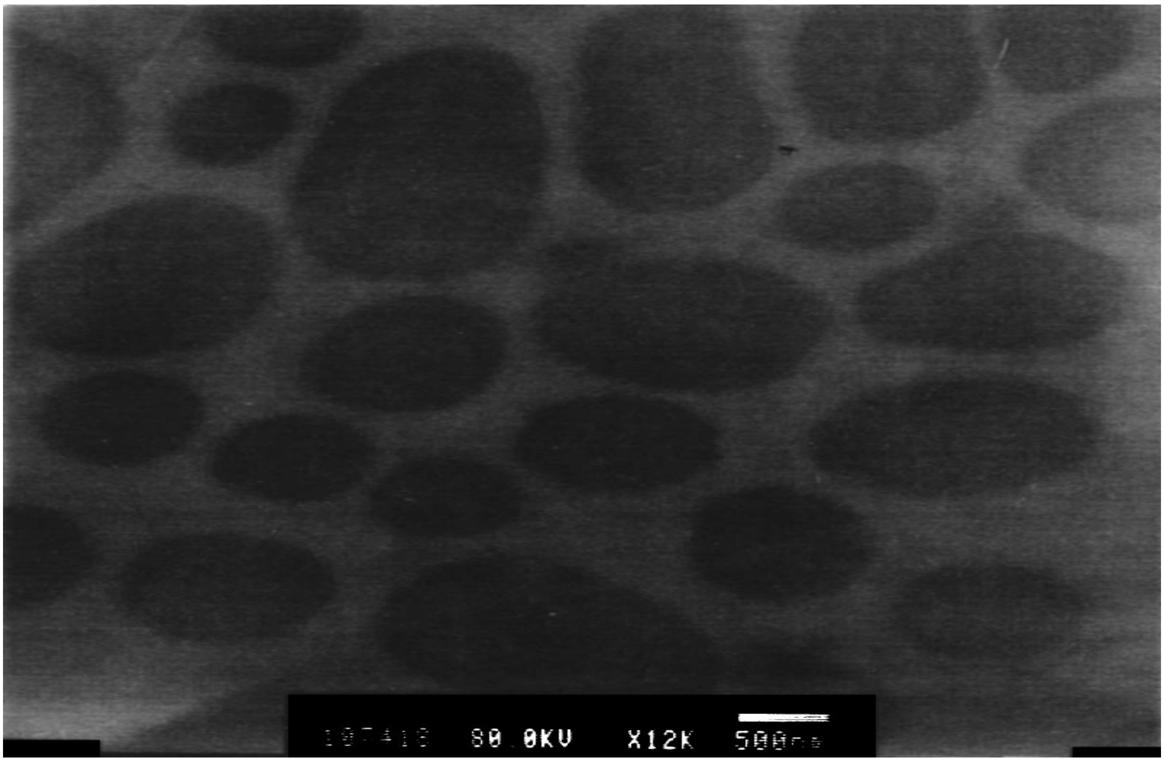


Figure 4Network formation in SBS modified bitumen (Chen et al 2002)

According to Gang et al. (2003) modification of bitumen thorough high speed agitation of desulphurized crumb rubber destroys the vulcanized bonds between rubber particles and avoids the reunion of crumb rubber particles, and it remarkably increases the swelling capacity of crumb rubber in bitumen and improves the elasticity and stability of modified bitumen. As per Morales et al., (2004) the micro-structural changes, related to the development of a polymer-rich phase have a significant influence on the flow behaviour

of the modified bitumen and on its in-service performance. Interestingly Masson et al. (2005) found no significant correlation between the morphology and composition of bitumen. However it was noticed that the morphology and the molecular arrangements in bitumen would be governed by the size and shape of molecular planes and the ionic content.

Morales et al. (2006) studied the effect of bitumen modification using waste polymers. The results revealed that blending of Ethyl Vinyl Acetate (EVA) and low density polyethylene (LDPE) enhances the mechanical properties of bitumen and mixtures at high temperatures due to the development of a polymer network throughout the modified bitumen. Investigations carried out by Fu et al. (2007) showed that compatibility of SBS with bitumen could be improved by addition of grafted SBS and also addition of vinyl monomer increases storage stability. Fu et al., also found that modification of asphalt bitumen using SBS could result in the formation of network in the blended system, which would result in asphalt bitumen having advantage in high temperature performance and also reduced temperature susceptibility.

Wekumbura et al. (2007) studied the destruction and reformation of the internal structure of polymer-modified binders by an interrupted shear test. The results showed that in polymer modified binders, the stress overshoots during steady shear and reaches a steady value, and the same was not observed in case of unmodified binders. They also concluded that the disturbed structure of polymer modified binders during shear, can reform with time and impart the ability of self-healing. According to Lee et al. (2008) modifying bitumen with crumb rubber increases the viscosity, enhances the mechanical properties and also high percentages of crumb rubber reduces low temperature susceptibility of modified binders. Attia and Abdelrahman (2008) showed that the interactions resulting due to crumb rubber modification depend upon the crumb rubber particle size, content, mixing speed and temperature. Comprehensive work by Larsen et al. (2009) showed that the high shear rate and temperature used during manufacturing of polymer modified bitumen induce SBS copolymer degradation. These degraded fragments distribute into maltenic phase and could be responsible for the change in rheological properties of polymer modified binders. Larsen et al., also found that polymers of different molecular weight will attain optimal rheological characteristics at different shear rates and time of blending. Hence in polymer modified binders, optimization of blend composition, shear rate, temperature and time produces the best rheological properties of modified bitumen.

2.2.6 *Effect of aging on longevity of modified binders*

Aging is induced by chemical and physical changes and is usually accompanied by hardening of the bitumen. For pavement applications, bitumen is exposed to aging at three different stages: (i) storage, (ii) mixing, transport and laying and as well as (iii) during service life. Aging is a very complex process in conventional binders and the complexity increases when modifiers are added. Pioneering work by Petersen (1984) showed that formation of highly polar and strongly interacting functional groups of oxygen due to aging, results in the change in internal structure of bitumen. Similarly Oliver and Tredrea (1997) showed that aging results in large changes in the rheological behaviour of the polymer modified binders and these changes were likely to reduce the advantage of fresh polymer modified binders over conventional neat binders. Dynamic mechanical characterisation of polymer modified binders by Gahvari (1997) showed that modification of bitumen with thermoplastic block copolymers will result in profound change in dynamic mechanical properties when compared to unmodified bitumen as noticed from the relaxation spectrum and isochronal plots. Airey and Brown (1998)have made similar observations**.** As per Airey and Brown, the changes in the EVA modified binders might be due to chemical change in the semi crystalline copolymer and in SBS modified binders due to a breakdown of the molecular structure of the copolymer to form a lower molecular weight polymer substructure.

Dynamic mechanical analysis and microscopic investigations carried out by Lu and Isacsson (1998) showed that aged modified bitumen exhibit better rheological properties when compared to aged base binders. Siddiqui and Ali (1999) termed aging as the irreversible change in internal structural composition of bitumen. This irreversible change was contributed to oxidation of bitumen constituents, which results in significant change in structure and composition of bitumen in service. Lu and Isacsson (2000) studied the physical hardening of bitumen and indicated that degree and kinetics of physical hardening were dependent on the base binders, and in most cases, the effect of polymer modification was insignificant. Lu and Isacsson showed that aging reduces the aromatic content whereas increases both resins and asphaltenes. Lu and Isacsson also pointed that saturates are inert to oxygen and hence aging has little effect on the saturate content in the bitumen (Figure 5).

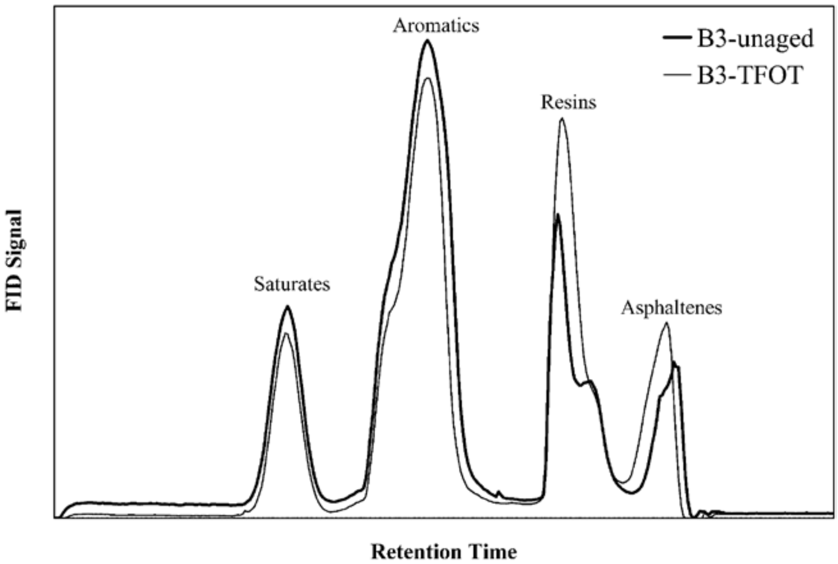


Figure 5 Effect of ageing on bitumen TLC-FID chromatogram (Lu and Isacsson 2002)

Indian Roads Congress Special Publication No SP:53- 2010 reports that aging properties of conventional binders are normally characterized by measuring rheological properties such as viscosity and softening point before and after artificial aging in the laboratory. This procedure is not adequate in the case of modified binders since, thermolytic degradation of the modifier may occur during aging and the fragments formed may contribute to lowering of the consistency. Therefore, when assessing the aging properties of modified bitumen, further characteristics, such as elastic recovery and chemical composition have to be evaluated. According to Mahrez and Karim (2003) aging index could be applied to evaluate the performance of modified and unmodified binders. Mahrez and Karim (2003) also pointed out that the linear visco-elastic parameters such as complex modulus and phase angle changes significantly with aging. Similar studies carried out by Raun et al., 2003 showed that aging reduces the temperature susceptibility of both modified and unmodified binders, further damages the effectiveness of polymer network in improving bitumen flexibility. However, it is also interesting to observe that there is significant difference in the complex modulus of polymer modified binders even after aging when compared to unmodified binders at lower frequencies (Figure 6)

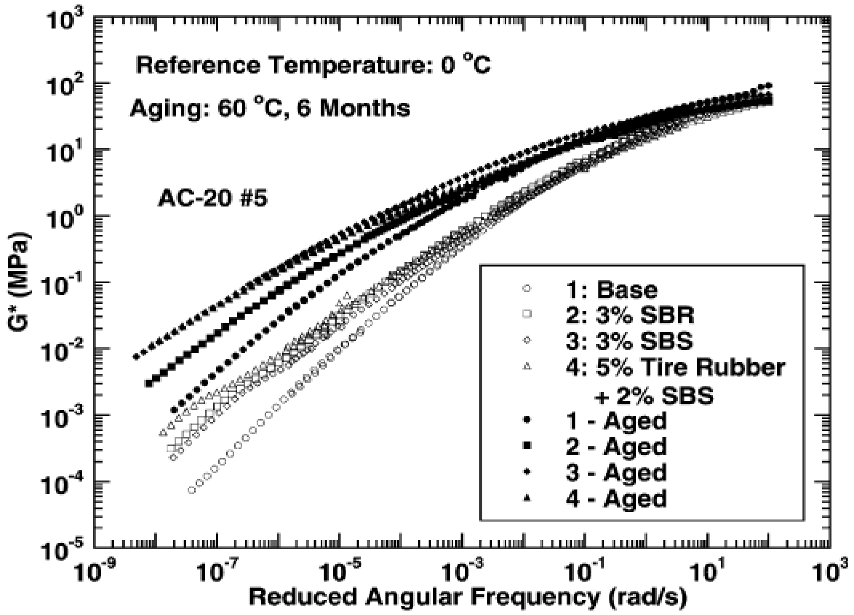


Figure 6 Master curves developed at 0 °C (Raun et al 2003)

Cortizo et al. (2004) showed that aging increases higher molecular size polar compounds, which essentially explains the structural modification on behaviour of polymer modified binders during their aging. Huang et al. (2006) found that the addition of crumb rubber to bitumen reduces viscosity build-up with aging. In addition, rubber modification dramatically increased the elasticity of binders. As per Rajan et al. (2009), temperature susceptibility of binders depends on crude source; processing method and blend proportion. Rajan et al. also showed that proper blending process, selection of crude source and proportioning ensures less temperature susceptible binders.

2.2.7 Effect of mix design methods on performance of bituminous mixtures with modified binders

Bituminous mix design deals with determining the proportion of mineral aggregates with bitumen to obtain the bitumen content that optimizes the desired performance, such that the property of the resultant mix has better resistance to distresses caused by traffic loads and environment. A well designed bituminous mixture should be durable and capable of being placed and compacted with minimum effort. Commonly used mix design methods worldwide such as Marshall, Hubbard-field, Hveem and Tri-axial test method require strength testing and further are limited to unmodified binders. Among these, the Marshall method is the most popular, possibly due to its simplicity and low cost. Superpave is an ongoing effort to design bituminous mixtures using rational principle developed under the Strategic Highway Research Program (SHRP) **(**Superpave Manual Series 2). Superpave

system incorporates performance based bituminous material characterization with design environmental conditions to improve the performance by controlling rutting, low temperature cracking and fatigue cracking. The significant differentiating aspects of the Superpave method of mix design when compared to Marshall method of mix design is, use of the gyratory compactor to simulate field kneading compaction and the volumetric approach to the mix design. The method also takes into account factors such as aging during mixing, transporting, placing and compaction.

Studies have reported that Superpave method of mix design results in higher optimal bitumen content when compared to Marshall Method of mix design for rubber modified bitumen (Gowda et al. 1996). Significant differences were not observed in terms of rutting resistance and fatigue cracking when mixtures designed using Superpave method were compared with mixtures designed using Marshall method **(**Gowda et al. 1996; Asi, 2007; and Sirin et al., 2008). Various researchers (Habib et al., 1998; Khosla and Kawaguchi, 2000; Watson and Brown, 2005) have shown that kneading action simulated using a gyratory compactor results in better aggregate orientation, thus leading to a lower bitumen content in the Superpave design method when compared to the Marshall design method (at 4 % level of air voids). Gyratory shear compaction at an angle of 1.25^o is found to simulate field conditions (Khan et al., 1998). For a given aggregate gradation, decrease in number of gyrations results in increased bitumen requirement (Habib et al., 1998). It has also been reported that field compaction and durability of Superpave designed mixtures can be improved by increasing bitumen content without adversely affecting the rutting resistance (Watson and Brown, 2005).

2.2.8 Effect of modification on engineering properties of bituminous mixtures

The engineering properties like tensile strength, resistance to fracture, rutting and moisture induced damaged were found to be strongly improved by using modified binders (Khosla and Goetz, 1979; Khosla and Zahan, 1989;Valkering et al., 1990; Collins et al., 1991; Xicheng Qi et al (1995); Isacsson and Lu, 1999; Khattak and Baladi, 2001; Panda and Mazumdar , 2002; Zubeck et al. (2002); Sridhar et al., 2004; Palit et al., 2004; Punith et al., 2005; Awanti et al., 2006; Tayfur et al. 2007). King et al. (1986) brought out that each polymer offers a unique combination of performance related benefits that may or may not serve a particular road-related deficiency. Knowing the benefits that can accrue in a pavement with modified materials, the real savings should come from the extended service life and not from material short cuts (Terrel and Walter, 1986). Akthrhusein et al.

(1991) observed that the rheological properties of modified binders could be used to justify the improved performance of modified bitumen mixtures over unmodified bitumen mixtures on permanent deformation.

Among the mix properties, shear modulus was found to be more reasonable to rank the modified bituminous mixtures based on their resistance to load related distresses according to Wong et al. (2004). As per Sirin et al., (2008), rutting in bituminous mixtures with unmodified bitumen was a combination of densification and shoving whereas it was only densification in mixtures with modified bitumen. Jain et al. (2006) observed that the traditional physical properties of bitumen do not correlate with the performance of bituminous mixtures. On the other hand, rheological properties of bitumen were found to directly explain the deformation behaviour of bituminous mixtures. Studies have also showed that the modifier type, size, content and mix design methods substantially influence the deformation characteristics of bituminous mixtures (Liu et al. 2009 and Anjan kumar, and Veeraragavan, 2010).

2.2.9 Influence of bitumen properties on field performance

In order to relate bitumen properties to pavement performance, it is necessary to understand the fundamental relationships between bitumen properties and mix properties. Mix properties are needed for the pavement response models that provide the necessary input for the pavement performance models. To minimize the deterioration of a flexible pavement due to influence from traffic and climate, the bituminous layers should be stiff enough at elevated service temperatures to avoid permanent deformation (rutting), show good load-associated fatigue resistance, possess good stripping resistance (low water susceptibility), show time-independent properties (good ageing properties), have good flexibility at low temperatures (resistance to low temperature cracking) and be effective against studded tyres (good wear resistance). All of these performance-related properties of the mix are influenced to some extent by bitumen properties (Coplantz et al., 1993; Bhaia et al., 2001; Martin and Jenkins, 2003; Bennert et al., 2003; Zeng and Huang, 2006; Quintus et al., 2007).

Stock et al. (1992) showed that the special binders outperform the conventional bitumen by a significant margin, and also that there was variation in performance between different polymer systems. After extensively monitoring the in-place performance of a highway overlaid with polymer modified mixtures for a period of five years Johnson and

Freeman (1999) showed that rut development and cracking increased in the unmodified pavement sections as compared to modified ones. Similarly Anderson et al. (1999) indicated that the raveling, surface cracking and general deterioration of the pavement improved in the sections with modified binders. Likewise Chipps et al. (2001) revealed from their field investigations on crumb rubber modified asphalt binders in dense graded mixtures that, performance of the binders with rubber materials improved over the base bitumen. Also the life cycle cost of high cure crumb rubber modified bitumen sections were favourable when compared to conventional bitumen sections. Modified bituminous mixtures exhibited appreciable decrease in rutting when compared to unmodified bituminous mixtures in the field (Mc Dainel and Bahia 2003).

Central Road Research Institute (2000) carried out field trials on SBS modified bitumen in flexible pavements. The study reported the findings of the full-scale field trials under different traffic and climatic conditions. Results from the investigations revealed that the performance of SBS modified bituminous overlay and renewal coats are superior to conventional 60/70 and 80/100 penetration grade bitumen under the extreme traffic and climatic conditions. The life expectancy of renewals with modified bitumen was nearly two folds as compared to conventional bitumen from field trials. The same was also observed by Molenaar and Nirmal (2001) by using modified bituminous mixtures for heavy-duty pavement in India. From the test programme, Molenaar and Nirmal (2001) concluded that the resistance to permanent deformation as well as the tensile strength and the fracture toughness tremendously improved when polymer modification was done and significant savings in overlay thickness can be realized. In Indian Road Congress (Special Publication IRC: SP: 53-2002) it is mentioned that the time period of new renewal may be extended by 50% in case of bituminous resurfacing with modified bitumen than neat bitumen. Asphalt Institute (2005) quantified the effect of polymer-modified asphalt as compared to conventional mixtures in terms of pavement life and surface distress. The distress comparisons and damage analysis showed that the use of modified mixtures result in less cracking and rutting, extending the service life of flexible pavements and overlays.

2.3 SUMMARY

It can be inferred that the above reported background studies on modified binders primarily looked at the linear visco-elastic properties of modified and unmodified binders during various stages (aging). The development of internal structure and transitory nature in multi-constituent material like bitumen is the prime concern in understanding its

mechanical behaviour (Krishnan and Rajagopal 2005). The results have also shown that not all additives can improve the bitumen properties. The expected change through modification depends on the base bitumen properties and compatibility between bitumen and modifier. Hence understanding the transitory nature becomes more complicated when the bitumen is modified.

Studies have shown that the various mix design methods yielded different optimum bitumen contents. Most of the existing literature evaluates design methods at a given or specified air void content. Parameters like compaction, aging, gradation and source of the raw materials influence the desired performance. The influence of mix design methods with different modified binders and its effect on the durability and performance on bituminous mixtures also needs to be understood carefully.

Modification manifests the transitory nature of bitumen from viscoelastic solid-like to viscoelastic fluid-like behaviour at higher temperatures. At this high pavement temperature, rutting is the most anticipated distress under traffic loading. Investigations on the rutting resistance of bituminous mixtures with temperature varying from intermediate to higher range could explain the influence of bitumen modification on the transitory nature of the mix. It could be a difficult task to differentiate the effect of bitumen content and type on the mechanical response of mixtures under loading at constant volumetric and compaction level. Investigations carried out on bituminous mixes with constant bitumen content should separate out the effect of bitumen modification on the mechanical response of the mixtures.

Aging is considered to be a long-term phenomenon and is used to characterize the fracture resistance of bituminous mixtures. During its service life, flexible pavement with bituminous mixtures in the wearing course will be subjected to significant variation in pavement temperature. Whenever the pavement attains the higher temperature, rutting accumulates due to shear deformation but might not be because of densification. However accumulation of rutting varies upon the change in stiffness of the bitumen due to aging. Hence the investigations duly considering the effect of aging on mixture rutting resistance will also help in understanding the durability of modified binders.

In summary, conventional bitumen tests on modified and unmodified binders do not correlate well with mix performance. Dynamic rheological analysis could provide

fundamental explanations on the performance of binders. Measurements of the viscoelastic properties of the binders over a range of possible road temperature could be well correlated with the behaviour of the bitumen. Studies on the various parameters affecting the performance of the bituminous mixtures should be carried out. Detailed investigations for a wide variety of modified and unmodified bitumen during several stages of aging are also needed to assess the longevity. Also the combined effect of frequency, temperature and bitumen type on the observed mechanical response of bituminous mixtures are to be evaluated, so as to provide the much needed information on the benefits of use of modified binders for enhanced pavement life. Investigations on the fundamental properties and mechanical characteristics to understand the response under loading will facilitate ranking of the performance of bituminous mixtures with different modified binders and their comparison with bituminous mixtures with unmodified binders. The lacuna in research literature and the needed research on the performance of bituminous mixes with different modified binders are addressed in the present investigation. Most importantly, the field investigations of the performance of different modified binders will provide the much needed information on the longevity of modified binders over conventional bitumen under actual traffic, climate and environmental conditions.

EXPERIMENTAL INVESTIGATIONS

3.1 GENERAL

The wearing course layer bears the highest stresses due to the repeated loads and this result in rutting and cracking. Wearing course has the requirement of being effective in re-bounding against the dynamic effect of traffic load. In other words, the top bituminous courses should have adequate stiffness to resist rutting coupled with the flexibility. This layer is always a bound course and therefore consists of bitumen and aggregates. The mixture of this layer has to be designed carefully to have adequate strength, stiffness and durability.

In this chapter, the complete details of the materials tested as part of this investigation are reported. To understand the influence of modification on the rheological properties of bitumen, four different types of modified binders typically recommended for similar climatic conditions and popularly used in India were identified. Detail discussions on working principle of equipments used to characterize the materials were made.

3.2 *MATERIALS*

The various binders used in the present work are:

- Un-modified bitumen:
  - Viscosity Grade 30 (VG30)
- Modified binders:
  - Polymer Modified Bitumen (PMB70)
  - Crumb Rubber Modified Bitumen (CRMB55)
  - Natural Rubber Modified Bitumen (NRMB70)
  - Waste Plastics Modified Bitumen (WPMB70)

Crushed granite stone aggregates were used as coarse and fine aggregates and also stone dust was used as mineral filler in the investigations carried out in this work.

3.2.1 Viscosity Measurements Using Rotational Viscometer

The Brookfield DV-II+Pro rotational viscometer is used in present investigations to measure the apparent viscosity at temperature regime of 135 to 180 ^{o}C. Principally, it measures the torque required to rotate an immersed element (the spindle) in a fluid (bitumen). The spindle is driven by a motor through a calibrated spring. For a given material, the viscous drag, or resistance to flow (indicated by the degree to which the spring winds up), is proportional to the spindle's speed of rotation and is related to the spindle's size and shape (geometry). The drag will increase as the spindle size and/or rotational speed increase. It follows that for a given spindle geometry and speed, an increase in viscosity will be indicated by an increase in deflection of the spring. Measurements were made using a specified spindle (SC4-21) at different speeds to detect and evaluate the rheological properties of the binders. The Viscometer is composed of several mechanical sub-assemblies. Figure 7 shows a schematic view of the major components of a basic dial-reading Viscometer.

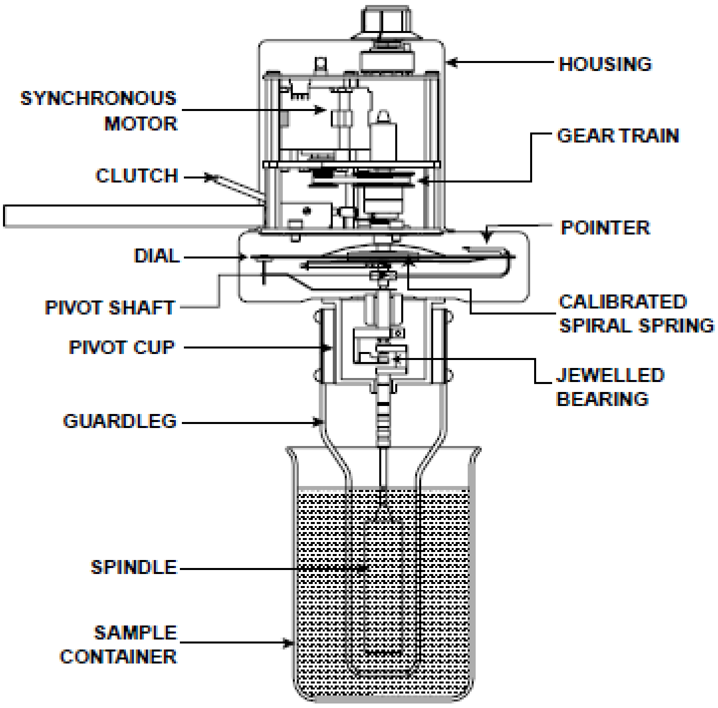


Figure 7 Mechanism of Rotational viscometer (Brookfield Engineering labs., Inc. 2005)

Steady shear experiments were carried to measure apparent viscosity as per ASTM 4402 with SC4-21 spindle. Bitumen of 8 gm was weighed accurately and filled into a coaxial cylinder which is fixed from rotation. Once the bitumen inside the cylinder attains the test

temperature, the spindle is lowered slowly so that the torque never exceeds 3 percent. A time of 30 min was maintained in thermo-chamber to attain temperature equilibrium. Care was taken to bring the temperature to test value 10 min before the actual testing. The speed was selected to maintain the torque between 10 to 98 percent. Most of the apparent viscosity measurements were made at the torque level of 40 to 60 % for accuracy.

