SUITABILITY OF MODIFIED BINDERS FOR SUSTAINABLE FLEXIBLE PAVEMENT CONSTRUCTION IN CONTEXT OF BANGLADESH

By

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Department of Civil Engineering

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Declaration

I hereby declare that the work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the Thesis contains no material previously published or written by another person except where due reference is cited. Furthermore, the Thesis complies with PLAGIARISM and ACADEMIC INTEGRITY regulation of CUET.

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Author

Abstract

60/70 bitumen is used as the main binder in pavement construction of Bangladesh which experiences numerous types of defects require frequent maintenance and are extremely vulnerable to traffic loading, moisture damage and temperature changes. Hence, an effort has been made to enhance the bitumen quality by adding modifiers with the neat bitumen. And also, bituminous concrete mixes have been evaluated for some performance parameters to justify the bitumen quality. On the other hand, vehicles are increasing approximately 0.5 million per year in Bangladesh with the increase of life standard, country development, economic zones, population and road network which produce a significant amount (150,000 tons) of non-biodegradable waste tires. It may be advantageous for the environment and the economy by using this waste material as a bitumen modifier, producing Crumb Rubber Modified Bitumen (CRMB). Polymer Modified Bitumen (PMB) is used in many countries over the world due to its enhanced properties, so it has also been considered to verify the suitability over neat binder and CRMB.

The research includes laboratory investigation of binders (60/70, PMB & CRMB) properties and found CRMB has more enhanced. Marshall mix design approach has been used to determine the Marshall properties and Optimum Bitumen Content (OBC). The OBC's of bituminous mixes prepared by neat 60/70 bitumen, PMB, and CRMB were found to be 5.05%, 5.10% and 5.30% respectively. The retained stability of 60/70 bitumen, PMB, and CRMB mixtures were found to be 79.0%, 92.6% and 95.0% respectively. Based on Indirect Tensile Strength (IDT) test, the Tensile Strength Ratio (TSR) values for the respective mixtures were found to be 84.0%, 94.4% and 93.2%. Again, based on moisture induced damage test, the TSR values were found to be 83.1%, 90.1% and 93.0% for the respective bituminous mixes.

The modified bitumen showed higher softening point, higher elastic recovery, lower temperature susceptibility and lower stripping value. Moreover, higher resistance to moisture induced damage and retained stability were observed for the modified bituminous mixes. Finally, it can be concluded that, the performance of modified binders are better than that of neat 60/70 bitumen as they are less susceptible to temperature and moisture, causing less maintenance and rehabilitation costs over the pavement's lifespan. Since the CRMB performed best out of the two modified bitumen, it can be considered as a sustainable alternative for durable and effective road development in Bangladesh.

Keywords: Flexible pavement, Water sensitivity, Temperature variation, Waste tires, CRMB, PMB, Sustainable Development.