In a typical rotational coaxial viscometer of the type used here, the inner spindle rotates and the outer container is stationary. The flow is assumed to be a rotational laminar flow without any motion in the radial or axial directions and all the quantities are assumed to be functions of the radius 'r' only. The Margules equation as given below is then used to calculate the shear rate from the angular velocity of the spindle (Brookfield Engineering Laboratories, Inc. (2005)).

$$\dot{\gamma} = \frac{2\omega R_c^2 R_b^2}{x^2 (R_c^2 - R_b^2)}$$

Here $\dot{\gamma}$ is the shear rate in reciprocal seconds, ω is the angular velocity of the spindle in radian per second, R_c is the radius of the container, R_b is the radius of the spindle and x is the radius at which the shear rate is calculated (see Figure 8). For the calculation of viscosity, the shear rate is normally measured at the surface of the spindle.

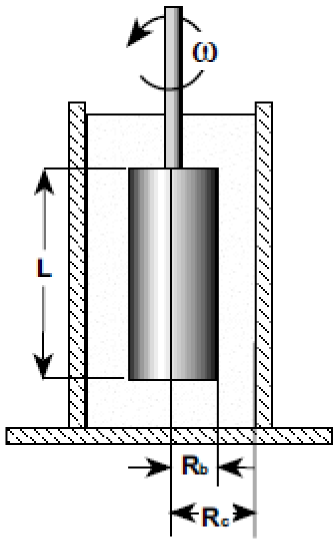


Figure 8 Coaxial geometry (Brookfield Engineering labs., Inc. 2005)

3.2.2 Short Term Aging Studies Using Rolling Thin Film Oven

The rolling thin film oven equipment as per ASTM D2872-88 requirements was used to simulate short term aging conditions. Essentially the short-term aging simulates the oxidation of bitumen resulting due to temperature at production, transportation, laying and compaction of bituminous mixtures. In the investigations that were carried out, the bitumen was heated to pouring consistency. 35 gm of bitumen was filled into RTFO bottles and aged at 165 ^{o}C for 85 min with air flow rate of 4 l/min (Figure 9). Loss in mass was determined after testing and samples were used for further testing within 72 h.

Figure 9 Rolling thin film oven

3.2.3 Long Term Aging Studies Using Pressure aging vessel

The pressure aging vessel equipment which met ASTM D6521-08 requirements was used to simulate the long-term aging of bitumen. It is a process of accelerated aging of bitumen by means of pressurized air at elevated temperature. Generally, bitumen samples subjected to short-term aging using RTFO are used. The accelerated aging intends to simulate the oxidation of bitumen during the first 5-10 years' service. Investigations were carried out at a pressure of 2.1 MPa and temperature of 100 ^{o}C. 50 gm of RTFO aged sample was used for the same. After conditioning for 20 h in PAV, the residue is degassed in a vacuum oven immediately (Figure 10).

Figure 10 Pressure aging vessel and vacuum degasser

3.2.4 Rheological Studies Using Dynamic Shear Rheometer

The dynamic shear rheometer used for the experimentation is the Physica MCR 301 manufactured by Anton Paar. It measures torque with an accuracy of 10^{-6} Nm and normal force with an accuracy of 0.002 N. Moreover, it can maintain temperature with an accuracy of 10^{-20}C and can maintain the gap at 1 mm with 10^{-4} mm accuracy. The instrument comes with software – *Rheoplus*. Dynamic shear rheometer (Figure 11) was used to characterize the rheological properties of unaged, short-term aged and long-term aged binders. The rutting parameter as defined by ASTM D6373-99 was characterized with RTFO aged bitumen samples which provides an indication of rutting resistance. 25 mm parallel plate geometry was used to evaluate the rheological properties at an angular frequency of 10 rad/s for 10 cycles.

Figure 11 Experimental setup of dynamic shear rheometer

3.2.5 Binder Stiffness Studies Using Bending Beam Rheometer

Thermal cracking of bituminous mixtures is critically governed by the stiffness of bitumen at lower temperatures. This is essentially due to the fact that at very low temperatures, the binders behave like brittle elastic solid due to increase in stiffness, which is reflected as thermal cracking during the cold climatic conditions in flexible pavements. Bending beam rheometer was used to calculate the low-temperature properties of binders. PAV aged bitumen sample were used to determine the low temperature range from +6 °C to -36 °C. The process determines the critical cracking temperature for bitumen based on the determination of the temperature at which the strength of the bitumen equals its thermal stress. The temperature so determined is intended to yield a low temperature performance grade of the sample being tested. Bitumen beam specimen of 6.35 mm thick, 12.70 mm wide and 127 mm long is subjected to a 980 mN load for 240 s, as per the ASTM D6816 standard test method (Figure 12). The bitumen beam is simply supported with the load applied at mid-span at constant temperature. Creep stiffness and creep rate is calculated based on the deflection measurements of loaded bitumen beam as follows:

$$S = \frac{Pl^3}{4bh^3\delta}$$

Where P is the test load, l is beam length, b is the beam width, h is the thickness of beam and δ is the measured deflection.

Figure 12 Bending Beam Rheometer

3.2.6 Superpave Mix Design

Superpave mix design integrates material selection and mix design into procedures based on project's climate and design traffic. Salient features of this mix design are the compaction using gyratory compactor which simulates the compaction close to roller through kneading action and the performance testing of designed mixtures to ensure expected performance. Laboratory compaction was carried out using a gyratory compactor and it gives information about the compactability of the particular mix by capturing data during compaction process. Volumetric approach of mix design is used in selecting the bitumen content. The performance of the bituminous mixtures immediately after construction is influenced by mix properties resulting from mixing, transporting, laying and compaction. Therefore the loose mixture is subjected to short-term aging after mixing before actual compacting. In this investigation, gyration level corresponding to medium and high traffic level of N_{ini} of 8, N_{des} of 100 and N_{max} of 160 gyrations were selected.

3.3 RUTTING STUDIES USING THE WHEEL TRACKER

Wheel tracking apparatus consisting of a loaded wheel that bears on a specimen held securely on a table. The table beneath the wheel moves to and fro. The rate at which the rut develops on the surface of the test specimen was monitored. Vertical ply in the loaded wheel mechanism is restricted to less than 0.25 mm. The apparatus includes:

3.3.1.1 Loading frame

Tyre of outside diameter between 200 mm and 205 mm fitted to the wheel. The tyre is treadless and has a rectangular cross profile with a width of 50 mm. The tyre thickness is 20 ± 2 mm. The tyre is of solid rubber with a hardness number of 80 IRHD units. The hardness may be confirmed according to ISO 48. The wheel load under standard test conditions is measured at the level on top of the test specimen and normal to the plane of the specimen table. The loading is conveniently achieved by the use of a weighted cantilever arm. The pressure exerted by the loaded tyre is 600 ± 30 kPa.

3.3.1.2 Sample table

It is constructed so as to enable a 200 mm minimum diametrical or rectangular, cored or laboratory-prepared test specimen which is held firmly in place with its upper surface horizontal. The required tracking plane is positioned in the centre to ensure symmetrical tracking motion.

3.3.1.3 Wheel-tracking machine

It is constructed so as to enable the test specimen in its cradle to be moved backwards and forwards under the loaded wheel in a fixed horizontal plane (Figure 13). The centre line of the tyre track is maintained such that it is not more than 5 mm from the theoretical centre of the specimen. The centre of the contact area of the tyre describes simple harmonic motion with respect to the centre of the top surface of the test specimen with a total distance of travel of 230 ± 10 mm and a frequency of 26.5 load cycles per 60 s for the test device. Linear variable differential transformer (LVDT) is used to measure the vertical position of the loaded wheel to a range 0.2 to 20 mm.

3.3.1.4 Temperature control

The temperature of the test specimen during testing is uniform and maintained constant at the specified temperature ±1 °C with the help of environmental chamber which has heaters and fans for circulating hot air. The capacity of environmental chamber is 30 to 60 ^{o}C.

3.3.1.5 Data acquisition

The rut profile is collected after every pass and recorded at 15 locations using a data acquisition system. The system is capable of recording temperature and speed of loading simultaneously. After 100 cycles, the data at every 100 cycles is recorded upto specified failure criteria.

3.3.1.6 Rut depth calculations

The proportional rut depth, *P*i, measured from the specimen for the given conditions like temperature and speed is calculated using the following relationship:

$$P_i = 100 \times \sum_{j=1}^{15} \frac{(m_{ij} - m_{oj})}{(15 \times h)}$$

Where P_i is the measured proportional rut depth in percent, m_{ij} is the local deformation in mm, m_{oj} is the initial measurement at the *j* location, and *h* is the specimen thickness in mm.

3.3.1.7 Test procedure

1) Cylindrical specimens of 150 mm dia and 50 mm height were prepared using gyratory compactor.
2) Three specimens per test condition were prepared with different modified binders at optimum bitumen content.
3) Specimens were conditioned in the environmental chamber for 6 h to bring the specimens to test temperature.
4) Since the mould size was 300 mm and wheel movement was upto 210 mm, the remaining portion of the mold was supported by wooden fixtures.

5) Once the specimen attained the test temperature as monitored by the specimen, the mounted resistance temperature detectors (RTD) were initiated.
6) For the present investigation, failure condition was defined as 10000 passes or 10 mm rut depth, whichever is earlier.
7) Initial 15 passes were used to establish the datum profile to make rut measurements by the data acquisition system
8) Speed of 26.5 cycles per min was maintained constant for a load of 720 N which exerts a pressure of 650 kPa.
9) Data acquisition automatically terminates the test once either of the terminal criteria is attained.

Figure 13 Wheel Tracker assembly with tested samples

CHARACTERIZATION OF MODIFIED AND UNMODIFIED BINDERS

4.1 INTRODUCTION

Bitumen exhibits visco-elastic characteristics at service temperature. As the temperature changes from a higher to a lower value, the bitumen exhibits transitory behaviour ranging from Newtonian fluid to brittle elastic solid. Also the visco-elastic response of bitumen is dependent on both time and temperature of testing. Hence, bitumen which imparts visco-elastic nature to the aggregate mixtures undergoes both reversible and irreversible change in its internal structure and composition during mix production and in-service. The resistance to change in properties over the service life due to variation in climate and loading has significant influence on the performance of pavements with bituminous mixtures. Hence, characterization of bitumen for its physical and rheological properties under different states (unaged, short and long-term aged) will provide the information on the expected performance of bituminous mixtures.

The physical properties of conventional unmodified binders is relatively simple and behaviour can be predicted through the use of traditional tests such as penetration, softening point and viscosity testing at various temperatures and material states. On the other hand, the rheology of modified binders is highly complex and, although the results from traditional tests may indicate a significant improvement in properties, the in-service performance of these binders is not easily categorized. This chapter presents detailed investigations on the physical and rheological properties of modified binders in comparison with unmodified bitumen using current Indian specifications and also the parameters found from the literature which substantially influence the performance of flexible pavements. Firstly, it gives a detail characterization of physical properties. Later, investigations on the rheological properties considering the effect of aging are presented. The detailed information on the longevity of different type of modified binders over the unmodified bitumen is presented.

4.2 CHARACTERIZATION FOR PHYSICAL PROPERTIES

The objective of characterization of physical properties of binders is to easily identify the material type which ensures certain specified performance requirements. The specifications for physical properties were framed to easily identify the material in the

field without the requirement of sophisticated instrumentation. Modified and unmodified binders were characterized for their physical properties according to Indian specifications (IS 73 and IS 15462). Table 2 shows the physical properties of different binders used in the present investigations.

Table 2 Physical properties of modified and unmodified binders

Properties	Binder Type				
	VG30	**PMB70**	**CRMB55**	**NRMB70**	**WPMB70**
Penetration at 25 ^oC 0.1mm, 100g, 5s	60 to70 (60 to 70)	50 to 60 (50 to 90)	30 to 40 (< 60)	50 to 60 (50 to 90)	30 to 40 (30 to 50)
Softening point (R&B), ^oC	46 (45-55)	60 (55 min)	56 (55 min)	50 (50 min)	62 (60 min)
Flash Point, ^oC	> 220 (175 min)	> 220 (220 min)	> 220 (220 min)	> 220 (220 min)	220 (220 min)
Ductility at 27 ^oC cm	80 (75 min)	100 +	57.7	78.5	34
Specific gravity, gm/cc	1 (0.99 min)	1.03	1.03	1	1.045
Elastic recovery at 15 ^oC (%)	71	77 (70 min)	68 (50 min)	55 (40 min)	23.67 (50 min)
Viscosity at 150 ^oC, (@ 135 ^oC for VG30), Poise	5.29 (3 min)	7.29 (2-6)	7.87 (2-6)	2.97 (2-6)	5.33 (3-9)
Separation, Difference in softening Point, ^oC	---	1 (3)	2 (3)	2 (3)	3 (3)
After subjecting to aging in thin film oven					
Loss in weight (%)	0.42 (1 max)	0.19 (1 max)	0.35 (1 max)	0.3 (1 max)	1.01 (1 max)
Reduction in penetration of residue at 25 ^oC (%)	18.23 (48 max)	12.72 (35 max)	28.57 (40 max)	11.67 (40 max)	26.67 (35 max)
Increase in softening Point, ^oC	4	2 (6 max)	4 (6 max)	3 (6 max)	7 (6 max)
Elastic recovery at 25 ^oC (%)	---	60 (50 min)	48 (35 min)	32 (25 min)	23 (35 min)

* Values in the parentheses show the specification requirements.

The results presented in Table 2 are the average of three trials. These trails were carried out to eliminate sampling error. From Table 2, it can be inferred that Waste Plastics Modified Bitumen (WPMB) failed to fulfill the elastic recovery criteria under both unaged and aged conditions. Elastic recovery behaviour indicates that the bitumen recovers most or all of its initial state when the load that causes deformation is removed. The elastic recovery of bitumen is commonly used to measure the fatigue resistance of bitumen or its ability to absorb large stresses without cracks or deformation. Waste

plastics used to modify asphalt bitumen in the present study consisted of low and high-density polyethylene, which are plastomeric in nature. Form the investigation, it may be inferred that the use of waste plastics as modifier might form a rigid phase or network, imparting low elastic recovery properties to the base asphalt bitumen but induces a high stiffness. Loss in weight is also higher than the specified limits in case of WPMB. This may be due to the reason waste plastics as a modifier gradually changes its properties over time due to heat, oxidation, ultra violet radiation and loss of volatile components.

Viscosity of unaged PMB70 and CRMB55 were found to be higher than the specified values. The increase in viscosity may be due to higher concentration of polymer and crumb rubber in the base bitumen. From the physical properties evaluated (Table 2) it can be seen that PMB70 shows highest elastic recovery and was found to be least susceptible to aging. The elastic recovery and viscosity of NRMB70 was found to be lower than the CRMB. This could be due to type, size and percentage of rubber added for modification of the base asphalt bitumen. Thus, it is to be noted that there is a need for standardization on the physical properties viz., size, gradation and percentage of the crumb rubber in the CRMB as well as the dosage of the polymer in the base bitumen, so that the modified binder will offer the expected performance. The properties of the base bitumen also have a significant influence on the properties of the modified binder. There is a need to characterize both the base bitumen as well as the modified bitumen, so that the benefits of the modified bitumen can be assessed.

4.3 RHEOLOGICAL CHARACTERISTICS

The ratio of stiffness modulus to sin of phase angle ($G^*/\sin\delta$) of bitumen is identified as a factor to evaluate the rutting resistance of bituminous mixes. Higher the temperature where the ratio is greater than or equal to 2.20 kPa, lower would be the rutting susceptibility. Essentially the concept is derived from the energy dissipation process of viscoelastic materials. More viscous the material, higher is the energy dissipated per loading cycle. According to rutting indicator, higher the G^* of bitumen, higher is the resistance to rutting. In the same manner, lower the δ (viscoelastic lag), higher recoverability after unloading. Table 3 shows the critical high temperature properties of different binders used in the present study. It can be observed that modification enhanced the stiffness of bitumen at high temperature when compared to unmodified bitumen.

WPMB70 has the highest critical temperature for rutting whereas PMB70 has the lowest phase angle. It shows that even though stiffness is higher, due to elastic nature (lower phase angle), PMB70 would result in better rutting resistance. It is interesting to infer from Table 3 that unmodified bitumen having higher stiffness at 74.5 ^{o}C, also showed highest phase angle. This shows that energy dissipated by unmodified bitumen is higher when compared to other modified binders considered in the present study.

Table 3 Rheological characteristics of different binders using DSR

Bitumen Type	**complex modulus, G* kPa**	**Phase angle, δ ^{o}**	**G*/sin δ >= 2.20 kPa**
VG30	2.20	86.68	74.5 °C
PMB70	2.09	71.80	82.2 °C
CRMB55	2.14	76.95	81.8 °C
NRMB70	2.17	79.87	79.8 °C
WPMB70	2.19	83.44	89.4 °C

The stress-strain response of flexible pavement is manifested by the viscoelastic behaviour of bituminous mixes. At lower temperatures, the stress relaxation property of bitumen critically dictates the thermal cracking resistance of flexible pavements. Hence to evaluate the thermal stress development and relaxation properties of bitumen, creep tests were carried out using BBR. Creep stiffness and rate were identified as the parameters to determine the critical thermal cracking temperature of bitumen and the bituminous mixes. Creep rate essentially explains the stress growth in the viscoelastic material. Higher the creep rate, higher is the stress relaxation. From Table 4 it is very interesting to observe that except PMB70 all other modified binders and unmodified bitumen have the same lowest critical thermal cracking temperature. This shows that only polymer modification can enhance both, high temperature rutting resistance and low temperature thermal cracking resistance.

Table 4 Rheological characteristics of different binders using BBR

Bitumen type	**m value**	**Stiffness, MPa**	**Low temperature, ^{o}C**
VG30	0.324	80.00	-10
PMB70	0.314	88.00	-16
CRMB55	0.313	46.00	-10
NRMB70	0.315	51.55	-10
WPMB70	0.372	81.95	-10

CHARACTERIZATION OF BITUMINOUS MIXTURES WITH MODIFIED BINDERS

5.1 INTRODUCTION

Bituminous mixes used for paving application consists of bitumen and mineral aggregates. The bitumen acts as a binding agent to glue aggregate particles into a dense mix. Performance of in-service pavements is significantly influenced by the bitumen and aggregate system and this is achieved by ensuring proper mix design. The ease with which a laboratory designed bituminous mix can be mixed, placed and compacted in the field can be defined as workability (Marvillet and Bougault, 1978). This chapter presents the details of the investigations carried out on the bituminous mixes with modified binders in comparison with the unmodified bitumen. The performance of the bituminous mixes under loading is evaluated using a rut wheel tester under varying temperature and material states.

The aggregate gradation recommended by MoRTH 4th revision for Bituminous Concrete Grade-2 surfacing course is considered in the present investigations (Table 5).

Table 5 Gradation used for the BC mix design as per MoRTH 4th revision

IS Sieve (mm)	Cumulative % by weight of total aggregate passing	Adopted mid level values selected in %	Cumulative % by weight retained
19	100	100	0
13.2	79-100	89.5	10.5
9.5	70-88	79	10.5
4.75	53-71	62	17
2.36	42-58	50	12
1.18	34-48	41	9
0.6	26-38	32	9
0.3	18-28	23	9
0.15	12-20	16	7
0.075	4-10	7	9
Percentage of fines = 7 %			

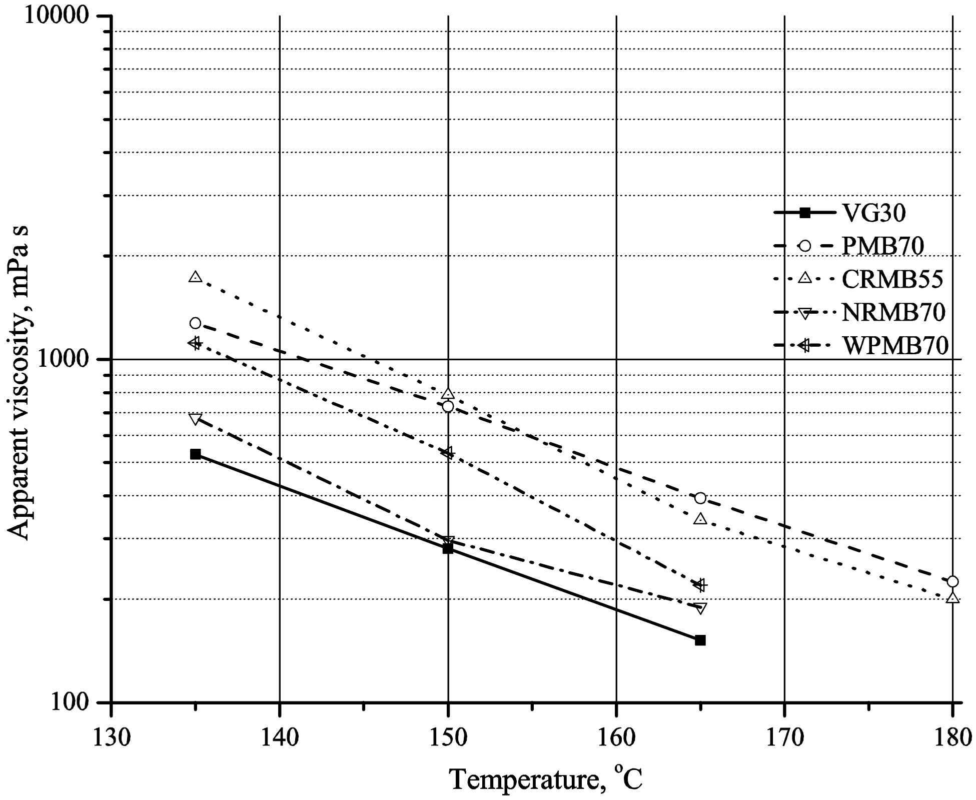


Figure 14 Apparent viscosity and temperature relationship

Mixing and compaction temperatures are determined from the apparent viscosity and temperature relation (ASTM D2493) where the apparent viscosity of the bitumen corresponds to 0.17 ± 0.02 Pa.s for mixing and 0.28 ± 0.03 Pa.s for compaction respectively (Figure 14). As expected, modification is found to increase the viscosity of the bitumen at higher temperature. The mixing and compaction temperatures for the NRMB and WPMB were found to be comparable with unmodified VG 30 bitumen and for PMB and CRMB they are found to be higher when compared to unmodified bitumen. The higher mixing and compaction temperatures in case of modified binders are possibly due to the formations of strong polymer network and absorption of oil fractions when compared to unmodified bitumen.

5.1.1 Mix design results

The rationale behind a bituminous mix design is optimizing the bitumen content for the desired aggregate gradation to satisfy the specified volumetric and strength requirements. The designed bituminous mix should be durable and cost effective. The mechanical behaviour of a designed bituminous mix is affected by the traffic loading and climatic

variations. The properties of the bituminous mixes with different binders is shown in Table 6.

In Superpave gyratory compactor, aggregates are oriented and compacted to a much denser state at particular bitumen content. Significant differences in the optimum bitumen content with different binders in the bituminous mixes were not found. However there was a significant difference in voids in mineral aggregate for the designed mixtures due to the change in bitumen type.

Table 6 Properties of bituminous mixtures designed using Superpave method

Properties/Bitumen types	VG30	PMB70	CRMB55	NRMB70	WPMB70
Optimum bitumen content, %	5.25	5.35	5.4	5.7	5.5
Effective bitumen content, %	4.24	4.37	4.36	4.27	4.40
Air voids, %	4	4	4	4	4
Voids in mineral aggregate, %	14.07	14.00	14.44	14.62	15.71
Volume of voids filled with bitumen, %	71.23	70.40	72.31	72.65	74.50
% G_{mm} (est) @ N_{ini}	82.65	88.93	88.95	88.79	88.70
% G_{mm} (est) @ N_{max}	96.58	96.41	96.55	96.45	96.49

5.1.2 Effect of temperature on rutting

The focus of this section is to understand the issues related to manifestation of bitumen modification on the rutting performance of bituminous mixtures under varying temperature. In order to relatively evaluate the performance of the mixtures with different binders, a constant bitumen content of 5.25 % was maintained. This bitumen content was the optimum in case of mixtures with VG30 unmodified bitumen. Compaction effort and aggregate gradation were the maintained constant as discussed in the earlier sections.

Figure 15 to 18 show the rutting resistance of bituminous mixtures with modified and unmodified binders under varying temperatures. It can be observed that at 30 ^{o}C, mixtures with natural rubber modified bitumen showed highest resistance to rutting when compared to mixtures with other modified and unmodified bitumen. Similarly at 40 and 50 ^{o}C , mixtures with crumb rubber modified bitumen showed higher resistance to rutting.

At 50 ^{o}C, mixtures with unmodified bitumen showed substantial increment in rutting when compared to its rutting resistance at lower temperatures. From the results, it can be understood that transition from viscoelastic solid-like to fluid-like bitumen behaviour initiates near a temperature of 50 ^{o}C in case of mixtures with unmodified bitumen whereas, mixtures with modified bitumen still tend to exhibit viscoelastic solid-like behaviour. This can also be substantiated by lower apparent viscosity of unmodified bitumen and lower temperature for rutting criteria (Tables 2 and 3). Also from Table 2 it can be observed that the unmodified bitumen has lowest softening point which can be correlated to transition and observed rutting sensitivity. At higher temperature of 60 ^{o}C, the mixtures with polymer modified bitumen were more resistant to rutting when compared to mixtures with other binders. It is found that mixtures with natural rubber modified bitumen showed substantial rutting when compared to mixtures with other type of modified binders. It essentially shows that at 60 ^{o}C, mixtures with natural rubber modified bitumen show viscoelastic fluid-like response under loading whereas, in case of other modified binders, transition from viscoelastic solid-like to viscoelastic fluid-like might occur at a higher temperature. This can also be substantiated by the physical and rheological properties of the binders shown in Tables 2 and 3.

It is observed that at all test temperatures, the mixtures with unmodified bitumen showed lowest rut resistance. A general trend of increase in temperature resulting in decrease of rut resistance of bituminous mixtures was observed irrespective of the bitumen type used. It is interesting to observe the dependency of the properties of bitumen on the rutting resistance at different temperatures. Mixtures with natural rubber and crumb rubber performed better at 30, 40 and 50 ^{o}C respectively when compared to mixtures with polymer modified bitumen. From Table 4 it can be observed that polymer modified bitumen showed the lowest temperature range (-16 ^{o}C), which means that polymer modified bitumen is more flexible when compared to other binders used in the study. This shows that in low temperature range, other modified binders could be stiffer than polymer modified bitumen. Hence, this could be a possible reason for higher resistance to deformation at lower temperature in mixtures with natural and crumb rubber modified binders.

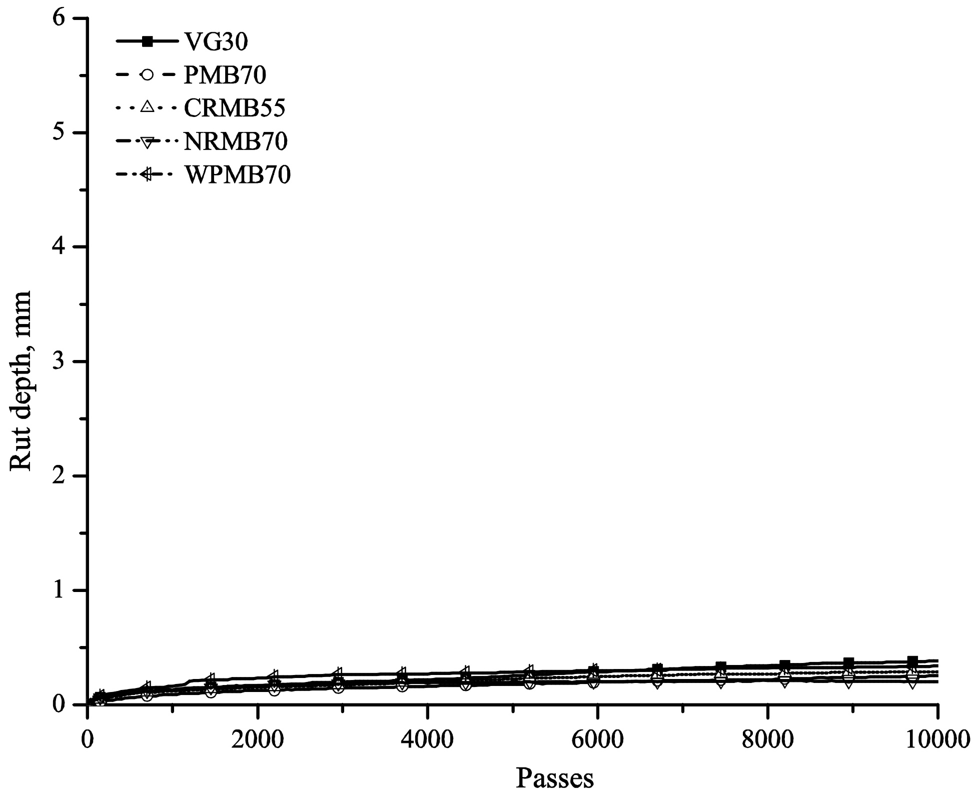


Figure 15 Rutting potential of bituminous mixes at 30 °C.

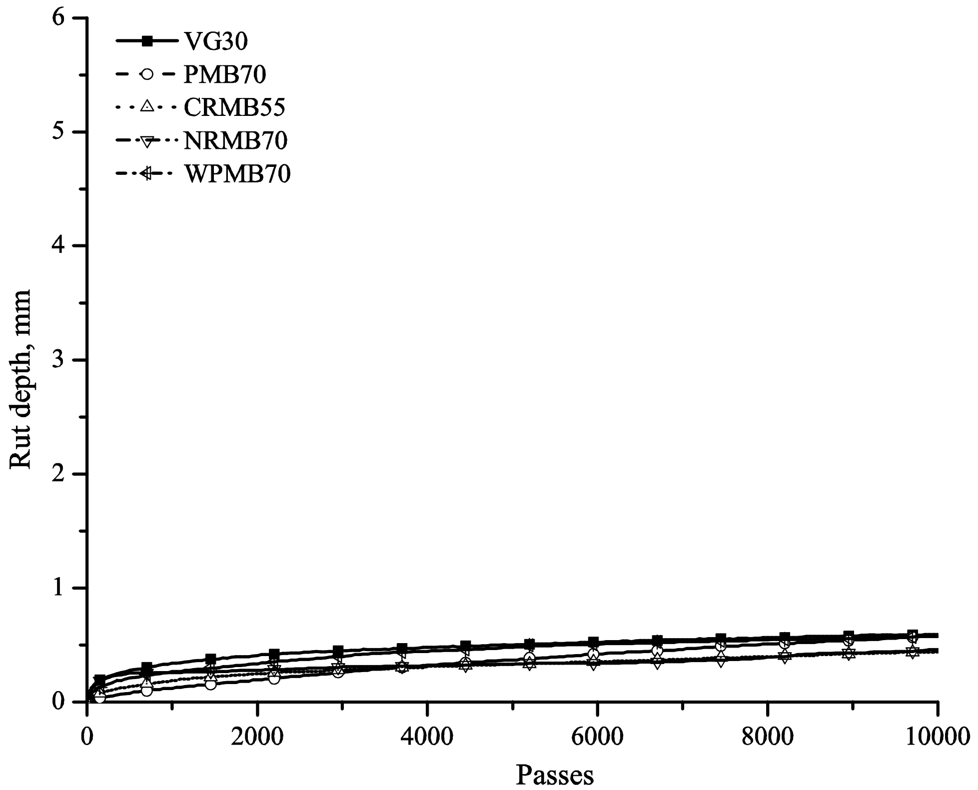


Figure 16 Rutting potential of bituminous mixes at 40 °C.

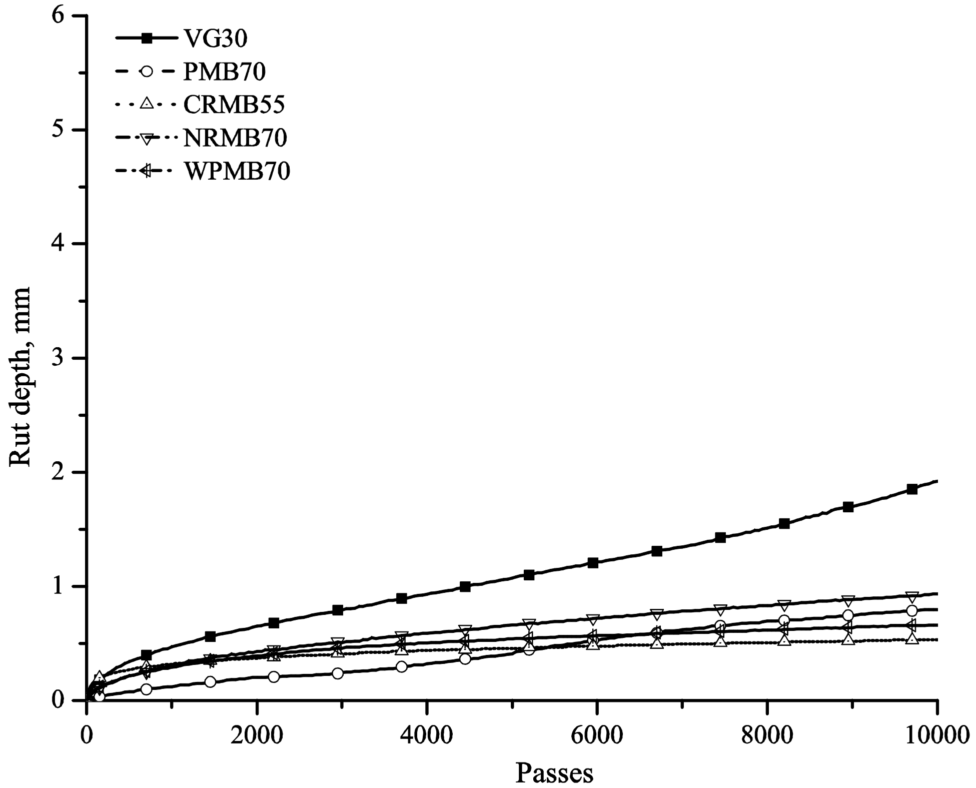


Figure 17 Rutting potential of bituminous mixes at 50 °C.

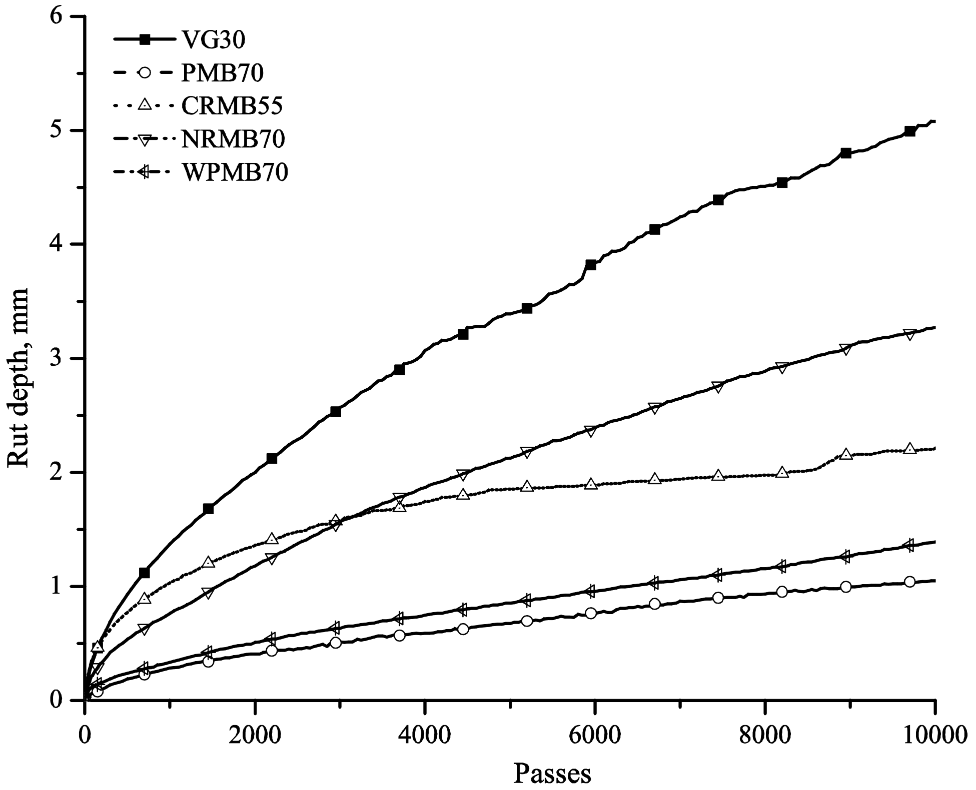


Figure 18 Rutting potential of bituminous mixes at 60 °C.

FIELD INVESTIGATIONS

The test stretch for the project was identified on National Highway NH-207 from Devanahalli (Ch.84.000) to Doddaballapur (Ch.104.000). The total length of the section is 20 km between the two places mentioned above. The project road in its present condition is a two lane undivided highway. The geographical location of the test strectch is shown in Figure 19.

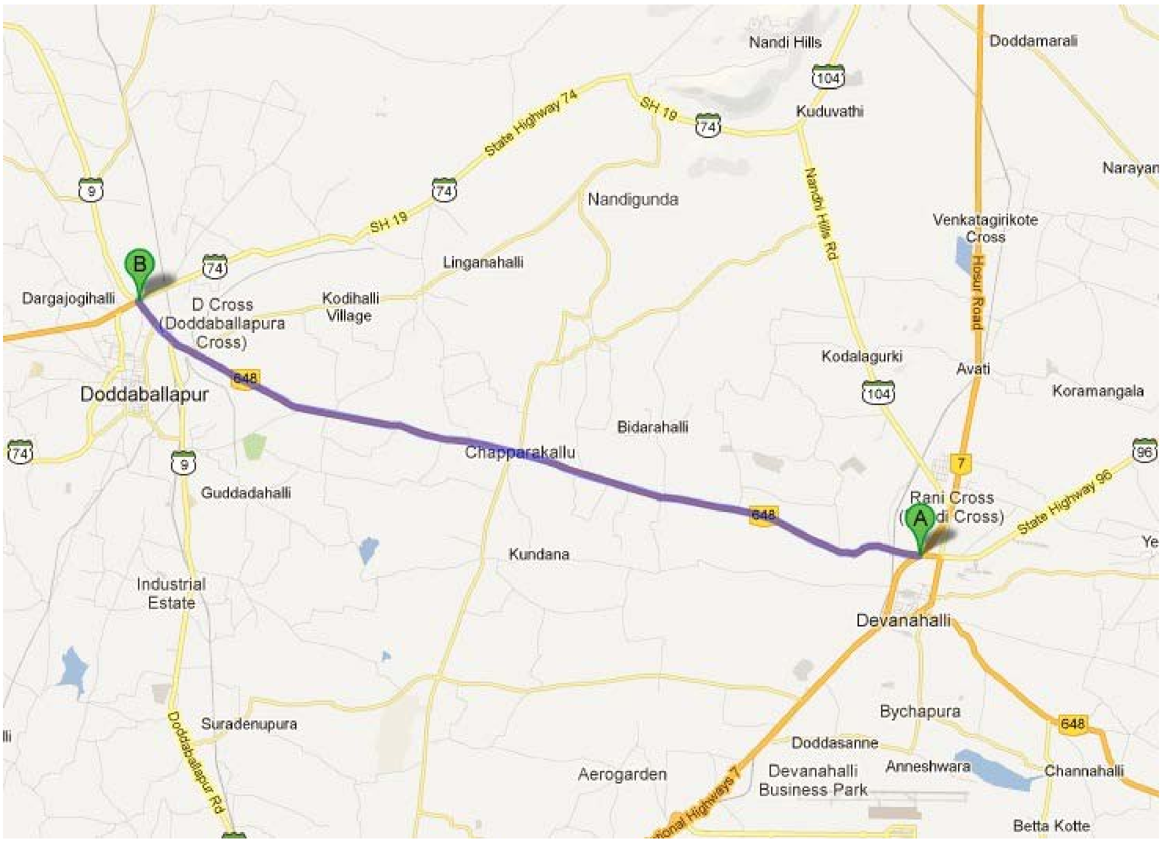


Figure 19 Location of the test stretch.

6.1 CONDITION OF TEST STRETCH BEFORE CONSTRUCTION

The selected reaches were scarified and rebuilt from the base layers and a profile corrective course of 50 mm thick bituminous macadam was overlaid for a length of 7.7 km. Figure 20 to 22 show the photos on the condition of test stretch before and after the construction of the profile corrective course. Figure 23 shows the strip plan of profile corrected and rebuilt sections. Figure 24 shows the bifurcated sections for overlaying with 25 mm thick semi dense bituminous concrete with respective modified and unmodified bituminous binders. The sections were bifurcated into homogeneous sections. The test

stretch was divided into five sections of each 4 km length. Each section was overlaid with semi-dense bituminous concrete overlay with different type of binders.

Figure 20 Condition of road before construction of PCC

Figure 21 Condition of road before construction of PCC

Figure 22 Condition of drainage of the road before construction of PCC

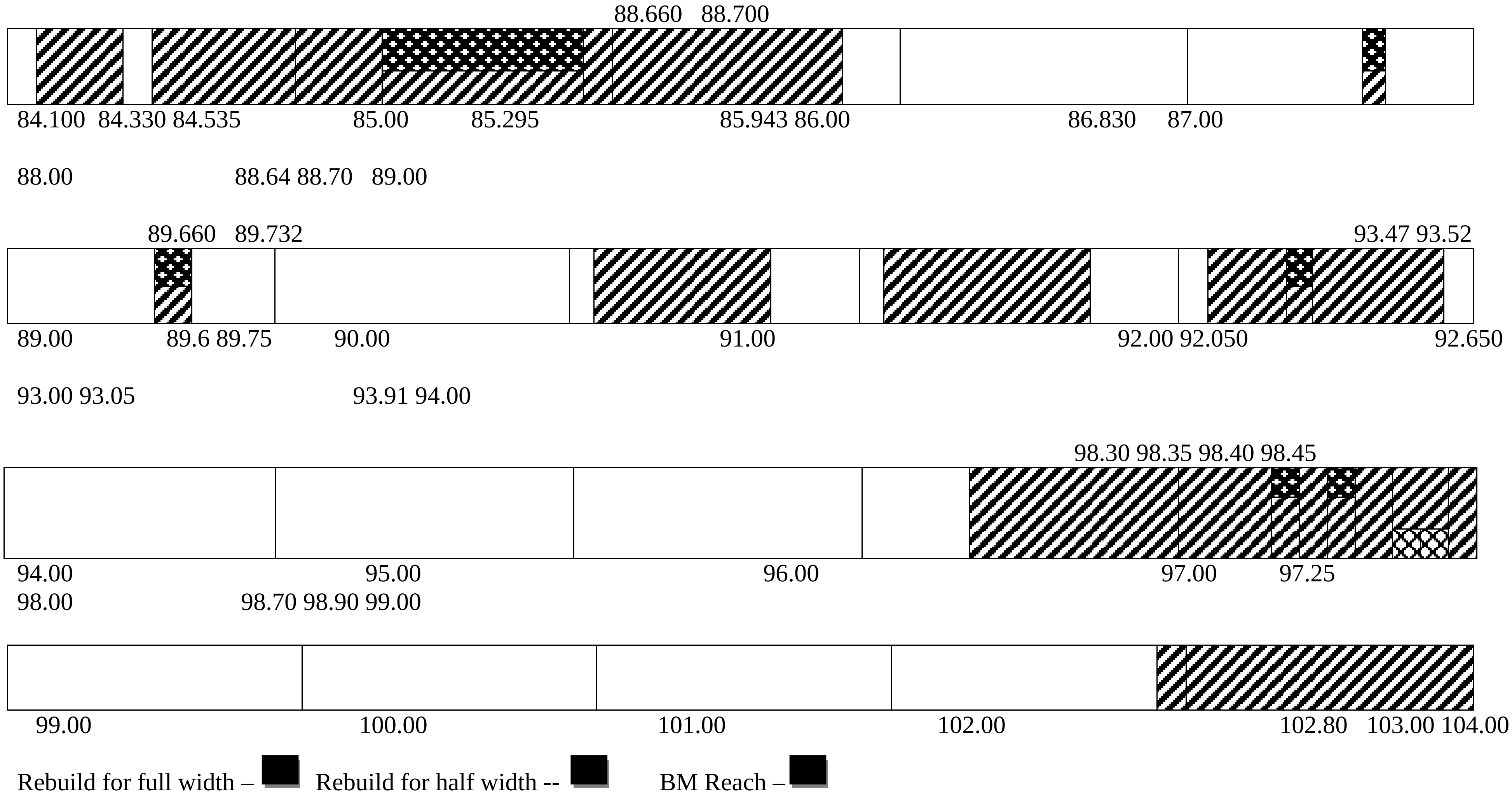


Figure 23 Strip plan showing the reaches of reconstruction and PCC with BM

Binders	VG 30	CRMB55	PMB70	NRMB70	WPMB70
Chainage, km	84 88	88 92	92 96	96 100	100 104

Figure 24 Bifurcated sections with unmodified and modified bituminous binders

6.2 FIRST CYCLE OF PAVEMENT EVALUATION BEFORE OVERLAY CONSTRUCTION (JULY 2009)

6.2.1 Benkelman beam deflection studies (July 2009)

Benkelman Beam deflection survey was carried out on the test sections as per IRC: 81-1997. The procedure adopted for carrying out Benkelman Beam deflection studies was as follows:

A standard truck with a loaded weight of 8170 kg on the rear axle fitted with dual tyre inflated to a pressure of 5.60 kg/cm^2 was used for loading the pavement. Before starting the survey, the Benkelman Beam was calibrated to ensure proper working of dial gauge as per procedure stated in Clause 4.3.4 of IRC: 81-1997. The measurement points in the longitudinal direction (i.e., along traffic direction) were at 50 m interval on both directions. Representative soil samples were collected from subgrade level for determination of moisture content, soil classification and Atterberg limits from test pits. The test results are shown in Table 7. Photo 25 shows the studies under progress.

Table 7 First cycle of deflection studies on test stretch before construction (July 2009)

Chainage	Bitumen type	Corrected Characteristic Deflection, mm	Chainage	Bitumen type	Corrected Characteristic Deflection, mm
84 to 85	VG30	0.269	94 to 95	PMB70	0.323
85 to 86		0.217	95 to 96		0.326
86 to 87		0.215	96 to 97	NRMB70	0.272
87 to 88		0.220	97 to 98		0.253
88 to 89	CRMB55	0.194	98 to 99		0.219
89 to 90		0.259	99 to 100		0.413
90 to 91		0.282	100 to 101	WPMB70	0.213
91 to 92		0.267	101 to 102		0.222
92 to 93	PMB70	0.223	102 to 103		0.359
93 to 94		0.286	103 to 104		0.507

Figure 25 Deflection studies being carried out at project road

6.2.2 Pavement roughness (July 2009)

The Roughness Survey was carried out using the ROMDAS. The roughness values are recorded in terms of roughness in m/km and later converted to unevenness index in mm per kilometre (Table 8). Three trail runs were made along each wheel path in each direction. The vehicle and the instrument used to determine the roughness of the test section are shown in Figure 26.

Table 8 Unevenness index of the test stretch before construction (July 2009)

Chainage	Bitumen type	Unevenness Index mm/km	Chainage	Bitumen type	Unevenness Index mm/km
84 to 85	VG30	4119	94 to 95	PMB70	4002
85 to 86		3416	95 to 96		3602
86 to 87		4244	96 to 97	NRMB70	4219

87 to 88		5207	97 to 98		4191
88 to 89	CRMB55	4176	98 to 99		4414
89 to 90		3514	99 to 100		4012
90 to 91		5224	100 to 101	WPMB70	3518
91 to 92		3199	101 to 102		3571
92 to 93	PMB70	3148	102 to 103		4161
93 to 94		3970	103 to 104		3913

Figure 26 Unevenness studies being carried out at project road before construction

6.2.3 Axle load survey (July 2009)

Axle Load Survey was carried out to determine the load spectrum and the trend of overloading. Weights of individual axles of different class of commercial vehicles were recorded and used to determine Vehicle Damage Factor (VDF). The survey was carried out at two locations in both directions for one day (24 hours). The set up and progress of axle load survey is shown in Figure 27. The summary of vehicle damage factor is presented in Table 9.

Figure 27 Axle load studies being carried out at project road

Table 9 Axle load summary (July 2009)

Type of vehicle	Vehicle damage factor	
	LHS	RHS
Light commercial vehicle	0.126	0.695
Two axle truck	6.530	5.148
Buses	1.154	0.241
Three axle truck	5.656	3.549
Semi truck trailer	6.163	9.702

6.3 SECOND CYCLE OF PAVEMENT EVALUATION BEFORE CONSTRUCTION (FEBRUARY 2010)

The construction of test stretch with the selected the modified binders was delayed by nine months from the period of first cycle of pre-evaluation studies and hence there was visible deterioration in the pavement condition. Hence it was decided to assess the condition of

pavement just before actual overlay construction. Table 10 shows the characteristics deflection measured using Benkelman Beam as per IRC 81: 1997.

Table 10 Second cycle of deflection studies on test stretch before construction (February 2010)

Chainage	Bitumen type	Corrected Characteristic Deflection, mm	Chainage	Bitumen type	Corrected Characteristic Deflection, mm
84 to 85	VG30	1.32	95 to 96	PMB70	0.79
85 to 86		1.09	96 to 97		1.04
86 to 87		0.82	97 to 98	NRMB70	0.98
87 to 88		0.55	94 to 95		1.26
88 to 89	CRMB55	0.78	98 to 99		1.30
89 to 90		0.91	99 to 100		0.90
90 to 91		1.02	100 to 101	WPMB70	0.88
91 to 92		1.23	101 to 102		0.78
93 to 94	PMB70	1.13	102 to 103		1.08
94 to 95		1.30	103 to 104		0.97

6.4 PREPARATION OF THE EXISTING SURFACE

The selected sections as shown in Figure 24 were rebuilt from granular layers and 50 mm bituminous macadam was laid over as profile corrective course at selected reaches as shown in Figure 23. All the operations were carried out to prepare the test stretch to receive the overlay are shown in Figure 28 to 33.

Figure 28 Scarification of badly damaged reaches

Figure 29 Test stretch after PCC

Figure 30 Rebuilt section near Pipe culvert

Figure 31 Test stretch after PCC

Figure 32 Section with PCC near level crossing

Figure 33 Rebuilt tank bund section

6.5 CONSTRUCTION OF TEST STRETCH

6.5.1 Execution and quality control during construction

Figure 34 Overlay construction: Compaction

Figure 35 Quality control by NH Bangalore division: Thickness, gradation, temperature and bitumen content

6.5.2 Quality control

The density, gradation and bitumen content measurements were carried out during and immediately after the construction of the test stretches to ensure that the quality of bituminous overlay construction is as per the specifications. Table 11 shows the density results of the bituminous layer in different sections. From Table 11, it can be observed that for a specific aggregate gradation, the use of different bitumen did not affect the density values significantly. However, the temperature range of production, transport and placing play an important role. It can also be observed that variation in density of bituminous mixes with waste plastic as an additive which may be due to variability involved in the process of production.

Table 11 Density control during construction (March-April 2010)

Chainage	Bitumen type	Bulk Density		
		No of samples	Mean	Std Dev
84 to 88	VG30	8	2.28	0.02
88 to 92	CRMB55	8	2.28	0.03
92 to 96	PMB70	8	2.30	0.03
96 to 100	NRMB70	8	2.28	0.03
100 to 104	WPMB70	8	2.30	0.10

6.6 DEFLECTION STUDIES AFTER CONSTRUCTION

6.6.1 Deflection studies

The structural adequacy of bituminous overlay with different modified binders was evaluated using Benkelman beam. The characteristic deflection measured is as shown in Table 12.

Table 12First cycle of deflection studies on test stretch after construction (August 2010)

Chainage	Bitumen type	Corrected Characteristic Deflection, mm	Chainage	Bitumen type	Corrected Characteristic Deflection, mm
84 to 85	VG30	0.82	94 to 95	PMB70	0.39
85 to 86		1.06	95 to 96		0.73
86 to 87		0.72	96 to 97	NRMB70	1.16
87 to 88		0.45	97 to 98		0.94
88 to 89	CRMB55	0.55	98 to 99		1.19
89 to 90		0.67	99 to 100		0.63
90 to 91		0.37	100 to 101	WPMB70	0.46
91 to 92		0.70	101 to 102		0.59
92 to 93	PMB70	1.11	102 to 103		0.52
93 to 94		1.02	103 to 104		0.39

6.6.2 Roughness studies

Improvement in riding quality due to overlay was assessed using fifth wheel bump integrator. Table 13 shows the roughness values of the test section immediately after overlaying.

Table 13 Roughness of the Test Stretch (August 2010)

Chainage	Bitumen type	Roughness, mm/km	Chainage	Bitumen type	Roughness, mm/km
84 to 85	VG30	2312	94 to 95	PMB70	1925
85 to 86		2035	95 to 96		1833
86 to 87		1920	96 to 97	NRMB55	1858
87 to 88		1901	97 to 98		1989
88 to 89	CRMB55	2025	98 to 99		2014
89 to 90		1952	99 to 100		2064
90 to 91		1902	100 to 101	WPMB70	1898
91 to 92		1896	101 to 102		1970
92 to 93	PMB70	1884	102 to 103		2045
93 to 94		1870	103 to 104		2165

6.6.3 Traffic volume count

The traffic volume count was collected from NH Bangalore Division during 2010. Table 14 summarizes the present classified traffic volume running on the test stretch at two different locations.