বিমূর্ত

বাংলাদেশের পাকা রাস্তা নির্মাণে 60/70 বিটুমিন প্রধান বাইন্ডার হিসেবে ব্যবহৃত হয় যা যানবাহনের চাপ, আর্দ্রতা ক্ষতি এবং তাপমাত্রার পরিবর্তনের জন্য অত্যন্ত ঝুঁকিপূর্ণ, যার ফলে রাস্তা ঘন ঘন রক্ষণাবেক্ষণের প্রয়োজন হয়। তাই, 60/70 পরিষ্কার বিটুমিনের সাথে সংশোধক যোগ করে বিটুমিনের মান উন্নত করার চেষ্টা করা হয়েছে এবং বিটুমিনের মানের ন্যায্যতা যাচাই করার জন্য বিটুমিনাস কংক্রিট মিশ্রণ এর কিছু কর্মক্ষমতা পরামিতি মূল্যায়ন করা হয়েছে। অন্যদিকে, জীবনযাত্রার মান, দেশের উন্নয়ন, অর্থনৈতিক অঞ্চল, জনসংখ্যা এবং সড়ক নেটওয়ার্ক বৃদ্ধির সাথে সাথে বাংলাদেশে প্রতি বছর যানবাহনের সংখ্যা প্রায় ০.৫ মিলিয়ন বৃদ্ধি পাচ্ছে যা উল্লেখযোগ্য পরিমাণে (১৫০,০০০ টন) অ-জৈব-পচনশীল বর্জ্য টায়ার তৈরি করে। এই বর্জ্য পদার্থকে বিটুমিন মডিফায়ার হিসেবে ব্যবহার করে ক্রাম্ব রাবার মডিফাইড বিটুমিন (CRMB) তৈরি করা হলে পরিবেশ এবং অর্থনীতির জন্য এটি সুবিধাজনক হতে পারে। উন্নত বৈশিষ্ট্যের কারণে বিশ্বের অনেক দেশে পলিমার মডিফাইড বিটুমিন (PMB) ব্যবহার করা হয়, তাই 60/70 বাইন্ডার এবং CRMB এর সাথে এটিও উপযুক্ততা যাচাই করার জন্য বিবেচনা করা হয়েছে।

এই গবেষণায় বাইন্ডারের (60/70, PMB এবং CRMB) বৈশিষ্ট্ সমূহ পরীক্ষাগারে যাচাই করার পর CRMB উন্নত বৈশিষ্ট্যযুক্ত বলে প্রমাণিত হয়েছে। মার্শাল বৈশিষ্ট্য এবং সর্বোত্তম বিটুমিন সামগ্রী (OBC) নির্ধারণের জন্য মার্শাল মিক্স ডিজাইন পদ্ধতি ব্যবহার করা হয়েছে। 60/70 বিটুমিন, PMB এবং CRMB দ্বারা প্রস্তুত বিটুমিনাস মিশ্রণের OBC যথাক্রমে ৫.০৫%, ৫.১০% এবং ৫.৩০% পাওয়া গেছে। 60/70 বিটুমিন, PMB এবং CRMB মিশ্রণের স্থায়ী স্থিতিশীলতা যথাক্রমে ৭৯.০%, ৯২.৬% এবং ৯৫.০% পাওয়া গেছে। পরোক্ষ প্রসার্য শক্তি (IDT) পরীক্ষার উপর ভিত্তি করে, সংশ্লিষ্ট মিশ্রণের জন্য প্রসার্য শক্তির অনুপাতের (TSR) মান ৮৪.০%, ৯৪.৪% এবং ৯৩.২% পাওয়া গেছে। আবার, আর্দ্রতা-প্ররোচিত ক্ষতি পরীক্ষার উপর ভিত্তি করে, সংশ্লিষ্ট বিটুমিনাস মিশ্রণের জন্য TSR এর মান ৮৩.১%, ৯০.১% এবং ৯৩.০% পাওয়া গেছে।

পরিবর্তিত বিটুমিন উচ্চতর নরমকরণ বিন্দু, উচ্চতর স্থিতিস্থাপক পুনরুদ্ধার, নিম্ন তাপমাত্রা সংবেদনশীলতা এবং নিম্ন স্ট্রিপিং মান দেখিয়েছে। অধিকন্তু, পরিবর্তিত বিটুমিনাস মিশ্রণের জন্য আর্দ্রতাজনিত ক্ষতির প্রতিরোধ ক্ষমতা এবং স্থিতিশীলতা বজায় রাখা লক্ষ্য করা গেছে। পরিশেষে, এই উপসংহারে পৌঁছানো যেতে পারে যে, মডিফাইড বাইন্ডারগুলির কর্মক্ষমতা পরিষ্কার 60/70 বিটুমিনের তুলনায় ভাল কারণ এগুলি তাপমাত্রা এবং আর্দ্রতার প্রতি কম সংবেদনশীল, যার ফলে পাকা রাস্তার জীবনকাল ধরে রক্ষণাবেক্ষণ এবং পুনর্বাসন খরচ কম হয়। যেহেতু দুটি মডিফাইড বিটুমিনের মধ্যে, CRMB ভালো কার্যকারিতা প্রদর্শন করেছে, তাই এটি বাংলাদেশে টেকসই এবং কার্যকর সড়ক উন্নয়নের জন্য একটি টেকসই বিকল্প হিসাবে বিবেচিত হতে পারে।