Table 14 Summary of classified traffic volume count (August 2010)

Location	**Cars**	**Motor Cycles**	**LCV**	**Buses**	**Two Axle trucks**	**Multi Axle vehicles**	**Agricultural Tractors**
84.00	1736	1470	849	501	3825	5063	787.5
102.54	2469	1821	1827	609	7755	6309	2223

6.6.4 Condition survey after construction

Pavement condition survey was carried out to physical inspect the distress and assess the condition of the test stretch. Table 15 summarizes the present pavement condition.

Table 15 Pavement condition survey (August 2010)

Chainage	Bitumen type	Cracking, sqm/km	Patching, sqm/km	Bleeding, sqm/km
84 to 85	VG30	8.9	0.05	0
85 to 86		1.05	20	0.45
86 to 87		0	0	0
87 to 88		2	1	0
88 to 89	CRMB55	1.5	0	0
89 to 90		0.5	0	0
90 to 91		0.48	0	0.15
91 to 92		0.65	0	0.13
92 to 93	PMB70	0	0	0.05
93 to 94		1.75	0	0
94 to 95		0	0	1
95 to 96		0	0	0

96 to 97	NRMB70	0	0	0
97 to 98		0.25	0	0
98 to 99		1.5	0	0
99 to 100		1.5	0	0.05
100 to 101	WPMB70	0.08	0.15	0.15
101 to 102		3. 9	0	0.43
102 to 103		5.08	14	0.25
103 to 104		10.3	0	0.08

6.7 OBSERVATIONS ON THE FIRST CYCLE OF EVALUATION

Table 16 summarizes the deflection growth and the improvement in riding quality. It was also observed that throughout the test stretch the shoulder was not maintained to the required level and grade and also the longitudinal drains were completely chocked. As a result edge failures, potholes, settlements, fatigue cracking and rutting along the wheel path were observed (Figure 39).

Table 16 Evaluation studies before and after construction

Chainage	Bitumen type	Characteristic deflection, mm			Unevenness, mm/ km	
		First cycle before construction	Second cycle before construction	First cycle after construction	First cycle before construction	First cycle after construction
84 to 85	VG30	0.269	1.32	0.82	4119	2312
85 to 86		0.217	1.09	1.06	3416	2035
86 to 87		0.215	0.82	0.72	4244	1920
87 to 88		0.220	0.55	0.45	5207	1901
88 to 89	CRMB55	0.194	0.78	0.55	4176	2025
89 to 90		0.259	0.91	0.67	3514	1952
90 to 91		0.282	1.02	0.37	5224	1902
91 to 92		0.267	1.23	0.70	3199	1896
92 to 93	PMB70	0.223	1.13	1.11	3148	1884
93 to 94		0.286	1.30	1.02	3970	1870

94 to 95		0.323	0.79	0.39	4002	1925
95 to 96		0.326	1.04	0.73	3602	1833
96 to 97	NRMB70	0.272	0.98	1.16	4219	1858
97 to 98		0.253	1.26	0.94	4191	1989
98 to 99		0.219	1.30	1.19	4414	2014
99 to 100		0.413	0.90	0.63	4012	2064
100 to 101	WPMB70	0.213	0.88	0.46	3518	1898
101 to 102		0.222	0.78	0.59	3571	1970
102 to 103		0.359	1.08	0.52	4161	2045
103 to 104		0.507	0.97	0.39	3913	2165

Figure 36 Condition of test stretch after construction (August 2010)

PERFORMANCE ANALYSIS AND DISCUSSIONS

7.1 PERIODIC PAVEMENT PERFORMANCE EVALUATION

The pavement performance evaluation studies were conducted by studying the progression of distress like rutting, cracking, roughness and overall condition. The structural adequacy was measured with periodic evaluation of rebound deflection. Table 17 shows the variation in deflection values over the entire test stretch with different bituminous mixes.

Table 17 Deflection studies after construction

Chainage	Bitumen type	Characteristic deflection, mm			
		First cycle after construction	Second cycle after construction	Third cycle after construction	Fourth cycle after construction
84 to 85	VG30	0.82	1.11	1.25	1.29
85 to 86		1.06	1.39	1.61	2.01
86 to 87		0.72	0.98	1.19	1.22
87 to 88		0.45	0.65	0.82	0.91
88 to 89	CRMB55	0.55	0.77	0.88	1.18
89 to 90		0.67	0.92	1.14	1.30
90 to 91		0.37	0.54	0.9	1.31
91 to 92		0.7	0.96	1.25	1.45
92 to 93	PMB70	1.11	1.44	1.74	1.82
93 to 94		1.02	1.36	1.48	1.55
94 to 95		0.39	0.58	0.73	0.81
95 to 96		0.73	0.99	1.32	1.35
96 to 97	NRMB70	0.98	1.48	1.56	1.61
97 to 98		0.94	1.26	1.36	1.46
98 to 99		1.19	1.86	2.10	2.22
99 to 100		0.63	0.86	0.99	1.07
100 to 101	WPMB70	0.46	0.66	0.85	0.97
101 to 102		0.59	0.82	0.98	1.24

102 to 103		0.52	0.73	0.96	1.54
103 to 104		0.39	0.58	0.67	1.33

Figures 37 to 41 show the deflection progression with time with different binders in the wearing courses. The trend in deflection progression is captured with power law models correlating higher than 0.9 in all cases (Table 18). The models developed were based on the normalized deflections to account for the variation in the structural adequacy of the pavement structure before overlaying.

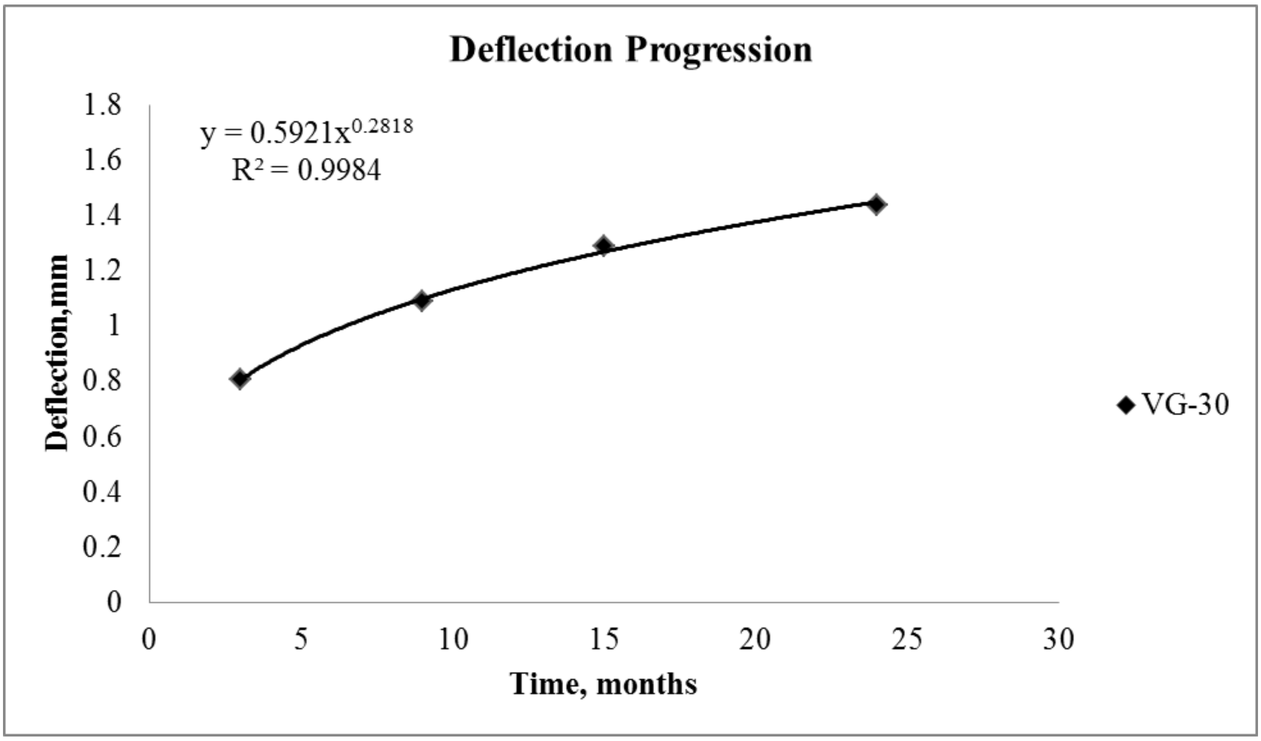


Figure 37 Deflection progression in pavement with VG-30 bitumen

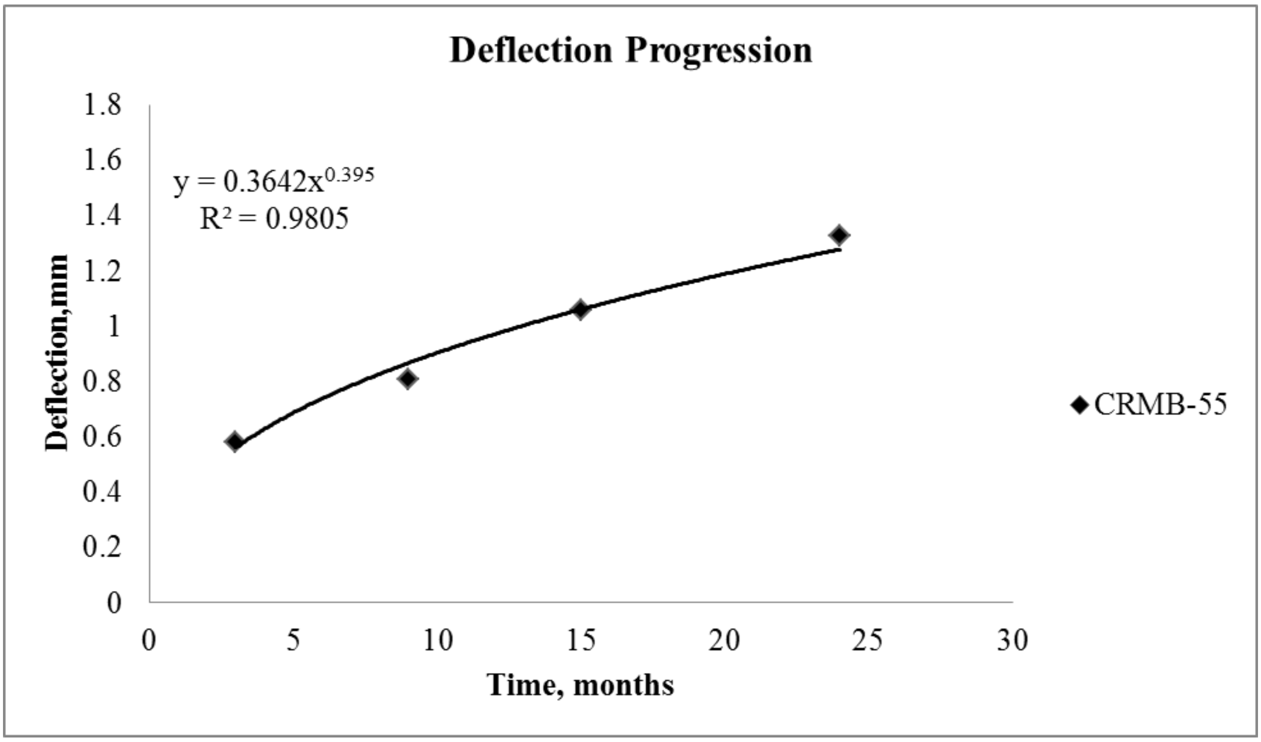


Figure 38 Deflection progression in pavement with CRMB-55 bitumen

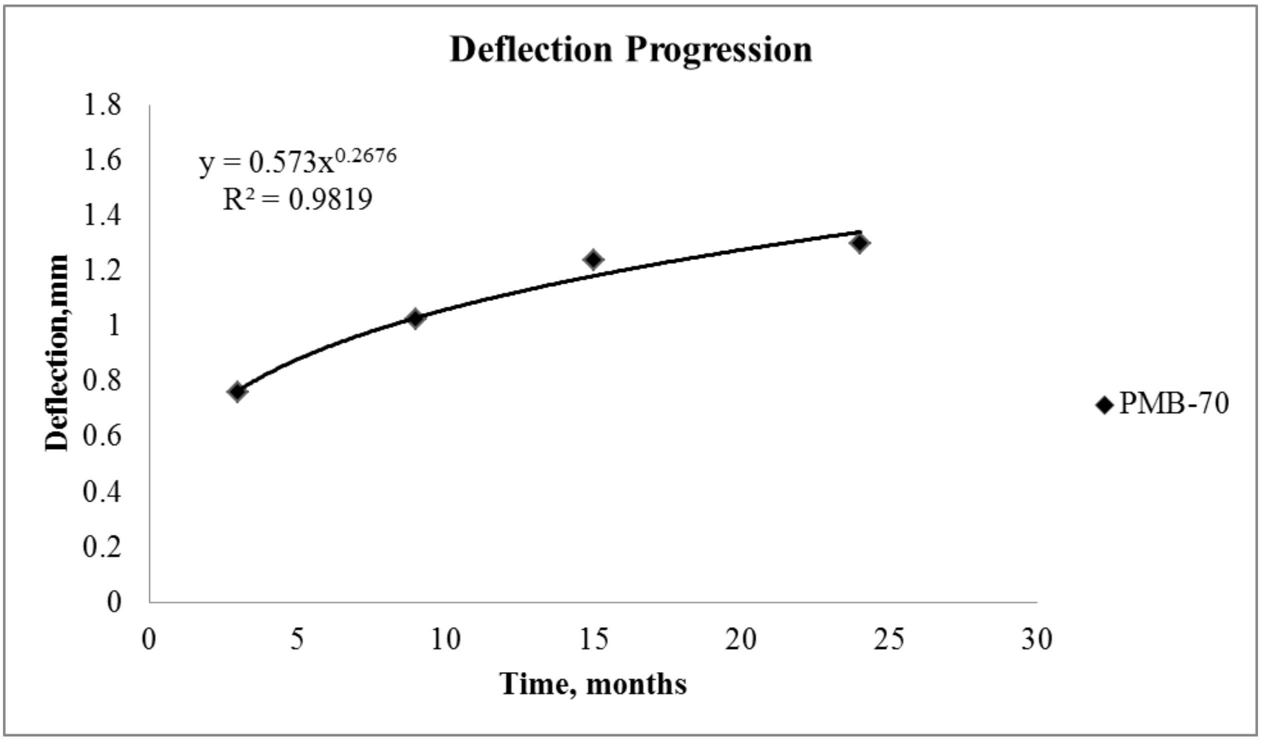


Figure 39 Deflection progression in pavement with PMB-70 bitumen

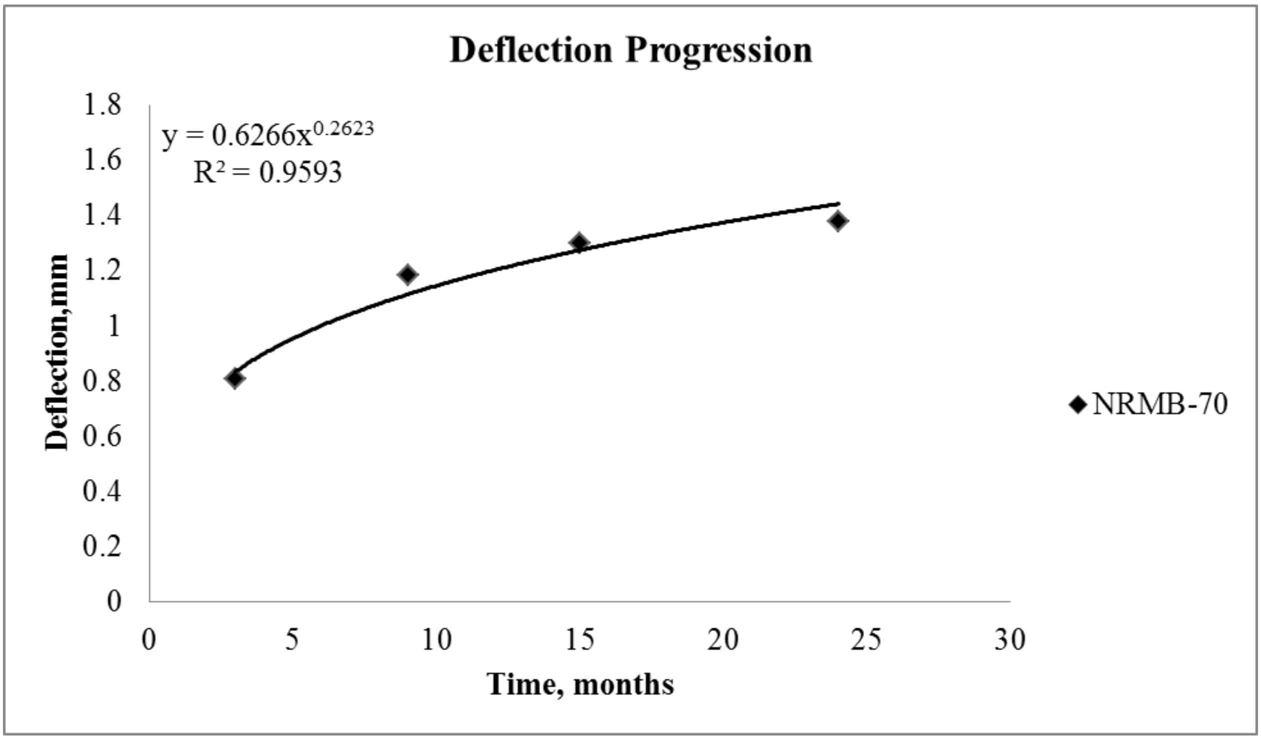


Figure 40 Deflection progression in pavement with NRMB-70 bitumen

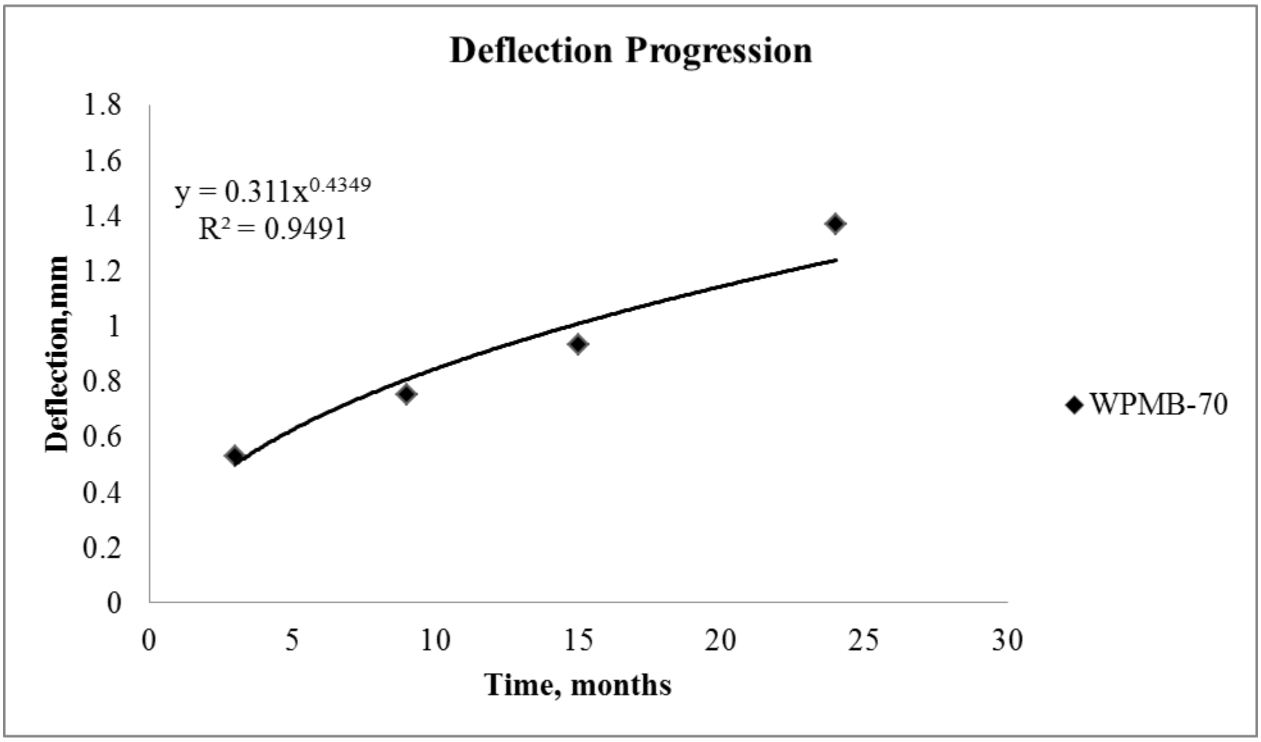


Figure 41 Deflection progression in pavement with WPMB-70 bitumen

Table 18 Deflection Progression Models with different binders

Bitumen type	Statistical Model	Correlation Coefficient
VG30	$0.5921(\boldsymbol{t})^{0.2818}$	0.9984
CRMB55	$0.3642(\boldsymbol{t})^{0.3950}$	0.9805
PMB70	$0.5731(\boldsymbol{t})^{0.2680}$	0.9819
NRMB70	$0.6266(\boldsymbol{t})^{0.2623}$	0.9593
WPMB70	$0.3110(\boldsymbol{t})^{0.4349}$	0.9491
*where ***t*** is the time in months		

Table 19 Roughness studies after overlay construction

Chainage	Bitumen	Roughness, m/km		
		First cycle after construction	Second cycle after construction	Third cycle after construction
84 to 88	VG30	3.27	3.42	3.66
88 to 92	CRMB55	3.34	3.49	3.58
92 to 96	PMB70	2.91	3.04	3.25
96 to 100	NRMB70	3.08	3.20	3.47
100 to 104	WPMB70	3.30	3.37	3.45

Table 19 presents the roughness progression with time. For the period of evaluation (upto 2 years) all the test sections offered similar roughness. The pavement structure with PMB-70 showed lowest roughness when compared to other sections with different modified and unmodified binders. However pavement structures with unmodified and other modified bituminous mixes were found to offer similar riding conditions.

7.2 LIFE CYCLE COST ANALYSIS (LCCA)

Life Cycle Cost Analysis (LCCA) is an indispensable technique that employs well-established principles of economic analyses to evaluate long-term performance of competing investment options (Kaan et al. 2003). It enables decision makers to optimize the expenditure of available funds to provide an economic assessment of competing design or rehabilitation strategies. For the present work, LCCA was carried out considering different modified

binders in the wearing course both theoretically and using the prediction models developed in this research work. The agency cost viz., construction cost, routine maintenance cost, rehabilitation cost and the salvage cost were considered in the analysis. Lane width of 7 m and length of 5 km was considered to estimate the total cost. The road user cost was not considered, since the traffic level was same and the roughness variation was not significant. All the costs were discounted to the present year at a rate of 6 % (for M-E PDG) and 6 to 10 % for prediction models.

7.2.1 Mechanistic-Empirical analysis

Mechanistic-Empirical Pavement Design Guide (M-E PDG) provides the pavement community the state-of-the-practice tool for the design of new and rehabilitated pavement structures (NCHRP, 2004). Specific site conditions and material properties can be incorporated for analyzing the pavement performance. Performance predictions are based on the mechanistic-empirical principles. The approach makes it possible to ensure that specific distress types are not likely to develop.

This study focuses on the comparison of rutting performance of bituminous mixes with modified and unmodified bitumen in the wearing courses. Even though M-E PDG was never calibrated for modified bituminous mixes, other than conventional mix, in the absence of any other more comprehensive materials-structural design system, an attempt has been made to use it for relative performance evaluation. However the assumption is that the properties of modified bitumen could also be reflected through the PG grade (Table 3), which is considered in the M-E PDG.

The pavement structure is composed bituminous mix in the wearing course, crushed stone base, crushed gravel sub-base and subgrade soil. The pavement structure was designed for an annual average daily traffic of 5000 vehicles, out of which 56 % of trucks were considered for a design life of 20 years. The analysis was carried out using the Mechanistic – empirical pavement design software. The region with similar climatic data was considered. Standard single axle and multi axle trucks were considered to study the effect of axle configuration on the performance of the flexible pavement considered in the present investigation.

7.2.1.1 Effect of Bitumen Type on Rutting Performance from theoretical predictions

From Table 3 it can be seen that polymer modified bituminous mix offers high resistance to rutting, and it also extends the pavement life. Rut depth of 20 mm total rut depth is reached only after 12 years of service (Table 21). The rutting in polymer modified bituminous mix is lower than the rutting in the mix containing unmodified bitumen. It can be seen that the bituminous mixes with modified bitumen offer longer predicted life than the mix with unmodified bitumen. The bituminous mixes with modified bitumen have higher life when compared to the unmodified bituminous mix.

It can be observed from Table 21, that temperature has a significant effect on the rutting behaviour of the bituminous mixes and hence the service life of pavement structure. The computed values of rutting for 59 ^{o}C are found to be higher than 53 ^{o}C. This clearly shows the effect of temperature on the rutting resistance of bituminous mixes is significant. The polymer modified bituminous mixes showed highest resistance to rutting at high temperatures. The service life of the pavement structure with polymer modified bitumen in the wearing course increases by 2 and 3 times when compared to unmodified bitumen at 53 and 59 ^{o}C respectively. It can also be observed that reduction in pavement service life due to increase in temperature was minimal in pavement structure with polymer modified bitumen in the wearing course. When compared to a pavement structure with unmodified bitumen in the wearing course, bituminous mixes with modified bitumen offered higher resistance to rutting.

Table 20 Reduction in pavement life with variation in pavement temperature (as predicted by ME-PDS)

Bitumen Type	Pavement life, years		Reduction in life with increase in pavement temperature, %
	Pavement temperature, ^{o}C		
	53	59	
VG-30	5.75	2.25	61
NRMB	7.58	3.58	53
WPMB	8.83	4.75	46

CRMB	**10.5**	**5.83**	**44**
PMB	**11.83**	**6.92**	**42**

7.2.1.2 Effect of Axle Configuration on Pavement Performance

The rut depths values for two axle configuration were studied viz., single and multi-axle trucks with an AADT of 5000. Figure 43 and 44 show the performance of unmodified and modified bituminous mixes for single and multi-axle type vehicles respectively. If multi-axle forms the predominant (74 %) composition in the traffic (AADT), the pavement service life is found to reduce by 40 % when compared to single axles, the predominant (56 %) composition. Pavements with wearing course of polymer and crumb rubber modified bituminous mixes offered highest resistance to heavy traffic loading when compared to pavements with wearing course of bituminous mixes with other bitumen types. Waste plastic modified and natural rubber modified bituminous mixes offered higher service life when compared to bituminous mix with unmodified bitumen. From this analysis, use of bituminous mixes with polymer modified bitumen is recommended for highways trafficked by heavier vehicles.

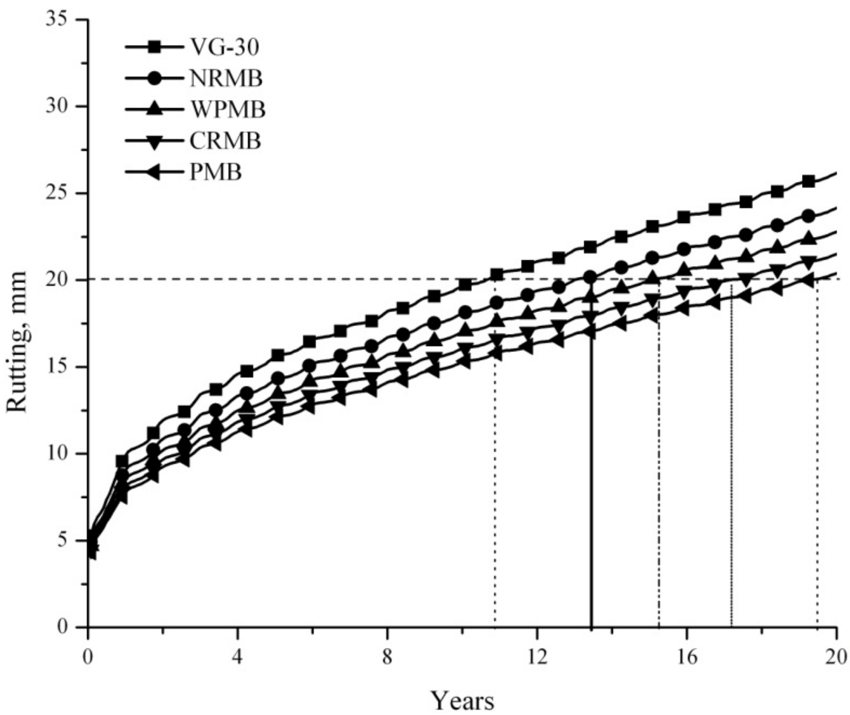


Figure 42 Variation of rut depth with varying bitumen types for single axle truck

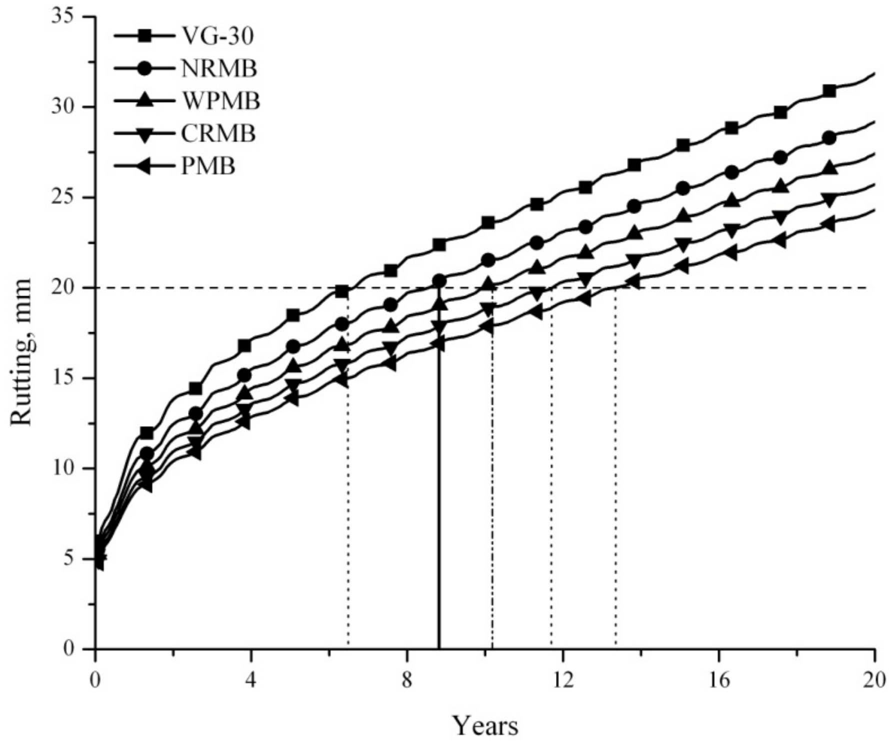


Figure 43 Variation of rut depth with varying bitumen types for tandem axle truck

7.2.2 Economics

Net Present Value (NPV) is the gross value of the net benefits discounted to the base year. Salvage Value (SV) represents the value of an investment alternative at the end of the analysis period. NPV and SV were calculated using the below relations (Walls and Smith, 1998). The cost for the analysis is considered from the present rate as per Karnataka state government schedule of rates.

$$NPV = Initial\ cost + \sum_{k=1}^{n} Rehabilitaion\ cost_k \left[\frac{1}{(1+i)^{nk}}\right] \tag{1}$$

where: i = discount rate

n = year of expenditure

$$SV = \left(1 - \frac{L_A}{L_E}\right) C \tag{2}$$

where: L_E = is the expected life of rehabilitation alternative

L_A = portion the expected life consumed

C = cost of the rehabilitation strategy

Table 21 Economic analysis based on mechanistic-empirical analysis for 20 years

Bitumen types	Agency cost, cr				Ratio of costs, (UM/M)
	Construction cost,	Routine Maintenance cost	Rehabilitation cost	Total costs	
VG-30	0.73	0.10	1.47	2.29	
NRMB	0.75	0.10	1.36	2.20	1.04
WPMB	0.75	0.10	1.27	2.12	1.08
CRMB	0.75	0.10	0.89	1.73	1.33
PMB	0.75	0.10	0.84	1.68	1.36

* UM = Unmodified bitumen, M = Modified bitumen

From Table 22 it can be seen that bituminous mixes with polymer modified bitumen offer higher benefits when compared to other alternatives considered in this study. However, compared to alternative with unmodified bitumen, all other alternatives with modified bitumen were found to be economical. The life cycle costs of mixes with other modified bitumen were found to be comparable with that of mix with unmodified bitumen.

Table 22 Economic analysis based on field prediction models for 5 years

Bitumen types	Agency cost, Rs.cr				Ratio of costs, (UM/M)
	Construction cost,	Routine Maintenance cost	Rehabilitation cost	Total costs	
VG-30	0.16	0.09	0.60	0.85	
NRMB	0.17	0.08	0.59	0.83	1.02
WPMB	0.17	0.08	0.59	0.83	1.02
CRMB	0.17	0.08	0.59	0.83	1.02
PMB	0.17	0.08	0.56	0.81	1.05

* UM = Unmodified bitumen, M = Modified bitumen

LCCA is also carried out with the use of deflection prediction models (Table 18). Using the statistical models, the deflection values are predicted for a period of five years. For the given

traffic level (50 msa) the overlay required in terms DBM and BC is estimated using IRC:81-1997. Cost benefit analysis was carried out based on the results from the prediction models and the same is presented in Table 23. From Table 23 it can be observed the cost analysis trend from the prediction models is comparable with the mechanistic-empirical predictions. In both case of cost analysis polymer modified bituminous mixes showed highest benefit ratio when compared to pavement structure with unmodified bituminous mix.

CONCLUSIONS

The test track was constructed with 25 mm thick semi-dense bituminous concrete resurfacing with different modified and unmodified bituminous binders to improve the riding quality. The deflection values before construction showed that the pavement section was structurally inadequate, requiring a strengthening overlay instead of thin resurfacing. The rapid deterioration in pavement condition was due to delay in the selection of test section, construction delays, increase in traffic volume more than expected and unexpected overloading in the selected test stretch due to quarrying. The test stretch was overlaid with 25 mm thick bituminous mix with different modified binders to relatively evaluate the performance of different mixes with different binders under the prevailing conditions. The significant findings from the study are listed.

1) Viscosity values of modified bitumen is found to increase by 1.5 times in case of rubber and waste plastic modified binders over unmodified binder after aging tests. The physical properties demonstrated that waste plastic modified bitumen fails to fulfill the elastic recovery properties after aging.
2) Significant high temperature rheological properties of SBS modified bitumen are: increased stiffness and not reduction in elasticity when compared to other modified binders and unmodified bitumen. The phase angle improved by 1.2 times for binders with SBS polymer modification over unmodified bitumen at high temperatures.
3) The flexural creep stiffness was found to be significantly lower in polymer modified bitumen at a particular temperature (-10 ^{o}C) when compared to other binders considered in the study. However, other modified binders and unmodified bitumen showed comparable flexural stiffness at -10 ^{o}C.
4) Bituminous mixes with unmodified bitumen were found to be more susceptible to rutting at high temperatures when compared to mixes with modified asphalt binders.
5) SBS polymer modified bituminous mix was found to offer 4.8 times higher rut resistance when compared to unmodified bitumen mix during laboratory rutting studies.

6) Statistical model developed for deflection progression showed that structural condition of pavement structure marginally improved when polymer modified bitumen was used.
7) From the parametric analysis, it was found that an increase in pavement temperature resulted in significant reduction in the pavement rutting resistance and thereby justifying the need for modified binders on all highways for improved performance.
8) For the traffic level, climatic conditions and pavement structure considered in the theoretical analysis, it was found that the polymer modified bituminous mixes offered longer service life when compared to unmodified bituminous mix.
9) The life cycle cost of pavement structure for 20 years with polymer modified bitumen showed a benefit of 1.36 times, when compared to pavement structure with unmodified bituminous mixes. Utilization of waste plastic and other modified bitumen are found to reduce the life cycle cost of pavement when compared to unmodified bitumen. However pavement with SBS polymer modified bituminous mixes resulted in lowest life cycle cost among all the alternatives considered in this study.
10) Based on the present research study, the relative order of performance of the semi-dense bituminous concrete mixes with different binders are as follows: (with the best performing binder as the first):
    i) SBS Modified Binder
    ii) Crumb Rubber Modified Binder
    iii) Waste Plastics Modified Binder
    iv) Natural Rubber Modified Binder
    v) Unmodified Binder

FURTHER STUDIES NEEDED

This research work aimed at characterizing and understanding the influence of different modified binders on the performance of bituminous mixes in pavement layers. The investigations focused on reporting experimental observations and presenting qualitative and quantitative results related to different modifiers influencing the performance of bituminous mixes. The statistical models developed present quantifiable benefits in terms of both performance and cost with different modified and unmodified bitumen. Further studies in this direction may consider the following:

- Study on the performance of modified and unmodified bitumen in all bituminous layers within the flexible pavement structure to develop the design charts.
- Studies on field performance of mixes with modified binder at varying traffic and climatic levels to develop the maintenance requirements of the flexible pavement structure with modified binders.
- Development and calibration of the mechanistic-empirical models from the numerical analysis and field observations for mixes with modified bitumen.

REFERENCES

[1] AASHTO R-30. (2002) Standard practice for mixture conditioning of hot-mix asphalt (HMA). American Association of State Highway and Transportation Officials (AASHTO), Washington DC, USA.

[2] AASHTO T-283. (2003) Standard method of test for resistance of compacted asphalt mixtures to moisture-induced damage. American Association of State Highway and Transportation Officials (AASHTO), Washington DC, USA.

[3] AASHTO TP-62. (2007) Standard method of test for determining dynamic modulus of hot-mix asphalt (HMA). American Association of State Highway and Transportation Officials (AASHTO), Washington DC, USA.

[4] Abdelrahman, M. A., and Carpenter, S. H. (1999) The mechanism of the interaction of asphalt cement with crumb rubber modifier (CRM). Transportation Research Record, 1661, 106-113.

[5] Airey G. D., and Brown S. F (1998) Rheological performance of aged polymer modified bitumen. Proceedings of the Association of Asphalt Paving Technologists, 67, 66-87.

[6] Akhtarhusein, A., Joseph, L., Jorge, B. S., and Monismith, C. L. (1991) Relationships between modified asphalt binders rheology and binder-aggregate mixture permanent deformation response. Proceedings of the Association of Asphalt Paving Technologists, 60, 121-159.

[7] Anderson, D. A., Christenen, D. W. Roque. R., and Robyak, R. K. (1992) Rheological properties of polymer modified emulsion residue. American Society of Testing Materials, ASTM STP 1108, 20-34.

[8] Anderson, D. A., Maurer, D., Ramirez, T., Christensen, D. W., Marastaena, M, O., and Mehta, Y. (1999) Field performance of modified asphalt binders evaluated with Superpave test methods. Proceedings of Annual Meeting of the Transportation Research Board, National Research Council, 78 (1661), 60-68.

[9] Anjan kumar, S., and Veeraragavan, A (2010) Performance based binder type selection using mixed integer programming technique. Construction and Building Materials, 24, 2091-2100.

[10] Asi, I. M (2007) Performance evaluation of Superpave and Marshall asphalt mix designs to suite Jordan climatic and traffic condition. Construction and Building Materials, 21, 1732-1740.

[11] Asphalt Academy. (2001) The use of modified bituminous binders in road construction. Technical Guideline, South Africa.

[12] ASTM D 6373-99. (1999) Standard Specification for Performance Graded Asphalt Binder. American Society of Testing Materials (ASTM) , 04.03, Pennsylvania, USA.

[13] ASTM D 2493-01. (2001) Standard viscosity temperature chart for asphalts. American Society of Testing Materials (ASTM), Pennsylvania, 05.01, USA.

[14] ASTM D 4402-02. (2002) Standard test method for viscosity determinations of unfilled asphalts using the brookfield thermosel apparatus. American Society of Testing Materials (ASTM), 04.03, Pennsylvania, USA.

[15] ASTM D 2872-88. (2004) Standard test method for effect of heat and air on a moving film of asphalt (Rolling Thin-Film Oven Test). American Society of Testing Materials (ASTM) , 04.03, Pennsylvania, USA.

[16] ASTM D 6931-07. (2007) Standard test method for indirect tensile (IDT) strength of bituminous mixtures. American Society of Testing Materials (ASTM) , 04.03, Pennsylvania, USA.

[17] ASTM D 6521-08. (2008) Standard practice for accelerated aging of asphalt binder using a pressurized aging vessel (PAV). American Society of Testing Materials (ASTM) , 04.03, Pennsylvania, USA.

[18] ASTM D 6816-11. (2011) Standard practice for determining low-temperature performance grade (PG) of asphalt binders. American Society of Testing Materials (ASTM) , 04.03, Pennsylvania, USA.

[19] Attia,Mand Abdelrahman, M. (2008) Enhancing the performance of crumb rubbermodified binders through varying the interaction conditions. International Journal of Pavement Engineering, 1-12.

[20] Awanti, S. S., Amarnath, M. S., and Veeraragavan, A. (2006) Influence of modified Marshall compaction technique on engineering properties of polymer modified and neat bituminous concrete mixes. Highway Research Bulletin, 75, 25-35.

[21] Bahia, H. U., Hanson, D. I., Zeng, M., Zhai, H., Khatri, M. A., and Anderson, R. M. (2001) Characterization of modified asphalt binders in Superpave mix design. Transportation Research Board, NCHRP-459, Washington, D.C., USA.

[22] Bennert, T., Maher, A., and Gucunski, N. (2003) Evaluation of modified binders. Department of Transportation, FHWA, USA.

[23] Boutevin, B., Pietrasanta, Y., and Robin, J. J. (1989) Bitumen-polymer blends for coatings applied to roads and public constuructions. Progress in Organic Coatings, 17, 221-249.

[24] Brookfield Engineering Laboratories, Inc., 2005. More Solutions to Sticky Problems, Technical Report, USA.

[25] Brule, B., Bcion, Y., and Tanguy, A (1988) Paving asphalt polymer blends: Relationships between composition structure and properties. Proceedings of the Association of Asphalt Paving Technologists, 57, 41-64.

[26] Chen, J. S., Liao, M. C., and Shiah, M. S. (2002) Asphalt modified by styrene butadiene-styrene triblock copolymer: morphology and model. Journal of Materials in Civil Engineering (ASCE) , 14, 224-229.

[27] Chipps, J. F., Davison, R. R., Estakhri, C. K., and Glover, C. J. (2001) Field tests and economic analysis of high-cure crumb-rubber modified asphalt binders in densegraded mixes. Proceedings of 80th Annual Meeting of the Transportation Research Board, National Research Council, Washington D.C., USA.

[28] Collins, J. H., Bouldin, M. G., Gelles, R., and Berker, A. (1991) Improved performance of paving asphalts by polymer modification. Proceedings of the Association of Asphalt Paving Technologists, 60, 43-79.

[29] Coplantz, J. S., Yapp, M. T., and Finn, F. N. (1993) Review of relationships between modified asphalt properties and pavement performance. Strategic Highway Research Program, Report No. SHRP-A-631, National research council, Washington, D.C.

[30] Cortizo, M. S., Larsen, D. O., Bianchetto, H. and Alessandrini, J. L. (2004) Effect of the thermal degradation of SBS copolymers during the aging of modified asphalts. Fuel, 86, 275-282.

[31] CRRI. (2000) Field trials on use of styrene-butadiene-styrene (SBS) modified binders in flexible pavements. Central Road Research Institute, Final Report, New Delhi, India.

[32] Drakos, C. G., Birgisson, B., and Roque, R. (2005) Guidelines for use of modified binders. Florida Department of Transportation, University of Florida.

[33] Dubabe, I. A., Wahhab, H. I. A., Ibrahim M. A., and Ali M. F. (1995) Polymer modification of Arab asphalt. Journal of Materials in Civil Engineering (ASCE), 10, 161-167.

[34] Elseifi, M. A., Flintsch, G.W., and Al-Quadi, I. L. (2003) Quantitative effect of elastomeric modification on binder performance at intermediate and high temperatures. Journal of Materials in Civil Engineering (ASCE), 15, 32-40.

[35] Gahvari, F. (1997) Effects of thermoplastic block copolymers on rheology of asphalt. Journal of Materials in Civil Engineering (ASCE), 9, 111-116.

[36] Giavarini, C. (2000) Polymer-modified bitumen. Asplhatenes and Asphalts, Development in Petroleum Sciences, 40, 381-400.

[37] Goodrich, J. L. (1992) Asphalt and polymer modified asphalt properties related to the performance of asphalt concrete mixes. Proceedings of the Association of Asphalt Paving Technologists, 57, 116-175.

[38] Gopal, V. T., Sebaaly, P. E., and Epps, J. (2002) Effect of crumb rubber particle size and content on the low temperature rheological properties of binders. Proceedings of 81th Annual Meeting of the Transportation Research Board, National Research Council, Washington D.C.

[39] Gowda., G. V., Hall, K. D., and Elliott, R. P. (1996) Arkansas experience with crumb rubber modified mixes using Marshall and strategic highway research program level I design methods. Transportation Research Record, 1530, 25-33.

[40] Habib, A., Hossain, M., Kaldate, R., and Fager G. A. (1998) Comparison of Superpave and Marshall mixtures for low-volume roads/shoulders. Transportation Research Board, 1609, 44-50.

[41] Huang, S. C., Pauli, T. R., and Robertson, R. E. (2006) Rheological changes in crumb rubber-modified asphalts with long-term aging. Transportation Research Board, 1631, 81-90.

[42] IRC: 37-01. (2001) Guidelines for the design of flexible pavements. The Indian Roads Congress, Second revision, New Delhi, India.

[43] IRC: SP-53. (2010) Guidelines on the Use of Polymer Modified Binder Specifications. The Indian Road Congress, Special Publication, New Delhi, India.

[44] IS: 15462-04. (2004) Polymer and Rubber Modified Bitumen-Specification. Bureau of Indian Standards (BIS) , New Delhi, India.

[45] IS: 73-06. (2006) Paving Bitumen-Specification. Bureau of Indian Standards (BIS) New Delhi, India.

[46] Isacsson, U., and Lu, X. (1999) Laboratory investigation of polymer modified binders. Proceedings of the Association of Asphalt Paving Technologists, 68, 35-45.

[47] Jain P. K., Sikdar P. K., Shanta Kumar., and Kamaraj. (2006) Studies on correlation of rheology and performance characteristics of mixes of modified binder for roads in high temperature areas. Highway Research Bulletin, 74, 17-27.

[48] Johnson, D. R., and Freeman, R. B. (1999) Field performance of polymer modified asphalt concrete designed for medium traffic. Proceedings of 78th Annual Meeting of the Transportation Research Board, National Research Council, Washington D.C., USA.

[49] Khan, Z. A., Wahab, H. A., Asi, I., and Ramadhan, R. (1998) Comparative study of asphalt concrete laboratory compaction methods to simulate field compaction. Construction and Building Materials, 12, 373-384.

[50] Khattak, M. J., and Baladi, G, Y. (2001) Fatigue and permanent deformation models for polymer modified asphalt mixtures. Proceedings of 80th Annual Meeting of the Transportation Research Board, National Research Council, Washington D.C, USA.

[51] Khosla, N. P., and Goetz, W. H. (1979) Tensile characteristics of bituminous mixtures as affected by modified binders. Proceedings of the Association of Asphalt Paving Technologists, 48, 34-64.

[52] Khosla, N. P., and Zahan, S. Z. (1989) A mechanistic evaluation of mixes containging conventional and polymer modified (styrelf) asphalts. Proceedings of the Association of Asphalt Paving Technologists, 58, 274-302.

[53] Khosla, P. N., and Kawaguchi, S. (2000) Comparative evaluation of design and performance of Marshall and Superpave mixes. Transportation Research Board, National Academics, Annual Meeting CD-ROM, Washington, D.C., USA.

[54] Kim, S., Loh, S.W., Zhai, H., and Bahia, H. U. (2000) Advanced characterization of crumb rubber modified asphalt using protocols developed for complex binder. Proceedings of 80th Annual Meeting of the Transportation Research Board, National Research Council, Washington D.C., USA.

[55] King G. N., Muncy H. W., and Prudhomme J. B. (1986) Polymer modification: Binders effect on mix properties. Proceedings of the Association of Asphalt Paving Technologists, 55, 519-540.

[56] Kraus, G (1982) Modification of asphalt by block polymers of butadiene and styrene. Rubber Chemistry and Technology, 55, 1386-1402.

[57] Krishnan, J. M., and Rajagopal, K. R (2005) On the mechanical behaviour of asphalt. Mechanics of Material, 37, 1085-1100.

[58] Kumar P., Chandra, S., and Bose, S. (2004) Rheology of polymer modified bitumen. Highway Research Bulletin, 71, 119-135.

[59] Larsen, D. O., Alessandrini, J. L., Bosch, A., and Cortizo. M. S. (2009) Micro structural and rheological characteristics of SBS-asphalt blends during their manufacturing. Construction and Building Materials, 23, 2769-2774.

[60] Lee, S. J., Akisetty, C. K., and Amirkhanian, S. N. (2008) The effect of crumb rubber modifier (CRM) on the performance properties of rubberized binders in HMA pavements. Construction and Building Materials, 22, 1368-1376.

[61] Liu, S., Cao, W., Fang, J.,and Shang, S. (2009) Variance analysis and performance evaluation of different crumb rubber modified (CRM) asphalt. Construction and Building Materials, 23, 2701-2708.

[62] Loeber, L., Sutton, O., Morel, J., Valleton, M. J., and Muller, G. (1995) New direct observations of asphalt and asphalt binders by scanning electron microscopy and atomic force microscopy. Journal of Microscopy, 182, 32-39.

[63] Lougheed, T. J., and Papagiannakis, A. T. (1996) Viscosity characteristics of rubber modified asphalts. Journal of Materials in Civil Engineering (ASCE), 8, 153-156.

[64] Lu, X., and Isacsson, U. (1996) Rheological characterization of styrene-butadienestyrene copolymer modified binders. Construction and Building Materials, 11, 23-32.

[65] Lu, X., and Isacsson, U. (2000) Laboratory study on the low temperature physical hardening of conventional and polymer modified binders. Construction and Building Materials, 14, 79-88.

[66] Lu, X., and Isacsson, U. (2002) Effect of ageing on bitumen chemistry and rheology. Construction and Building Materials, 16, 15-22.

[67] Mahrez, A., and Karim, R. M. (2003) Rheological evaluation of ageing properties of rubber crumb modified bitumen. Journal of the Eastern Asia Society for Transportation Studies, 34, 3-12.

[68] Martin, V. D., and Jenkins, V. K. (2003) Rheological characterisation of some (polymer modified) bitumen and bitumen-filler system at compaction and in-service temperatures. 6th Rilem Symposium PTEBM’03, Zurich.

[69] Marvillet, J. and P. Bougalt. (1978)Workability of bituminous mixes: Development of a workability meter. Proceedings of the Association of Asphalt Paving Technologist, 48, 91-110.

[70] Masson, J. F., Leblond, V., and Margeson, J. (2005) Bitumen morphologies by phase-detection atomic force microscopy. Journal of Microscopy, 221, 17-29.

[71] McDaniel, R. S., and Bahia, H. U. (2003) Field evaluation of asphalt additives to control rutting and cracking. Proceedings of 82th Annual Meeting of the Transportation Research Board, National Research Council, Washington D.C.

[72] Ministry of Road Transport and Highways. (2001) Specification for roads and bridge work. The Indian Roads Congress (MORT& H), 4thRevision, New Delhi, India.

[73] Molenaar, A. A. A., and Nirmal, S. K. (2001) Use of sealoflex modified mixtures for a heavy duty pavement in India. Sealoflex World Conference, Rome.

[74] Morales, G. M., Partal, P., Navarro, F. J., Boza, F. M., Gallegos, C., Gonzalez, N.,Gonzalez, O., and Munoz, M. E. (2004) Viscous properties and microstructure of recycled EVA modified bitumen. Fuel, 83, 31U″ 38.

[75] Morales, M. G., Partal, P., Navarro, F. J., and Gallegos, C. (2006) Effect of waste polymer addition on the rheology of modified bitumen. Fuel, 85, 936-943.

[76] NCHRP 1-37 A. (2002) Mechanistic-empirical design of New & rehabilitated pavement structures. National Cooperative Highway Research Program, (NCHRP), 2002, Washington D.C., USA.

[77] NCHRP 465. (2002) Simple performance testor for Superpave mix design. National Cooperative Highway Research Program, (NCHRP), 2002,Washington D.C., USA.

[78] NHAI. (2012) Indian Road Net work In National Highways Authority of India. http://www.nhai.org/roadnetwork.htm, Accessed on 4th October 2012.

[79] Nicholas, C. N., Bartdet, J., Eckmann, B., and Donal, B. S. (1989) Polymer modified asphalts for high performance hot mix pavement binders. Proceedings of the Association of Asphalt Paving Technologists, 5, 509-525.

[80] Oliver, J. W. H., and Tredrea, P. F. (1997) The change in properties of polymer modified binders with simulated field exposure. Proceedings of the Association of Asphalt Paving Technologists, 66, 570-592.

[81] Palit, S. K., Reddy, K. S., and Pandey, B. B. (2004) Laboratory Evaluation of crumb rubber modified asphalt mixes. Journal of Materials in Civil Engineering (ASCE),16, 45-53.

[82] Panda, M., and Mazumdar, M. (2002) Utilization of reclaimed polyethylene in bituminous paving mixes. Journal of Materials in Civil Engineering (ASCE), 14,527-

[83] Petersen, J. C. (1984) Chemical composition of asphalt as related to asphalt durability-state of art. Transport Research Record, 999, 13-30.

[84] Punith V. S., Reddy M. P. S., and Veeraragavan, A. (2005) Characterization of bituminous paving mixes under repeated load indirect tensile tests. Highway Research Bulletin, 73, 131-148.

[85] Quintus, V. H., Mallela, J., and Buncher, M. (2007) Quantification of the effect of polymer modified asphalt on flexible pavement performance. Transportation Research Board, 21-25.

[86] Rajan N. K., Selvavathi V. , Sairam B. and Krishnan J. M. (2008) Influence of crude source on the viscous properties of blended asphalt. International Journal of Road Materials and Pavement Design, 9, 67-86.

[87] Rozeveld, S. J., Shin, E. E., Bhurke, A., France, L., and Drzal, L. T. (1997) Network morphology of straight and polymer modified asphalt cements. Microscopy Research and Technique, 38, 529-543.

[88] Ruan, Y., Richard R. Davison, Charles J. G. (2003) The effect of long-term oxidation on the rheological properties of polymer modified asphalts. Fuel, 82, 1763-1773.

[89] Sirin, O., Kim, H. J., Tia, M., and Choubane, B. (2008) Comparison of rutting resistance of unmodified and SBS-modified Superpave mixtures by accelerated pavement testing. Construction and Building Materials, 22, 286-294.

[90] Sridhar R., Bose, S., Kumar, G., and Sharma, G. (2004) Performance characteristics of bituminous mixes modified by waste plastic bags. Highway Research Bulletin, 71, 01-10.

[91] Stock A. F., Planque L., and Gunderson B. (1992) Field and laboratory evaluation of specialist high performance binders. 7th International Conference on Asphalt Pavements: Design and Construction, Royal Centre, Nottingham, England.

[92] Terrel, R. L., and Walter, J. L. (1986) Modified asphalt pavement material-The European expericence. Proceedings of the Association of Asphalt Paving Technologists, 55, 482-518.

[93] The Asphalt Institute. (1974) Mix design methods for asphalt concrete and other Hot-Mix Types. Manual Series No. 2, Lexington, Kentucky, USA.

[94] The Asphalt Institute. (2001) Superpave mix designs. Superpave series No. 2 SP-2, 3rd Edition, Lexington, Kentucky, USA.

[95] The Asphalt Institute. (2005) Quantification of the effects of polymer modified asphalt for reducing pavement distress. Asphalt institute Research Park, Engineering Report 215.

[96] Valkering, C. P., Lancon, D. J. L., Deltilster, E., and Stoker, D. A. (1990) Rutting resistance of asphalt mixes containing non conventional and polymer modified binders. Proceedings of the Association of Asphalt Paving Technologists, 59, 590-609.

[97] Wang, J. N., Lin, J. D., Wang, J. M., and Chen, S. H. (2002) Laboratory evaluation of eight polymer modified asphalts. Proceedings of 81th Annual Meeting of the Transportation Research Board, National Research Council, Washington D.C.

[98] Watson, D. E., and Brown, E. R. (2005) Comparison of Superpave and Marshall mix performance in Alabama. Transportation Research Board, Annual Meeting CDROM, Washington, D.C, USA.

[99] Wekumbura, C., Stastna, J., and Zanzotto, L. (2007) Destruction and recovery of internal structure in polymer-modified asphalts. Journal of Materials in Civil Engineering, ASCE, 19, 227-232.

[100] Wong, W. G., Han, H., He, G., Wang, K. C. P., and Lu, W. (2004) Rutting response of hot-mix asphalt to generalized dynamic shear moduli of asphalt binder. Construction and Building Materials, 18, 399-408.

[101] Xicheng Qi, X., Sebaaly, P. E., and Epps, J. A. (1995) Evaluation of polymer modified asphalt concrete mixtures. Journal of Materials in Civil Engineering (ASCE), 7, 117-124.

[102] Yildirim, Y. (2007) Polymer modified asphalt binders. Construction and Building Materials, 21, 66-72.

[103] Yousefi, A. A. (2002) Rubber-modified Binders. Iranian Polymer Journal, 11, 303-309.

[104] Yousefi, A. A., Kadi, A. A., and Roy, C. (2000) Composite asphalt binders; Effect of modified RPE on asphalt. Journal of Materials in Civil Engineering (ASCE), 12, 113-123.

[105] Zaman, A. A., Fricke, A. L., and Beatty, C. L. (1995) Rheological properties of rubber modified asphalt. Journal of Materials in Civil Engineering (ASCE) , 121, 461-467.

[106] Zeng, M., and Huang, S. C. (2006) Characterizing the asphalt-aggregate mixtures using rheological properties of asphalt binders. Journal of Testing and Evaluation (ASTM), 34, 1-6.

[107] Zubeck, H., Raad, L., Saboundjian, S., Minassian, G., and Ryer, J. (2002) Performance of polymer modified asphalt-aggreate mixtures in Alaska. Journal of Cold Regions Engineering (ASCE), 16, 170-190.

APPENDIX

Table 1 Existing crust details of the test sections

Sl. No.	Chainage	Bituminous	Granular
1	84+400	110	90
2	85+000	113	130
3	86+000	65	80
4	87+000	115	150
5	88+000	118	210
6	89+000	105	175
7	90+000	55	260
8	91+000	58	176
9	92+000	50	233
10	93+000	50	300
11	94+000	74	155
12	95+000	103	152
13	96+000	58	165
14	97+000	90	230
15	98+000	60	242
16	99+000	76	220
17	100+000	97	115
18	101+000	64	169
19	102+000	74	172
20	103+000	117	225

Table 2 Subgrade soil classification

CHAINAGE	Liquid Limit	Plastic Limit	Plasticity Index	SOIL CLASSIFICATION
84	20.6	18.13	2.47	SM
85	29.6	17.3	12.3	SC
86	24.18	20.66	3.52	SM
87	37.61	26.46	11.15	SC
88	26.4	17.07	9.33	SC
89	27	22.59	4.41	SM
90	31.12	24.06	7.06	CL
91	26.4	20.78	5.62	CL

92	32	21.62	10.38	SC
93	25.3	12.84	12.46	SC
94	28.19	24.43	3.76	SM
95	28.43	19.73	8.7	SC
96	33.8	20.09	13.71	CL
97	15.2	13.35	1.85	SM
98	22.1	12.58	9.52	SC
99	26.6	22.53	4.07	SM
100	27.6	19.55	8.05	SC
101	32.7	21.5	11.2	CL
102	34.48	21.44	13.04	SM
103	21.2	16.43	4.77	SC
104	28.14	19.29	8.85	SC

Table 3 Axle load Analysis in the RHS Direction

Light Commercial Vehicles						
Axle load category (Tonnes)	**Number of axles (n)**	**% of each category (n/N)x100**	**Cumulative percentage**	**Equivalency factors (e)**	**Equivalent standard axles (n x e)**	**% of damaging effect (e x n / B) x 100**
0.900 - 1.810	8	30.77	30.77	0.002	0.02	0.18
1.810 - 2.720	6	23.08	53.85	0.009	0.05	0.60
2.720 - 3.630	3	11.54	65.38	0.031	0.09	1.03
3.630 - 4.540	3	11.54	76.92	0.080	0.24	2.66
5.440 - 6.350	3	11.54	88.46	0.350	1.05	11.62
8.160 - 9.070	2	7.69	96.15	1.550	3.10	34.32
10.890 - 11.790	1	3.85	100.00	4.480	4.48	49.60
N =	**26**			**B=**	**9.03**	**100**
No of Axles Weighed, X = N = 26				Total Damaging Effect, Z = B = 9.03		
No of Vehicles Weighed, Y = 13				Axle Equivalency, (Z/X) = 0.35		
Vehicle damage factor, (Z/Y)= 0.695						

Two Axle Trucks						
Axle load category	**Number of axles**	**% of each category**	**Cumulative percentage**	**Equivalency factors**	**Equivalent standard axles**	**% of damaging effect**
(Tonnes)	**(n)**	**(n/N)x100**		**(e)**	**(n x e)**	**(e x n / B) x 100**
0.000 - 0.900	2	0.45	0.45	0.0002	0.00	0.00
0.900 - 1.810	3	0.67	1.12	0.002	0.01	0.00
1.810 - 2.720	24	5.36	6.47	0.009	0.22	0.02
2.720 - 3.630	96	21.43	27.90	0.031	2.98	0.26
3.630 - 4.540	90	20.09	47.99	0.080	7.20	0.62
4.540 - 5.440	46	10.27	58.26	0.176	8.10	0.70
5.440 - 6.350	38	8.48	66.74	0.350	13.30	1.15
6.350 - 7.260	43	9.60	76.34	0.610	26.23	2.27
7.260 - 8.160	17	3.79	80.13	1.000	17.00	1.47
8.160 - 9.070	16	3.57	83.71	1.550	24.80	2.15
9.070 - 9.980	6	1.34	85.04	2.300	13.80	1.20
9.980 - 10.890	6	1.34	86.38	3.270	19.62	1.70
10.890 - 11.790	14	3.13	89.51	4.480	62.72	5.44
11.790 - 12.700	6	1.34	90.85	5.980	35.88	3.11
12.700 - 13.610	7	1.56	92.41	7.800	54.60	4.74
13.610 - 14.520	4	0.89	93.30	10.000	40.00	3.47
14.520 - 15.420	7	1.56	94.87	12.500	87.50	7.59
15.420 - 16.320	3	0.67	95.54	15.500	46.50	4.03
16.320 - 17.230	1	0.22	95.76	19.000	19.00	1.65
17.230 - 18.140	4	0.89	96.65	23.000	92.00	7.98
18.140 - 19.051	3	0.67	97.32	27.700	83.10	7.21
19.051 - 19.958	3	0.67	97.99	33.000	99.00	8.59
19.958 - 20.865	5	1.12	99.11	39.300	196.50	17.04
20.865 - 21.772	2	0.45	99.55	46.500	93.00	8.07
21.772 - 22.680	2	0.45	100.00	55.000	110.00	9.54
N =	448			**B=**	**1153.04**	**100**
No of Axles Weighed, X = N =			448	Total Damaging Effect, Z = B =		1153.04
No of Vehicles Weighed, Y =			224	Axle Equivalency, (Z/X) =		2.57
Vehicle damage factor, (Z/Y)=				**5.148**		

Buses						
Axle load category	**Number of axles**	**% of each category**	**Cumulative percentage**	**Equivalency factors**	**Equivalent standard axles**	**% of damaging effect**
(Tonnes)	**(n)**	**(n/N)x100**		**(e)**	**(n x e)**	**(e x n / B) x 100**
1.810 - 2.720	1	12.50	12.50	0.009	0.01	0.94
2.720 - 3.630	3	37.50	50.00	0.031	0.09	9.67
3.630 - 4.540	2	25.00	75.00	0.080	0.16	16.63
5.440 - 6.350	2	25.00	100.00	0.350	0.70	72.77
N =	**8**			**B=**	**0.96**	**100**
No of Axles Weighed, X = N = 8				Total Damaging Effect,Z = B = 0.96		
No of Vehicles Weighed, Y = 4				Axle Equivalency, (Z/X) = 0.12		
Vehicle damage factor, (Z/Y)= 0.241						

Three Axle Truck						
Axle load category	**Number of axles**	**% of each category**	**Cumulative percentage**	**Equivalency factors**	**Equivalent standard axles**	**% of damaging effect**
(Tonnes)	**(n)**	**(n/N1)x 100**		**(e)**	**(n x e)**	**(e x n / B1) x 100**
1.810 - 2.720	4	2.47	2.47	0.009	0.04	0.06
2.720 - 3.630	6	3.70	6.17	0.031	0.19	0.30
3.630 - 4.540	25	15.43	21.60	0.080	2.00	3.26
4.540 - 5.440	32	19.75	41.36	0.176	5.63	9.17
5.440 - 6.350	53	32.72	74.07	0.350	18.55	30.21
6.350 - 7.260	31	19.14	93.21	0.610	18.91	30.80
7.260 - 8.160	8	4.94	98.15	1.000	8.00	13.03
8.160 - 9.070	1	0.62	98.77	1.550	1.55	2.52
9.980 - 10.890	2	1.23	100.00	3.270	6.54	10.65
N1 =	**162**			**B1=**	**61.40**	**100**

Tandem Rear Axle						
Axle load category	**Number of axles**	**% of each category**	**Cumulative percentage**	**Equivalency factors**	**Equivalent standard axles**	**% of damaging effect**
(Tonnes)	**(n)**	**(n/N2)x 100**		**(e)**	**(n x e)**	**(e x n / B2) x 100**
3.630 - 4.540	3	1.85	1.85	0.006	0.02	0.00
4.540 - 5.440	10	6.17	8.02	0.013	0.13	0.03
5.440 - 6.350	6	3.70	11.73	0.024	0.14	0.03
6.350 - 7.260	2	1.23	12.96	0.043	0.09	0.02
8.160 - 9.070	1	0.62	13.58	0.110	0.11	0.02
9.070 - 9.980	1	0.62	14.20	0.166	0.17	0.03
9.980 - 10.890	3	1.85	16.05	0.242	0.73	0.14
10.890 - 11.790	1	0.62	16.67	0.342	0.34	0.07
11.790 - 12.700	2	1.23	17.90	0.470	0.94	0.18
12.700 - 13.610	8	4.94	22.84	0.633	5.06	0.99
13.610 - 14.520	4	2.47	25.31	0.834	3.34	0.65
14.520 - 15.420	5	3.09	28.40	1.080	5.40	1.05
15.420 - 16.320	9	5.56	33.95	1.380	12.42	2.42
16.320 - 17.230	10	6.17	40.12	1.730	17.30	3.37
17.230 - 18.140	10	6.17	46.30	2.140	21.40	4.17
18.140 - 19.051	24	14.81	61.11	2.610	62.64	12.20
19.051 - 19.958	13	8.02	69.14	3.160	41.08	8.00
19.958 - 20.865	16	9.88	79.01	3.790	60.64	11.81
20.865 - 21.772	8	4.94	83.95	4.490	35.92	6.99
21.772 - 22.680	4	2.47	86.42	5.280	21.12	4.11
22.680 - 23.587	4	2.47	88.89	6.170	24.68	4.81
23.587 - 24.494	3	1.85	90.74	7.150	21.45	4.18
24.494 - 25.401	5	3.09	93.83	8.200	41.00	7.98
25.401 - 26.308	1	0.62	94.44	9.400	9.40	1.83
26.308 - 27.216	1	0.62	95.06	10.700	10.70	2.08
27.216 - 28.123	4	2.47	97.53	12.100	48.40	9.42
29.030 - 29.937	1	0.62	98.15	15.400	15.40	3.00
29.937 - 30.844	2	1.23	99.38	17.200	34.40	6.70
30.844 - 31.752	1	0.62	100.00	19.200	19.20	3.74
N2 =	**162**			**B2=**	**513.61**	**100**
No of Axles Weighed, X = N1+N2 =			324	Total Damaging Effect, Z = B1+B2 =		575.02
No of Vehicles Weighed, Y =			162	Axle Equivalency, (Z/X) =		1.77
Vehicle damage factor, (Z/Y)=				**3.549**		

Single Front Axle, and Middle Axle						
Axle load category	**Number of axles**	**% of each category**	**Cumulative percentage**	**Equivalency factors**	**Equivalent standard axles**	**% of damaging effect**
(Tonnes)	**(n)**	**(n/N1)x100**		**(e)**	**(n x e)**	**(e x n / B1) x 100**
4.540 - 5.440	3	30.00	30.00	0.176	0.53	5.96
5.440 - 6.350	1	10.00	40.00	0.350	0.35	3.95
6.350 - 7.260	3	30.00	70.00	0.610	1.83	20.66
8.160 - 9.070	1	10.00	80.00	1.550	1.55	17.50
9.070 - 9.980	2	20.00	100.00	2.300	4.60	51.93
N1 =	**10**			**B1=**	**8.86**	**100**

Tandem Rear Axle						
Axle load category	**Number of axles**	**% of each category**	**Cumulative percentage**	**Equivalency factors**	**Equivalent standard axles**	**% of damaging effect**
(Tonnes)	**(n)**	**(n/N2)x100**		**(e)**	**(n x e)**	**(e x n / B2) x 100**
9.070 - 9.980	2	40.00	40.00	0.166	0.33	0.84
9.980 - 10.890	1	20.00	60.00	0.242	0.24	0.61
19.051 - 19.958	1	20.00	80.00	3.160	3.16	7.97
36.288 - 37.000	1	20.00	100.00	35.920	35.92	90.58
N2 =	**5**			**B2=**	**39.65**	**100**
No of Axles Weighed, X = N1+N2 =			15	Total Damaging Effect,Z = B1+B2 =		48.51
No of Vehicles Weighed, Y =			5	Axle Equivalency, (Z/X) =		3.23
Vehicle damage factor, (Z/Y)=				**9.702**		

Table 4 Axle load Analysis in the LHS Direction

Light Commercial Vehicles						
Axle load category (Tonnes)	**Number of axles (n)**	**% of each category (n/N)x100**	**Cumulative percentage**	**Equivalency factors (e)**	**Equivalent standard axles (n x e)**	**% of damaging effect (e x n / B) x 100**
0.900 - 1.810	19	25.68	25.68	0.002	0.04	0.81
1.810 - 2.720	26	35.14	60.81	0.009	0.23	5.00
2.720 - 3.630	11	14.86	75.68	0.031	0.34	7.29
3.630 - 4.540	11	14.86	90.54	0.080	0.88	18.81
4.540 - 5.440	1	1.35	91.89	0.176	0.18	3.76
5.440 - 6.350	4	5.41	97.30	0.350	1.40	29.92
6.350 - 7.260	1	1.35	98.65	0.610	0.61	13.04
7.260 - 8.160	1	1.35	100.00	1.000	1.00	21.37
N =	**74**			**B=**	**4.68**	**100**
No of Axles Weighed, X = N = 74				Total Damaging Effect,Z = B = 4.68		
No of Vehicles Weighed, Y = 37				Axle Equivalency, (Z/X) = 0.06		
Vehicle damage factor, (Z/Y)= 0.126						

Light Commercial Vehicles						
Axle load category	**Number of axles**	**% of each category**	**Cumulative percentage**	**Equivalency factors**	**Equivalent standard axles**	**% of damaging effect**
(Tonnes)	**(n)**	**(n/N)x100**		**(e)**	**(n x e)**	**(e x n / B) x 100**
1.810 - 2.720	3	50.00	50.00	0.009	0.03	1.69
5.440 - 6.350	1	16.67	66.67	0.350	0.35	21.92
6.350 - 7.260	2	33.33	100.00	0.610	1.22	76.39
N =	**6**			**B=**	**1.60**	**100**
No of Axles Weighed, X = N = 6				Total Damaging Effect, Z = B = 1.60		
No of Vehicles Weighed, Y = 3				Axle Equivalency, (Z/X) = 0.27		
Vehicle damage factor, (Z/Y)= 0.532						

Two Axle Trucks						
Axle load category	**Number of axles**	**% of each category**	**Cumulative percentage**	**Equivalency factors**	**Equivalent standard axles**	**% of damaging effect**
(Tonnes)	**(n)**	**(n/N)x100**		**(e)**	**(n x e)**	**(e x n / B) x 100**
0.000 - 0.900	2	0.56	0.56	0.0002	0.00	0.00
0.900 - 1.810	3	0.84	1.40	0.002	0.01	0.00
1.810 - 2.720	21	5.90	7.30	0.009	0.19	0.02
2.720 - 3.630	41	11.52	18.82	0.031	1.27	0.11
3.630 - 4.540	56	15.73	34.55	0.080	4.48	0.39
4.540 - 5.440	30	8.43	42.98	0.176	5.28	0.45
5.440 - 6.350	43	12.08	55.06	0.350	15.05	1.29
6.350 - 7.260	32	8.99	64.04	0.610	19.52	1.68
7.260 - 8.160	14	3.93	67.98	1.000	14.00	1.20
8.160 - 9.070	10	2.81	70.79	1.550	15.50	1.33
9.070 - 9.980	17	4.78	75.56	2.300	39.10	3.36
9.980 - 10.890	13	3.65	79.21	3.270	42.51	3.66
10.890 - 11.790	12	3.37	82.58	4.480	53.76	4.62
11.790 - 12.700	8	2.25	84.83	5.980	47.84	4.12
12.700 - 13.610	17	4.78	89.61	7.800	132.60	11.41
13.610 - 14.520	8	2.25	91.85	10.000	80.00	6.88
14.520 - 15.420	3	0.84	92.70	12.500	37.50	3.23
15.420 - 16.320	5	1.40	94.10	15.500	77.50	6.67
16.320 - 17.230	5	1.40	95.51	19.000	95.00	8.17
17.230 - 18.140	4	1.12	96.63	23.000	92.00	7.91
18.140 - 19.051	5	1.40	98.03	27.700	138.50	11.91
19.051 - 19.958	5	1.40	99.44	33.000	165.00	14.19
19.958 - 20.865	1	0.28	99.72	39.300	39.30	3.38
20.865 - 21.772	1	0.28	100.00	46.500	46.50	4.00
N =	356			**B=**	**1162.41**	**100**
No of Axles Weighed, X = N =			356	Total Damaging Effect, Z =		1162.41
No of Vehicles Weighed, Y =			178	Axle Equivalency, (Z/X) =		3.27
Vehicle damage factor, (Z/Y)=				**6.530**		

Buses

Axle load category	Number of axles	% of each category	Cumulative percentage	Equivalency factors	Equivalent standard axles	% of damaging effect
(Tonnes)	**(n)**	**(n/N)x100**		**(e)**	**(n x e)**	**(e x n / B) x 100**
1.810 - 2.720	3	7.14	7.14	0.009	0.03	0.11
2.720 - 3.630	6	14.29	21.43	0.031	0.19	0.77
3.630 - 4.540	10	23.81	45.24	0.080	0.80	3.30
4.540 - 5.440	7	16.67	61.90	0.176	1.23	5.09
5.440 - 6.350	4	9.52	71.43	0.350	1.40	5.78
6.350 - 7.260	6	14.29	85.71	0.610	3.66	15.11
7.260 - 8.160	2	4.76	90.48	1.000	2.00	8.26
8.160 - 9.070	1	2.38	92.86	1.550	1.55	6.40
9.070 - 9.980	1	2.38	95.24	2.300	2.30	9.49
9.980 - 10.890	1	2.38	97.62	3.270	3.27	13.50
12.700 - 13.610	1	2.38	100.00	7.800	7.80	32.20
N =	**42**			**B=**	**24.23**	**100**

No of Axles Weighed, X = N =	42	Total Damaging Effect, Z = B =	24.23
No of Vehicles Weighed, Y =	21	Axle Equivalency, (Z/X) =	0.58
Vehicle damage factor, (Z/Y)=	**1.154**		

<u>Three Axle Truck</u>

Single Front Axle

Axle load category	Number of axles	% of each category	Cumulative percentage	Equivalency factors	Equivalent standard axles	% of damaging effect
(Tonnes)	**(n)**	**(n/N1)x100**		**(e)**	**(n x e)**	**(e x n / B1) x 100**
2.720 - 3.630	5	4.35	4.35	0.031	0.16	0.21
3.630 - 4.540	23	20.00	24.35	0.080	1.84	2.49
4.540 - 5.440	21	18.26	42.61	0.176	3.70	5.01
5.440 - 6.350	10	8.70	51.30	0.350	3.50	4.74
6.350 - 7.260	23	20.00	71.30	0.610	14.03	19.01
7.260 - 8.160	11	9.57	80.87	1.000	11.00	14.91
8.160 - 9.070	16	13.91	94.78	1.550	24.80	33.61
9.070 - 9.980	5	4.35	99.13	2.300	11.50	15.58
9.980 - 10.890	1	0.87	100.00	3.270	3.27	4.43
N1 =	**115**			**B1=**	**73.79**	**100**

<u>Three Axle Truck</u>

Tandem Rear Axle

Axle load category	Number of axles	% of each category	Cumulative percentage	Equivalency factors	Equivalent standard axles	% of damaging effect
(Tonnes)	**(n)**	**(n/N2)x100**		**(e)**	**(n x e)**	**(e x n / B2) x 100**
4.540 - 5.440	10	8.70	8.70	0.013	0.13	0.02
5.440 - 6.350	12	10.43	19.13	0.024	0.29	0.05
6.350 - 7.260	13	11.30	30.43	0.043	0.56	0.10
7.260 - 8.160	3	2.61	33.04	0.070	0.21	0.04
8.160 - 9.070	1	0.87	33.91	0.110	0.11	0.02
9.070 - 9.980	2	1.74	35.65	0.166	0.33	0.06
9.980 - 10.890	2	1.74	37.39	0.242	0.48	0.08
10.890 - 11.790	1	0.87	38.26	0.342	0.34	0.06
16.320 - 17.230	2	1.74	40.00	1.730	3.46	0.60
17.230 - 18.140	1	0.87	40.87	2.140	2.14	0.37
18.140 - 19.051	4	3.48	44.35	2.610	10.44	1.81
19.051 - 19.958	3	2.61	46.96	3.160	9.48	1.64
19.958 - 20.865	2	1.74	48.70	3.790	7.58	1.31
20.865 - 21.772	4	3.48	52.17	4.490	17.96	3.11
21.772 - 22.680	5	4.35	56.52	5.280	26.40	4.58
22.680 - 23.587	10	8.70	65.22	6.170	61.70	10.70
23.587 - 24.494	9	7.83	73.04	7.150	64.35	11.16
24.494 - 25.401	8	6.96	80.00	8.200	65.60	11.38
25.401 - 26.308	8	6.96	86.96	9.400	75.20	13.04
26.308 - 27.216	6	5.22	92.17	10.700	64.20	11.13
28.123 - 29.030	1	0.87	93.04	13.700	13.70	2.38
29.937 - 30.844	3	2.61	95.65	17.200	51.60	8.95
30.844 - 31.752	4	3.48	99.13	19.200	76.80	13.32
32.660 - 33.566	1	0.87	100.00	23.600	23.60	4.09
N2 =	**115**			**B2=**	**576.67**	**100**
No of Axles Weighed, X = N1+N2 =			230	Total Damaging Effect, Z = B1+B2 =		650.46
No of Vehicles Weighed, Y =			115	Axle Equivalency, (Z/X) =		2.83
Vehicle damage factor, (Z/Y)=				**5.656**		

Semi Truck Trailor with Tandem Rear Axle Single Front Axle and Middle Axle						
Axle load category	**Number of axles**	**% of each category**	**Cumulative percentage**	**Equivalency factors**	**Equivalent standard axles**	**% of damaging effect**
(Tonnes)	**(n)**	**(n/N1)x100**		**(e)**	**(n x e)**	**(e x n / B1) x 100**
2.720 - 3.630	1	16.67	16.67	0.031	0.03	0.57
3.630 - 4.540	1	16.67	33.33	0.080	0.08	1.47
4.540 - 5.440	1	16.67	50.00	0.176	0.18	3.23
5.440 - 6.350	1	16.67	66.67	0.350	0.35	6.41
8.160 - 9.070	1	16.67	83.33	1.550	1.55	28.40
9.980 - 10.890	1	16.67	100.00	3.270	3.27	59.92
N1 =	**6**			**B1=**	**5.46**	**100**

Semi Truck Trailor with Tandem Rear Axle Tandem Rear Axle						
Axle load category	**Number of axles**	**% of each category**	**Cumulative percentage**	**Equivalency factors**	**Equivalent standard axles**	**% of damaging effect**
(Tonnes)	**(n)**	**(n/N2)x100**		**(e)**	**(n x e)**	**(e x n / B2) x 100**
10.890 - 11.790	1	33.33	33.33	0.342	0.34	2.62
20.865 - 21.772	1	33.33	66.67	4.490	4.49	34.45
24.494 - 25.401	1	33.33	100.00	8.200	8.20	62.92
N2 =	**3**			**B2=**	**13.03**	**100**
No of Axles Weighed, X = N1+N2 =			9	Total Damaging Effect, Z = B1+B2 =		18.49
No of Vehicles Weighed, Y =			3	Axle Equivalency, (Z/X) =		2.05
Vehicle damage factor, (Z/Y)=				**6.163**		

Table 5 Roughness Values Before Construction of Test Section

Chainage, Km		IRI, m/Km						Average	Unevenness Index mm/Km
From	To	Left Lane			Right Lane				
		Trial 1	Trial 2	Trial 3	Trial 1	Trail 2	Trial 3		
84.000	84.100	3.59	3.79	3.69	6.46	6.66	6.56	5.13	3928
84.100	84.200	3.98	4.18	4.08	5.30	5.45	5.38	4.73	3589
84.200	84.300	4.60	4.80	4.70	5.32	5.57	5.45	5.07	3883
84.300	84.400	7.63	7.83	7.73	5.17	5.37	5.27	6.50	5126
84.400	84.500	5.01	5.21	5.11	5.62	5.77	5.70	5.40	4167
84.500	84.600	3.72	3.92	3.82	5.33	5.58	5.46	4.64	3512
84.600	84.700	3.62	3.82	3.72	5.45	5.65	5.55	4.64	3510
84.700	84.800	4.44	4.64	4.54	10.40	10.55	10.48	7.51	6024
84.800	84.900	4.98	5.18	5.08	4.66	4.91	4.79	4.93	3763
84.900	85.000	4.99	5.19	5.09	4.49	4.69	4.59	4.84	3684
85.000	85.100	4.38	4.58	4.48	4.49	4.64	4.57	4.52	3415
85.100	85.200	4.42	4.62	4.52	4.32	4.57	4.45	4.48	3381
85.200	85.300	4.38	4.58	4.48	5.10	5.30	5.20	4.84	3684
85.300	85.400	3.71	3.91	3.81	5.07	5.22	5.15	4.48	3377
85.400	85.500	3.87	4.07	3.97	4.62	4.87	4.75	4.36	3276
85.500	85.600	4.81	5.01	4.91	5.07	5.27	5.17	5.04	3855
85.600	85.700	3.62	3.82	3.72	5.19	5.34	5.27	4.49	3389
85.700	85.800	3.61	3.81	3.71	4.21	4.46	4.34	4.02	2995
85.800	85.900	4.49	4.69	4.59	3.93	4.13	4.03	4.31	3236
85.900	86.000	3.95	4.15	4.05	5.25	5.40	5.33	4.69	3555
86.000	86.100	4.85	5.05	4.95	5.24	5.49	5.37	5.16	3956
86.100	86.200	4.46	4.66	4.56	5.61	5.81	5.71	5.14	3937
86.200	86.300	4.26	4.46	4.36	5.42	5.57	5.50	4.93	3759
86.300	86.400	3.67	3.87	3.77	4.72	4.97	4.85	4.31	3234
86.400	86.500	5.96	6.16	6.06	6.33	6.53	6.43	6.25	4902
86.500	86.600	6.84	7.04	6.94	4.62	4.77	4.70	5.82	4527
86.600	86.700	5.78	5.98	5.88	4.74	4.99	4.87	5.37	4141
86.700	86.800	8.32	8.52	8.42	4.50	4.70	4.60	6.51	5135
86.800	86.900	6.41	6.61	6.51	4.54	4.69	4.62	5.56	4306
86.900	87.000	6.80	7.00	6.90	4.64	4.89	4.77	5.83	4540
87.000	87.100	8.01	8.21	8.11	4.29	4.49	4.39	6.25	4906
87.100	87.200	11.08	11.28	11.18	4.49	4.64	4.57	7.87	6353
87.200	87.300	9.24	9.44	9.34	4.98	5.23	5.11	7.22	5769
87.300	87.400	8.37	8.57	8.47	5.07	5.27	5.17	6.82	5410
87.400	87.500	9.41	9.61	9.51	4.52	4.67	4.60	7.05	5617
87.500	87.600	7.96	8.16	8.06	7.75	8.00	7.88	7.97	6439

87.600	87.700	10.70	10.90	10.80	5.60	5.80	5.70	8.25	6695
87.700	87.800	6.70	6.90	6.80	3.74	3.89	3.82	5.31	4085
87.800	87.900	3.69	3.89	3.79	5.36	5.61	5.49	4.64	3512
87.900	88.000	3.76	3.96	3.86	4.78	4.98	4.88	4.37	3286
88.000	88.100	7.59	7.79	7.69	5.35	5.50	5.43	6.56	5177
88.100	88.200	4.41	4.61	4.51	5.40	5.65	5.53	5.02	3836
88.200	88.300	4.55	4.75	4.65	5.23	5.43	5.33	4.99	3813
88.300	88.400	4.59	4.79	4.69	4.89	5.04	4.97	4.83	3674
88.400	88.500	3.74	3.94	3.84	4.69	4.94	4.82	4.33	3250
88.500	88.600	9.01	9.21	9.11	3.73	3.93	3.83	6.47	5100
88.600	88.700	4.69	4.89	4.79	7.49	7.64	7.57	6.18	4842
88.700	88.800	8.06	8.26	8.16	4.63	4.88	4.76	6.46	5089
88.800	88.900	4.20	4.40	4.30	5.47	5.67	5.57	4.94	3765
88.900	89.000	3.90	4.10	4.00	4.49	4.64	4.57	4.28	3212
89.000	89.100	5.32	5.52	5.42	3.92	4.17	4.05	4.73	3593
89.100	89.200	4.43	4.63	4.53	4.05	4.25	4.15	4.34	3261
89.200	89.300	9.68	9.88	9.78	5.44	5.59	5.52	7.65	6150
89.300	89.400	3.15	3.35	3.25	4.17	4.42	4.30	3.77	2787
89.400	89.500	3.86	4.06	3.96	3.92	4.12	4.02	3.99	2968
89.500	89.600	3.94	4.14	4.04	4.17	4.32	4.25	4.14	3095
89.600	89.700	3.96	4.16	4.06	4.06	4.31	4.19	4.12	3078
89.700	89.800	5.73	5.93	5.83	4.35	4.55	4.45	5.14	3941
89.800	89.900	3.85	4.05	3.95	4.40	4.55	4.48	4.21	3154
89.900	90.000	3.92	4.12	4.02	4.23	4.38	4.31	4.16	3112
90.000	90.100	6.61	6.81	6.71	4.48	4.63	4.56	5.63	4366
90.100	90.200	10.27	10.47	10.37	4.72	4.87	4.80	7.58	6092
90.200	90.300	8.56	8.76	8.66	3.85	4.00	3.93	6.29	4943
90.300	90.400	10.13	10.33	10.23	4.42	4.57	4.50	7.36	5894
90.400	90.500	10.89	11.09	10.99	4.11	4.26	4.19	7.59	6096
90.500	90.600	9.61	9.81	9.71	4.01	4.16	4.09	6.90	5479
90.600	90.700	10.06	10.26	10.16	4.06	4.21	4.14	7.15	5702
90.700	90.800	9.12	9.32	9.22	3.68	3.83	3.76	6.49	5115
90.800	90.900	7.57	7.77	7.67	3.95	4.10	4.03	5.85	4554
90.900	91.000	6.23	6.43	6.33	4.00	4.15	4.08	5.20	3995
91.000	91.100	7.08	7.28	7.18	3.78	3.93	3.86	5.52	4267
91.100	91.200	4.10	4.30	4.20	4.16	4.31	4.24	4.22	3158
91.200	91.300	3.47	3.67	3.57	3.83	3.98	3.91	3.74	2758
91.300	91.400	3.72	3.92	3.82	4.43	4.58	4.51	4.16	3112
91.400	91.500	4.73	4.93	4.83	3.92	4.07	4.00	4.41	3322
91.500	91.600	3.31	3.51	3.41	3.64	3.79	3.72	3.56	2614
91.600	91.700	3.65	3.85	3.75	4.21	4.36	4.29	4.02	2991

91.700	91.800	4.45	4.65	4.55	4.89	5.04	4.97	4.76	3614
91.800	91.900	3.48	3.68	3.58	4.27	4.42	4.35	3.96	2945
91.900	92.000	3.65	3.85	3.75	4.72	4.87	4.80	4.27	3204
92.000	92.100	3.98	4.18	4.08	4.43	4.58	4.51	4.29	3221
92.100	92.200	4.12	4.32	4.22	4.13	4.28	4.21	4.21	3154
92.200	92.300	3.64	3.84	3.74	4.18	4.33	4.26	4.00	2974
92.300	92.400	4.37	4.57	4.47	5.08	5.23	5.16	4.81	3661
92.400	92.500	3.68	3.88	3.78	3.92	4.07	4.00	3.89	2883
92.500	92.600	3.12	3.32	3.22	3.99	4.14	4.07	3.64	2680
92.600	92.700	3.20	3.40	3.30	5.05	5.20	5.13	4.21	3154
92.700	92.800	3.91	4.11	4.01	3.87	4.02	3.95	3.98	2957
92.800	92.900	4.90	5.10	5.00	4.03	4.18	4.11	4.55	3440
92.900	93.000	4.23	4.43	4.33	4.51	4.66	4.59	4.46	3360
93.000	93.100	4.00	4.20	4.10	6.25	6.40	6.33	5.21	4003
93.100	93.200	3.59	3.79	3.69	6.25	6.40	6.33	5.01	3828
93.200	93.300	3.62	3.82	3.72	6.41	6.56	6.49	5.10	3909
93.300	93.400	3.36	3.56	3.46	8.41	8.56	8.49	5.97	4663
93.400	93.500	6.51	6.71	6.61	7.48	7.63	7.56	7.08	5644
93.500	93.600	4.89	5.09	4.99	5.06	5.21	5.14	5.06	3875
93.600	93.700	3.74	3.94	3.84	4.79	4.94	4.87	4.35	3271
93.700	93.800	4.61	4.81	4.71	4.89	5.04	4.97	4.84	3682
93.800	93.900	4.49	4.69	4.59	4.27	4.42	4.35	4.47	3368
93.900	94.000	4.24	4.44	4.34	4.72	4.87	4.80	4.57	3453
94.000	94.100	5.98	6.18	6.08	5.30	5.45	5.38	5.73	4449
94.100	94.200	5.12	5.32	5.22	4.75	4.90	4.83	5.02	3840
94.200	94.300	4.49	4.69	4.59	4.39	4.54	4.47	4.53	3419
94.300	94.400	4.01	4.21	4.11	4.08	4.23	4.16	4.13	3087
94.400	94.500	5.01	5.21	5.11	5.38	5.53	5.46	5.28	4064
94.500	94.600	10.47	10.67	10.57	5.35	5.50	5.43	8.00	6466
94.600	94.700	3.56	3.76	3.66	4.53	4.68	4.61	4.13	3087
94.700	94.800	4.67	4.87	4.77	5.54	5.69	5.62	5.19	3986
94.800	94.900	7.80	8.00	7.90	4.82	4.97	4.90	6.40	5036
94.900	95.000	2.27	2.47	2.37	4.61	4.76	4.69	3.53	2585
95.000	95.100	5.75	5.95	5.85	3.99	4.14	4.07	4.96	3785
95.100	95.200	5.14	5.34	5.24	3.92	4.07	4.00	4.62	3495
95.200	95.300	4.83	5.03	4.93	4.68	4.83	4.76	4.84	3687
95.300	95.400	4.99	5.19	5.09	4.59	4.74	4.67	4.88	3716
95.400	95.500	4.83	5.03	4.93	4.04	4.19	4.12	4.52	3415
95.500	95.600	5.12	5.32	5.22	3.83	3.98	3.91	4.56	3449
95.600	95.700	4.81	5.01	4.91	5.00	5.15	5.08	4.99	3815
95.700	95.800	4.13	4.33	4.23	5.66	5.81	5.74	4.98	3806

95.800	95.900	4.11	4.31	4.21	4.57	4.72	4.65	4.43	3335
95.900	96.000	4.55	4.75	4.65	4.57	4.72	4.65	4.65	3521
96.000	96.100	5.86	6.06	5.96	5.06	5.21	5.14	5.55	4293
96.100	96.200	5.02	5.22	5.12	5.30	5.45	5.38	5.25	4034
96.200	96.300	5.59	5.79	5.69	4.29	4.44	4.37	5.03	3845
96.300	96.400	5.98	6.18	6.08	4.89	5.04	4.97	5.52	4271
96.400	96.500	7.47	7.67	7.57	4.30	4.45	4.38	5.97	4663
96.500	96.600	6.64	6.84	6.74	5.09	5.24	5.17	5.95	4645
96.600	96.700	4.77	4.97	4.87	4.79	4.94	4.87	4.87	3708
96.700	96.800	5.16	5.36	5.26	6.51	6.66	6.59	5.92	4619
96.800	96.900	5.05	5.25	5.15	5.76	5.91	5.84	5.49	4245
96.900	97.000	4.43	4.63	4.53	5.51	5.66	5.59	5.06	3870
97.000	97.100	4.34	4.54	4.44	5.11	5.26	5.19	4.81	3661
97.100	97.200	5.32	5.52	5.42	5.53	5.68	5.61	5.51	4262
97.200	97.300	5.94	6.14	6.04	4.74	4.89	4.82	5.43	4189
97.300	97.400	5.49	5.69	5.59	5.03	5.18	5.11	5.35	4120
97.400	97.500	5.69	5.89	5.79	4.34	4.49	4.42	5.10	3909
97.500	97.600	7.41	7.61	7.51	5.00	5.15	5.08	6.29	4943
97.600	97.700	6.09	7.61	6.85	5.20	5.35	5.28	6.06	4741
97.700	97.800	3.94	6.29	5.12	5.84	5.99	5.92	5.52	4265
97.800	97.900	4.00	4.14	4.07	6.03	6.18	6.11	5.09	3896
97.900	98.000	4.50	4.20	4.35	5.81	5.96	5.89	5.12	3922
98.000	98.100	5.89	4.70	5.30	4.94	5.09	5.02	5.16	3954
98.100	98.200	6.71	6.09	6.40	5.11	5.26	5.19	5.79	4506
98.200	98.300	5.16	6.91	6.04	4.38	4.53	4.46	5.25	4031
98.300	98.400	4.84	5.36	5.10	5.48	5.63	5.56	5.33	4102
98.400	98.500	4.30	5.04	4.67	5.52	5.67	5.60	5.13	3935
98.500	98.600	4.03	4.50	4.27	6.88	7.03	6.96	5.61	4347
98.600	98.700	5.98	4.23	5.11	4.84	4.99	4.92	5.01	3830
98.700	98.800	5.02	6.18	5.60	6.48	6.63	6.56	6.08	4755
98.800	98.900	5.82	5.22	5.52	7.10	7.25	7.18	6.35	4992
98.900	99.000	4.94	6.02	5.48	8.71	8.86	8.79	7.13	5688
99.000	99.100	4.09	5.14	4.62	2.78	2.93	2.86	3.74	2756
99.100	99.200	3.64	4.29	3.97	6.86	7.01	6.94	5.45	4208
99.200	99.300	3.74	3.84	3.79	8.66	8.81	8.74	6.26	4917
99.300	99.400	3.88	3.94	3.91	7.36	7.51	7.44	5.67	4401
99.400	99.500	3.56	4.08	3.82	6.11	6.26	6.19	5.00	3823
99.500	99.600	4.24	3.76	4.00	7.65	7.80	7.73	5.86	4567
99.600	99.700	3.99	4.44	4.22	6.99	7.14	7.07	5.64	4373
99.700	99.800	4.23	4.19	4.21	5.10	5.25	5.18	4.69	3559
99.800	99.900	4.03	4.43	4.23	5.88	6.03	5.96	5.09	3900

99.900	100.000	4.28	4.23	4.26	5.19	5.34	5.27	4.76	3616
100.000	100.100	4.74	4.48	4.61	4.58	4.73	4.66	4.63	3508
100.100	100.200	3.99	4.94	4.47	4.73	4.88	4.81	4.64	3510
100.200	100.300	3.48	4.19	3.84	4.89	5.04	4.97	4.40	3311
100.300	100.400	3.77	3.68	3.73	5.38	5.53	5.46	4.59	3472
100.400	100.500	4.39	3.97	4.18	4.49	4.64	4.57	4.37	3288
100.500	100.600	3.67	4.59	4.13	5.22	5.37	5.30	4.71	3576
100.600	100.700	4.63	3.87	4.25	6.07	6.22	6.15	5.20	3991
100.700	100.800	3.90	4.83	4.37	5.11	5.26	5.19	4.78	3629
100.800	100.900	3.67	4.10	3.89	4.40	4.55	4.48	4.18	3126
100.900	101.000	3.76	3.87	3.82	5.99	6.14	6.07	4.94	3770
101.000	101.100	3.57	3.96	3.77	4.67	4.82	4.75	4.26	3189
101.100	101.200	3.50	3.77	3.64	4.67	4.82	4.75	4.19	3135
101.200	101.300	5.37	3.70	4.54	5.72	5.87	5.80	5.17	3963
101.300	101.400	3.56	5.57	4.57	5.16	5.31	5.24	4.90	3736
101.400	101.500	4.03	3.76	3.90	5.18	5.33	5.26	4.58	3459
101.500	101.600	3.90	4.23	4.07	3.78	3.93	3.86	3.96	2943
101.600	101.700	4.62	4.10	4.36	4.78	4.93	4.86	4.61	3487
101.700	101.800	4.42	4.82	4.62	4.39	4.54	4.47	4.54	3432
101.800	101.900	6.02	4.62	5.32	6.17	6.32	6.25	5.78	4497
101.900	102.000	4.72	6.22	5.47	4.57	4.72	4.65	5.06	3870
102.000	102.100	4.70	4.92	4.81	2.50	2.65	2.58	3.69	2721
102.100	102.200	3.57	4.90	4.24	7.83	7.98	7.91	6.07	4748
102.200	102.300	4.96	3.77	4.37	6.96	7.11	7.04	5.70	4425
102.300	102.400	4.56	5.16	4.86	7.84	7.99	7.92	6.39	5027
102.400	102.500	5.65	4.76	5.21	5.60	5.75	5.68	5.44	4200
102.500	102.600	5.09	5.85	5.47	6.88	7.03	6.96	6.21	4873
102.600	102.700	4.44	5.29	4.87	7.37	7.52	7.45	6.16	4823
102.700	102.800	4.06	4.64	4.35	4.88	5.03	4.96	4.65	3525
102.800	102.900	4.58	4.26	4.42	4.93	5.08	5.01	4.71	3576
102.900	103.000	6.45	4.78	5.62	4.01	4.16	4.09	4.85	3693
103.000	103.100	5.40	6.65	6.03	4.23	4.38	4.31	5.17	3963
103.100	103.200	6.17	5.60	5.89	4.43	4.58	4.51	5.20	3988
103.200	103.300	7.08	6.37	6.73	4.26	4.41	4.34	5.53	4278
103.300	103.400	6.58	7.28	6.93	5.11	5.26	5.19	6.06	4737
103.400	103.500	5.04	6.78	5.91	4.62	4.77	4.70	5.30	4081
103.500	103.600	5.35	5.24	5.30	4.54	4.69	4.62	4.96	3783
103.600	103.700	4.02	5.55	4.79	4.60	4.75	4.68	4.73	3591
103.700	103.800	4.25	4.22	4.24	4.13	4.28	4.21	4.22	3160
103.800	103.900	4.96	4.45	4.71	4.03	4.18	4.11	4.41	3316
103.900	104.000	5.04	5.16	5.10	5.77	5.92	5.85	5.47	4228

Table 6 Roughness Values after Construction of Test Section

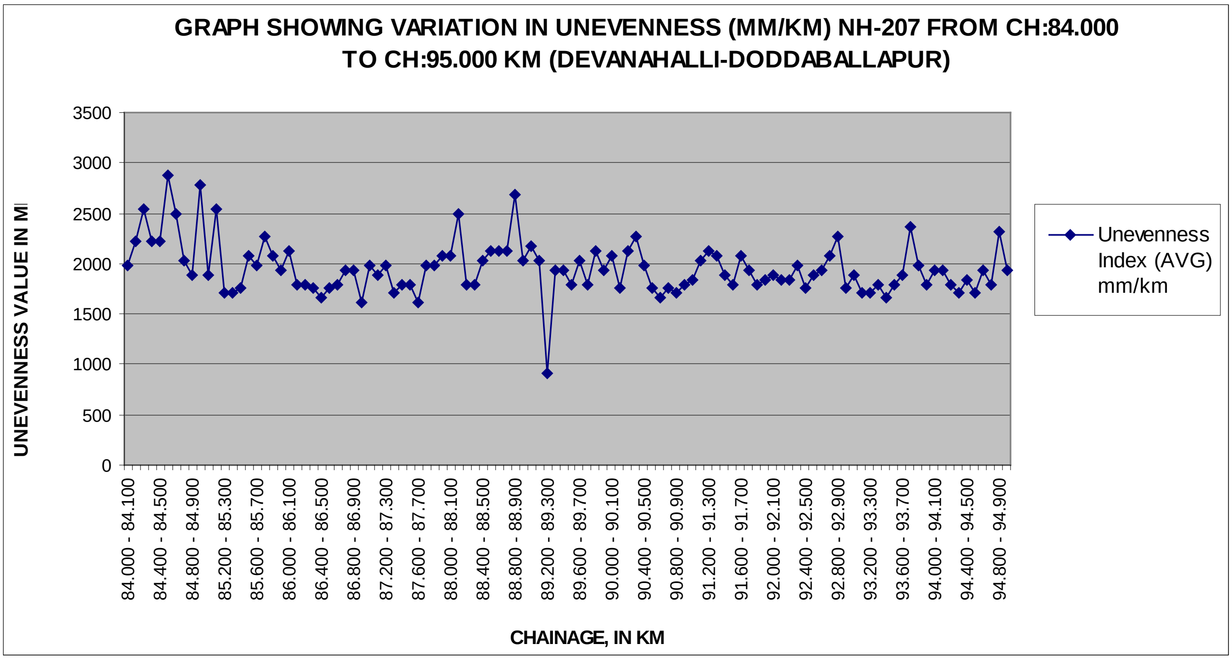
Chainage, km	LHS				RHS				
	Trial 1	Trial 2	Unevenness Index (AVG) mm/km	Average, IRI	Trial 1	Trial 2	Trial 3	Unevenness Index (AVG) mm/km	Average, IRI
84.000 - 84.100	2217	1750	1984	2.78	2031	3338	1750	2373	3.27
84.100 - 84.200	2217	2217	2217	3.08	2031	2124	2124	2093	2.92
84.200 - 84.300	3245	1844	2544	3.48	2031	2031	1657	1906	2.69
84.300 - 84.400	2311	2124	2217	3.08	2031	1750	1844	1875	2.65
84.400 - 84.500	2217	2217	2217	3.08	2217	2498	2217	2311	3.19
84.500 - 84.600	2217	3525	2871	3.87	2217	2498	2031	2249	3.11
84.600 - 84.700	3151	1844	2498	3.42	4926	5019	4459	4801	6.13
84.700 - 84.800	1750	2311	2031	2.84	1657	1564	1937	1719	2.45
84.800 - 84.900	1844	1937	1891	2.67	1844	1564	1750	1719	2.45
84.900 - 85.000	3899	1657	2778	3.76	2031	1844	1937	1937	2.73
85.000 - 85.100	1844	1937	1891	2.67	2031	1844	1470	1782	2.53
85.100 - 85.200	1470	3618	2544	3.48	1750	1750	1564	1688	2.41
85.200 - 85.300	1750	1657	1704	2.43	1937	2124	3805	2622	3.57
85.300 - 85.400	1750	1657	1704	2.43	2311	1844	1844	1999	2.80
85.400 - 85.500	1844	1657	1750	2.49	2217	2124	2031	2124	2.96
85.500 - 85.600	2124	2031	2077	2.90	2404	2311	1470	2062	2.88
85.600 - 85.700	1750	2217	1984	2.78	2684	2684	2591	2653	3.61
85.700 - 85.800	1750	2778	2264	3.13	2031	2311	1844	2062	2.88
85.800 - 85.900	2404	1750	2077	2.90	1750	2311	1937	1999	2.80
85.900 - 86.000	1937	1937	1937	2.73	1750	1937	1657	1782	2.53
86.000 - 86.100	1750	2498	2124	2.96	2311	2217	1750	2093	2.92
86.100 - 86.200	1377	2217	1797	2.55	1937	2031	2217	2062	2.88
86.200 - 86.300	1657	1937	1797	2.55	2031	2311	1844	2062	2.88
86.300 - 86.400	1470	2031	1750	2.49	2404	2124	2031	2186	3.04
86.400 - 86.500	1657	1657	1657	2.37	2498	2217	2124	2280	3.15
86.500 - 86.600	1657	1844	1750	2.49	2031	1937	1750	1906	2.69
86.600 - 86.700	1844	1750	1797	2.55	2124	1937	1844	1968	2.77
86.700 - 86.800	1750	2124	1937	2.73	2124	1750	1750	1875	2.65
86.800 - 86.900	1750	2124	1937	2.73	2031	1657	1844	1844	2.61
86.900 - 87.000	1657	1564	1610	2.31	2031	1937	1937	1968	2.77
87.000 - 87.100	2031	1937	1984	2.78	2031	1564	1657	1750	2.49
87.100 - 87.200	1937	1844	1891	2.67	2311	2031	2498	2280	3.15
87.200 - 87.300	1750	2217	1984	2.78	1844	1657	1564	1688	2.41
87.300 - 87.400	1564	1844	1704	2.43	1750	1750	1750	1750	2.49
87.400 - 87.500	1564	2031	1797	2.55	2031	2591	1750	2124	2.96
87.500 - 87.600	1657	1937	1797	2.55	2124	2031	1657	1937	2.73
87.600 - 87.700	1657	1564	1610	2.31	2031	2124	1750	1968	2.77
87.700 - 87.800	2311	1657	1984	2.78	1844	1844	1750	1813	2.57
87.800 - 87.900	1937	2031	1984	2.78	1750	1937	1937	1875	2.65
87.900 - 88.000	2031	2124	2077	2.90	2124	2217	1750	2031	2.84
88.000 - 88.100	2311	1844	2077	2.90	2311	1750	2311	2124	2.96
88.100 - 88.200	2684	2311	2498	3.42	2217	1844	2217	2093	2.92
88.200 - 88.300	1657	1937	1797	2.55	1750	1657	2031	1813	2.57
88.300 - 88.400	1937	1657	1797	2.55	1750	1750	1844	1782	2.53

Chainage, km	LHS				RHS				
	Trial 1	Trial 2	Unevenness Index (AVG) mm/km	Average, IRI	Trial 1	Trial 2	Trial 3	Unevenness Index (AVG) mm/km	Average, IRI
88.400 - 88.500	1844	2217	2031	2.84	1937	1750	1657	1782	2.53
88.500 - 88.600	1844	2404	2124	2.96	1937	1844	1844	1875	2.65
88.600 - 88.700	2124	2124	2124	2.96	1937	2031	2031	1999	2.80
88.700 - 88.800	2031	2217	2124	2.96	2124	2031	2031	2062	2.88
88.800 - 88.900	2124	3245	2684	3.65	2311	1750	1657	1906	2.69
88.900 - 89.000	2124	1937	2031	2.84	1750	1750	1844	1782	2.53
89.000 - 89.100	1937	2404	2171	3.02	1844	1750	2031	1875	2.65
89.100 - 89.200	2031	2031	2031	2.84	2031	1564	2311	1968	2.77
89.200 - 89.300	1750	60	905	1.38	2124	1844	2031	1999	2.80
89.300 - 89.400	1750	2124	1937	2.73	2124	2031	2031	2062	2.88
89.400 - 89.500	2031	1844	1937	2.73	3058	1657	2404	2373	3.27
89.500 - 89.600	1750	1844	1797	2.55	2217	1750	1937	1968	2.77
89.600 - 89.700	1937	2124	2031	2.84	2217	1750	1844	1937	2.73
89.700 - 89.800	1750	1844	1797	2.55	2498	1750	1844	2031	2.84
89.800 - 89.900	1937	2311	2124	2.96	2591	1750	1750	2031	2.84
89.900 - 90.000	1564	2311	1937	2.73	2871	1657	1844	2124	2.96
90.000 - 90.100	1657	2498	2077	2.90	2404	1564	2031	1999	2.80
90.100 - 90.200	1750	1750	1750	2.49	2031	1564	1657	1750	2.49
90.200 - 90.300	1937	2311	2124	2.96	2311	2031	1750	2031	2.84
90.300 - 90.400	2311	2217	2264	3.13	1844	1750	1844	1813	2.57
90.400 - 90.500	1657	2311	1984	2.78	1937	1657	2217	1937	2.73
90.500 - 90.600	1470	2031	1750	2.49	1750	1750	2031	1844	2.61
90.600 - 90.700	1564	1750	1657	2.37	1844	1937	2404	2062	2.88
90.700 - 90.800	1750	1750	1750	2.49	1657	1844	2124	1875	2.65
90.800 - 90.900	1657	1750	1704	2.43	1937	1844	2031	1937	2.73
90.900 - 91.000	1564	2031	1797	2.55	1750	1844	2217	1937	2.73
91.000 - 91.100	1750	1937	1844	2.61	1750	1937	1844	1844	2.61
91.100 - 91.200	2217	1844	2031	2.84	2031	2031	2124	2062	2.88
91.200 - 91.300	2031	2217	2124	2.96	1750	1657	1750	1719	2.45
91.300 - 91.400	1937	2217	2077	2.90	1844	2404	1657	1968	2.77
91.400 - 91.500	1844	1937	1891	2.67	1750	2031	1750	1844	2.61
91.500 - 91.600	2031	1564	1797	2.55	1657	1844	1750	1750	2.49
91.600 - 91.700	2217	1937	2077	2.90	1750	1844	1750	1782	2.53
91.700 - 91.800	1937	1937	1937	2.73	2124	1844	1657	1875	2.65
91.800 - 91.900	1750	1844	1797	2.55	1657	1844	1750	1750	2.49
91.900 - 92.000	1844	1844	1844	2.61	1657	1937	2124	1906	2.69
92.000 - 92.100	1844	1937	1891	2.67	1657	1750	1750	1719	2.45
92.100 - 92.200	1657	2031	1844	2.61	1657	2124	1564	1782	2.53
92.200 - 92.300	1657	2031	1844	2.61	1657	2031	1750	1813	2.57
92.300 - 92.400	1844	2124	1984	2.78	1657	2217	1750	1875	2.65
92.400 - 92.500	1657	1844	1750	2.49	1657	1844	1750	1750	2.49
92.500 - 92.600	1844	1937	1891	2.67	1750	2311	1657	1906	2.69
92.600 - 92.700	1470	2404	1937	2.73	1750	1844	1844	1813	2.57
92.700 - 92.800	1657	2498	2077	2.90	1750	2217	1750	1906	2.69
92.800 - 92.900	1844	2684	2264	3.13	1657	1937	2311	1968	2.77
92.900 - 93.000	1750	1750	1750	2.49	1844	1750	2124	1906	2.69

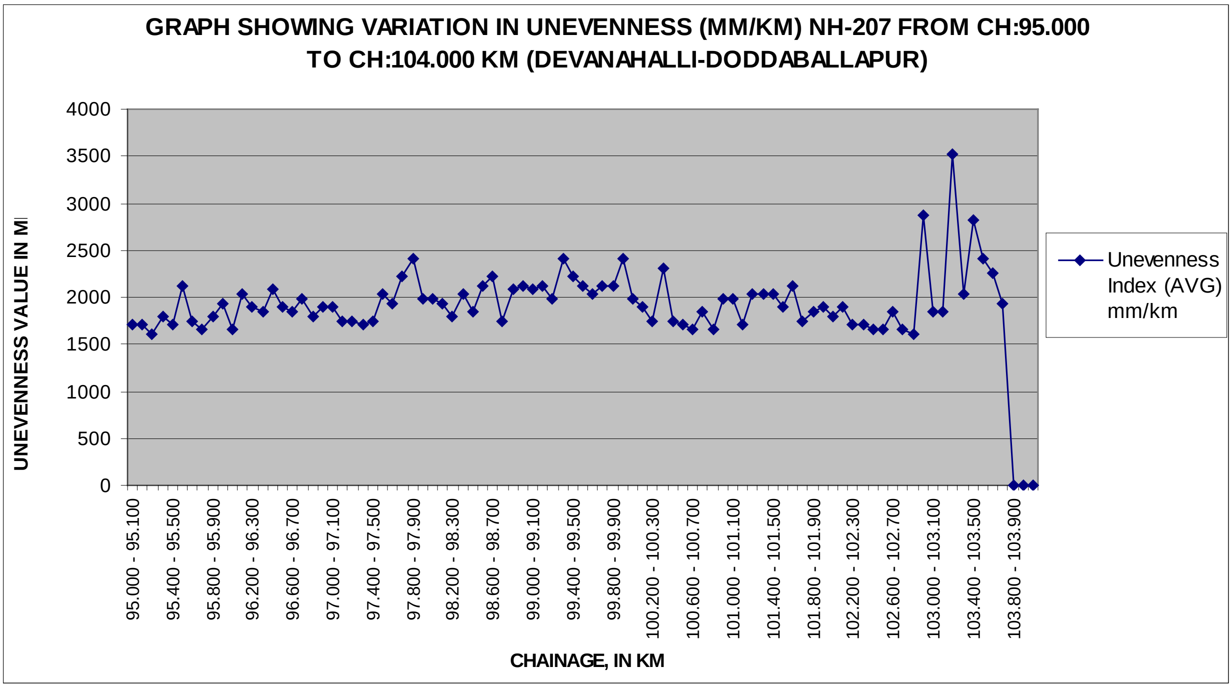
Chainage, km	LHS				RHS				
	Trial 1	Trial 2	Unevenness Index (AVG) mm/km	Average, IRI	Trial 1	Trial 2	Trial 3	Unevenness Index (AVG) mm/km	Average, IRI
93.000 - 93.100	1750	2031	1891	2.67	1844	2217	1844	1968	2.77
93.100 - 93.200	1657	1750	1704	2.43	1750	1844	1937	1844	2.61
93.200 - 93.300	1657	1750	1704	2.43	2124	2217	2217	2186	3.04
93.300 - 93.400	1564	2031	1797	2.55	1937	2031	1657	1875	2.65
93.400 - 93.500	1657	1657	1657	2.37	1750	2217	1657	1875	2.65
93.500 - 93.600	1844	1750	1797	2.55	1844	2311	1657	1937	2.73
93.600 - 93.700	1657	2124	1891	2.67	1750	1937	1657	1782	2.53
93.700 - 93.800	2124	2591	2358	3.25	1844	2404	1750	1999	2.80
93.800 - 93.900	1844	2124	1984	2.78	1750	2684	1657	2031	2.84
93.900 - 94.000	1750	1844	1797	2.55		2124	1844	1984	1.93
94.000 - 94.100	1750	2124	1937	2.73	1750	2217	2124	2031	2.84
94.100 - 94.200	1657	2217	1937	2.73	2124	2217	2217	2186	3.04
94.200 - 94.300	1750	1844	1797	2.55	1937	1844	1844	1875	2.65
94.300 - 94.400	1844	1564	1704	2.43	1844	1937	1844	1875	2.65
94.400 - 94.500	1937	1750	1844	2.61	1937	1937	1750	1875	2.65
94.500 - 94.600	1750	1657	1704	2.43	1937	2124	1750	1937	2.73
94.600 - 94.700	1937	1937	1937	2.73	2031	1937	2031	1999	2.80
94.700 - 94.800	1844	1750	1797	2.55	2031	1937	1937	1968	2.77
94.800 - 94.900	1937	2684	2311	3.19	2124	2031	1750	1968	2.77
94.900 - 95.000	1750	2124	1937	2.73	1844	1937	1844	1875	2.65
95.000 - 95.100	1657	1750	1704	2.43	1937	2311	1750	1999	2.80
95.100 - 95.200	1564	1844	1704	2.43	2124	2124	1657	1968	2.77
95.200 - 95.300	1470	1750	1610	2.31	2498	1844	1750	2031	2.84
95.300 - 95.400	1657	1937	1797	2.55	2124	1844	1657	1875	2.65
95.400 - 95.500	1564	1844	1704	2.43	1844	1750	2124	1906	2.69
95.500 - 95.600	1937	2311	2124	2.96	1937	1844	1564	1782	2.53
95.600 - 95.700	1844	1657	1750	2.49	1657	1844	1750	1750	2.49
95.700 - 95.800	1564	1750	1657	2.37	1937	1937	1657	1844	2.61
95.800 - 95.900	1844	1750	1797	2.55	1937	2031	1937	1968	2.77
95.900 - 96.000	1844	2031	1937	2.73	1750	1937	1564	1750	2.49
96.000 - 96.100	1657	1657	1657	2.37	2031	1937	1657	1875	2.65
96.100 - 96.200	2124	1937	2031	2.84	2124	2031	1844	1999	2.80
96.200 - 96.300	1750	2031	1891	2.67	1937	1844	1657	1813	2.57
96.300 - 96.400	1750	1937	1844	2.61	1937	1844	1470	1750	2.49
96.400 - 96.500	1844	2311	2077	2.90	1937	1750	1657	1782	2.53
96.500 - 96.600	1750	2031	1891	2.67	1937	1564	1844	1782	2.53
96.600 - 96.700	1750	1937	1844	2.61	1844	1750	1564	1719	2.45
96.700 - 96.800	2031	1937	1984	2.78	1844	1657	1750	1750	2.49
96.800 - 96.900	1844	1750	1797	2.55	1844	1937	1564	1782	2.53
96.900 - 97.000	1750	2031	1891	2.67	2124	2031	1844	1999	2.80
97.000 - 97.100	1750	2031	1891	2.67	1937	2031	1750	1906	2.69
97.100 - 97.200	1657	1844	1750	2.49	2124	1844	1377	1782	2.53
97.200 - 97.300	1564	1937	1750	2.49	2031	2031	1937	1999	2.80
97.300 - 97.400	1657	1750	1704	2.43	2217	1750	1750	1906	2.69
97.400 - 97.500	1657	1844	1750	2.49	2498	2217	1657	2124	2.96
97.500 - 97.600	1844	2217	2031	2.84	2031	2031	1750	1937	2.73

Chainage, km	LHS				RHS				
	Trial 1	Trial 2	Unevenness Index (AVG) mm/km	Average, IRI	Trial 1	Trial 2	Trial 3	Unevenness Index (AVG) mm/km	Average, IRI
97.600 - 97.700	1844	2031	1937	2.73	2498	2404	2124	2342	3.23
97.700 - 97.800	2124	2311	2217	3.08	1937	2591	1844	2124	2.96
97.800 - 97.900	1844	2965	2404	3.31	1844	1750	2498	2031	2.84
97.900 - 98.000	1844	2124	1984	2.78	2031	2124	2498	2217	3.08
98.000 - 98.100	1937	2031	1984	2.78	1750	2124	2498	2124	2.96
98.100 - 98.200	1937	1937	1937	2.73	2124	2031	2311	2155	3.00
98.200 - 98.300	1844	1750	1797	2.55	1937	2031	1844	1937	2.73
98.300 - 98.400	1750	2311	2031	2.84	2217	2031	2031	2093	2.92
98.400 - 98.500	1657	2031	1844	2.61	1750	2031	1937	1906	2.69
98.500 - 98.600	1937	2311	2124	2.96	2124	2124	2965	2404	3.31
98.600 - 98.700	1657	2778	2217	3.08	2217	1937	1750	1968	2.77
98.700 - 98.800	1564	1937	1750	2.49	2311	2031	1657	1999	2.80
98.800 - 98.900	2031	2124	2077	2.90	2031	1937	1657	1875	2.65
98.900 - 99.000	2217	2031	2124	2.96	2124	2124	1564	1937	2.73
99.000 - 99.100	2124	2031	2077	2.90	2124	2311	2217	2217	3.08
99.100 - 99.200	2217	2031	2124	2.96	2404	2217	1844	2155	3.00
99.200 - 99.300	2031	1937	1984	2.78	1937	2311	1844	2031	2.84
99.300 - 99.400	2311	2498	2404	3.31	1937	2124	1844	1968	2.77
99.400 - 99.500	2217	2217	2217	3.08	2217	2124	1937	2093	2.92
99.500 - 99.600	2217	2031	2124	2.96	1937	2217		2077	1.94
99.600 - 99.700	2404	1657	2031	2.84	1937	2031	1657	1875	2.65
99.700 - 99.800	2217	2031	2124	2.96	1844	2124	1844	1937	2.73
99.800 - 99.900	2031	2217	2124	2.96	1844	2124	2124	2031	2.84
99.900 - 100.000	2404	2404	2404	3.31	2031	2217	1844	2031	2.84
100.000 - 100.100	1937	2031	1984	2.78	2311	2311	1564	2062	2.88
100.100 - 100.200	1937	1844	1891	2.67	2311	2124	1657	2031	2.84
100.200 - 100.300	1564	1937	1750	2.49	1937	1937	1844	1906	2.69
100.300 - 100.400	2217	2404	2311	3.19	2031	1937	2031	1999	2.80
100.400 - 100.500	1750	1750	1750	2.49	1844	2124	2031	1999	2.80
100.500 - 100.600	1657	1750	1704	2.43	1844	2124	1470	1813	2.57
100.600 - 100.700	1564	1750	1657	2.37	1657	2031	1750	1813	2.57
100.700 - 100.800	1657	2031	1844	2.61	1750	2124	2311	2062	2.88
100.800 - 100.900	1564	1750	1657	2.37	1657	1844	1937	1813	2.57
100.900 - 101.000	1844	2124	1984	2.78	1657	2031	2124	1937	2.73
101.000 - 101.100	1657	2311	1984	2.78	2498	2591	1844	2311	3.19
101.100 - 101.200	1564	1844	1704	2.43	1564	2217	1937	1906	2.69
101.200 - 101.300	1844	2217	2031	2.84	1937	2404	2031	2124	2.96
101.300 - 101.400	1844	2217	2031	2.84	1937	2031	2031	1999	2.80
101.400 - 101.500	1750	2311	2031	2.84	1750	1937	2498	2062	2.88
101.500 - 101.600	1750	2031	1891	2.67	1657	1564	2311	1844	2.61
101.600 - 101.700	2031	2217	2124	2.96	1844	1844	1937	1875	2.65
101.700 - 101.800	1657	1844	1750	2.49	2217	1564	2031	1937	2.73
101.800 - 101.900	1750	1937	1844	2.61	2031	1750	2217	1999	2.80
101.900 - 102.000	1657	2124	1891	2.67	2031	2311	1844	2062	2.88
102.000 - 102.100	1657	1937	1797	2.55	2217	2965	1564	2249	3.11
102.100 - 102.200	1657	2124	1891	2.67	1750	1937	1937	1875	2.65

Chainage, km	LHS				RHS				
	Trial 1	Trial 2	Unevenness Index (AVG) mm/km	Average, IRI	Trial 1	Trial 2	Trial 3	Unevenness Index (AVG) mm/km	Average, IRI
102.200 - 102.300	1750	1657	1704	2.43	1750	1844	2684	2093	2.92
102.300 - 102.400	1564	1844	1704	2.43	1937	1844	2311	2031	2.84
102.400 - 102.500	1657	1657	1657	2.37	1844	1937	2124	1968	2.77
102.500 - 102.600	1564	1750	1657	2.37	1750	1657	2684	2031	2.84
102.600 - 102.700	1657	2031	1844	2.61	1657	2031	2031	1906	2.69
102.700 - 102.800	1657	1657	1657	2.37	2124	2124	1750	1999	2.80
102.800 - 102.900	1470	1750	1610	2.31	1750	2217	1937	1968	2.77
102.900 - 103.000	1937	3805	2871	3.87	3618	4179	5393	4397	5.67
103.000 - 103.100	1750	1937	1844	2.61	1657	1657	1750	1688	2.41
103.100 - 103.200	1750	1937	1844	2.61	1564	1470	1657	1564	2.25
103.200 - 103.300	5019	2031	3525	4.65	1937	1564	2217	1906	2.69
103.300 - 103.400	2031	2031	2031	2.84	1937	1657	1844	1813	2.57
103.400 - 103.500	3058	2591	2825	3.82	2031	1750	2031	1937	2.73
103.500 - 103.600	2871	1937	2404	3.31	2965	3338	2031	2778	3.76
103.600 - 103.700	2498	2031	2264	3.13	2498	1750	2217	2155	3.00
103.700 - 103.800	1937	1937	1937	2.73	2217	2124	2031	2124	2.96

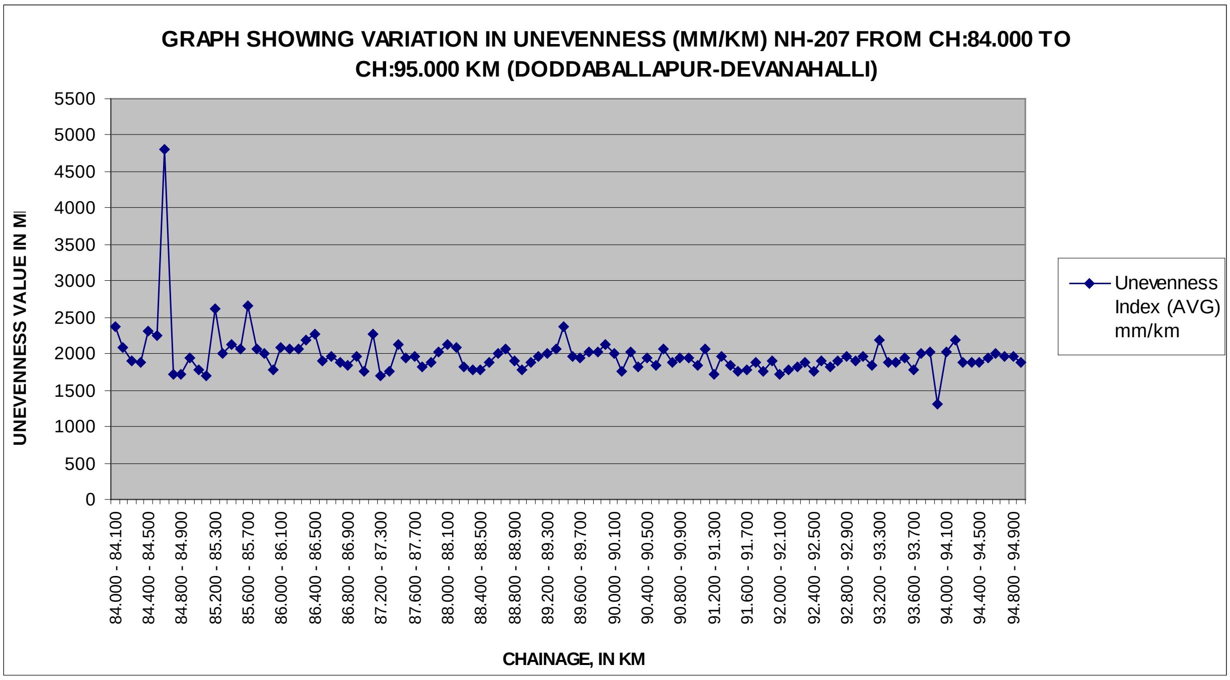


(a)

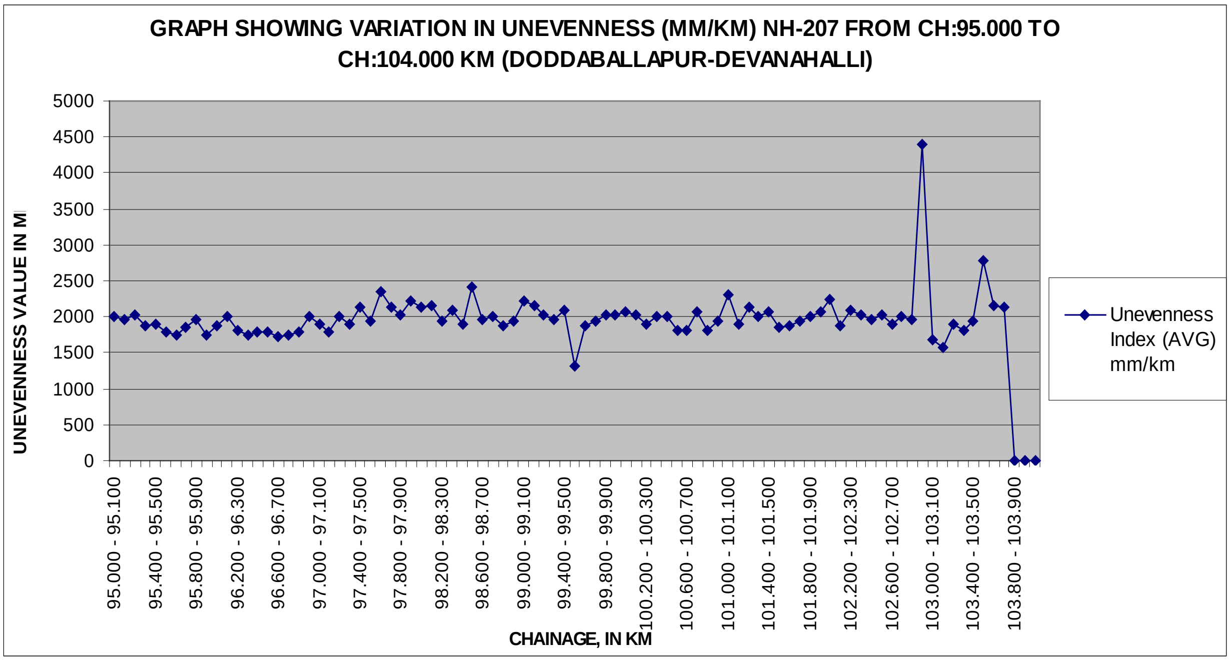


(b)

Figure 1 Variation in Unevenness along LHS



(a)



(b)
Figure 2 Variation in Unevenness along RHS

Table 7 Periodic Roughness Evaluation of the Test Sections-LHS

Chainage (km)	IRI, Feb-11	IRI, Dec-11	IRI,June 2012
84-85	4.16	4.02	3.51
85-86	2.65	3.05	3.52
86-87	3.15	3.24	3.41
87-88	3.11	3.21	3.81
88-89	3.75	3.98	3.77
89-90	3.56	3.62	3.83
90-91	3.14	3.23	3.21
91-92	3.1	3.35	3.43
92-93	2.78	2.88	3.39
93-94	2.7	3.22	2.90
94-95	2.84	2.72	3.00
95-96	2.78	2.9	3.00
96-97	3.13	3.22	3.60
97-98	2.86	2.96	3.22
98-99	2.86	2.81	3.07
99-100	3.59	3.56	3.80
100-101	3.36	3.36	3.69
101-102	3.07	3.23	3.46
102-103	2.58	2.69	2.80
103-104	4.11	3.11	3.90

Table 8 Periodic Roughness Evaluation of the Test Sections-RHS

Chainage (km)	IRI Feb-11	IRI Dec-11	IRI June 2012
104-103	3.30	4.38	3.14
103-102	3.53	3.53	3.64
102-101	3.41	3.49	3.63
101-100	3.01	3.15	3.34
100-99	3.09	3.21	3.49
99-98	3.16	3.72	3.67
98-97	2.66	2.84	3.21
97-96	3.27	3.29	3.67
96-95	2.67	2.81	2.90
95-94	3.41	3.33	3.71
94-93	3.29	3.38	3.59
93-92	2.8	3.07	3.51
92-91	2.98	3.08	3.37
91-90	3.52	3.39	4.01
90-89	3.25	3.51	3.72
89-88	3.38	3.79	3.89
88-87	3.31	3.56	3.88
87-86	3.51	3.58	3.95
86-85	2.71	2.86	3.51
85-84	3.59	3.84	3.06