মূলশব্দ: নমনীয় পাকা রাস্তা, জল সংবেদনশীলতা, তাপমাত্রার তারতম্য, বর্জ্য টায়ার, CRMB, PMB, টেকসই উন্নয়ন।

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Nomenclature

D	Specimen Diameter
P	Maximum Load
t	Specimen Height
G_b	Specific Gravity of Asphalt (Binder)
G_{sb}	Bulk Specific Gravity of Combined Aggregate
G_{se}	Effective Specific Gravity of Combined Aggregate
G_{sa}	Apparent Specific Gravity of Combined Aggregate
G_{mb}	Bulk Specific Gravity of Compacted Mix
G_{mm}	Theoretical Maximum Specific Gravity of Paving Mixture
P_b	Asphalt Content
P_{mm}	Percent by mass of total Loose Mixture
P_s	Aggregate (Stone) Percent
P_{be}	Effective Asphalt Percent by Weight of Total Mixture
P_{ba}	Absorbed Asphalt Percent by Total Weight of Aggregate
$S_{t(Conditioned)}$	Tensile Strength of the Moisture Conditioned Sub-Set
$S_{t(Unconditioned)}$	Tensile Strength of the Dry Sub-Set

List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ACV	Aggregate Crushing Value
AG	Oxidative Aging
AIV	Aggregate Impact Value
ASTM	American Society for Testing and Materials
BBS	Bangladesh Bureau of Statistics
BRTA	Bangladesh Road Transport Authority
CR	Crumb Rubber
CRMB	Crumb Rubber Modified Bitumen
FHWA	Federal Highway Administration
EVA	Ethyl Vinyl Acetate
FC	Fatigue Cracking
HMA	Hot Mix Asphalt
HiMA	Highly or Heavily Modified Asphalt
HP	High Polymer
IDT	Indirect Tensile Strength
IS	Indian Standards
LAA	Los Angeles Abrasion
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LTC	Low Temperature Cracking
MD	Moisture Damage
NMAS	Nominal Maximum Aggregate Size

NPV	Net Present value
NRMB	Natural Rubber Modified Bitumen
OBC	Optimum Bitumen / Binder Content
OD	Oven Dry
PD	Permanent Deformation
PG	Performance Graded
PMB	Polymer Modified Bitumen
RHD	Roads and Highways Department
RRMA	Reclaimed Rubber Modified Asphalt
SASEC	South Asian Sub-Regional Economic Cooperation
SB	Styrene Butadiene Di block
SBR	Styrene Butadiene Rubber Latex
SBS	Styrene Butadiene Styrene (Triblock)
SHRP	Strategic Highway Research Program
STP	Standard Test Procedure
TSR	Tensile Strength Ratio
VMA	Voids in Mineral Aggregate
VFA	Voids filled with Asphalt

Appendices

Appendix A **Test Data of Various Binders**

A-1: Penetration of Various Bitumen at Different Temperatures (ASTM D 5)

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Chapter 1: INTRODUCTION

This chapter outlines the general (section 1.1) discussion about the chapter, background (section 1.2) and problem identification (section 1.3) of the research and its objectives (section 1.4). Next, section 1.5 describes the scope of this research. Finally, section 1.6 shows organization of the thesis includes an outline of the chapters of the Thesis.

1.1 GENERAL

High population density, high productivity of land, intensive cultivation & farming and rapid industrialization have been contributing to the economic growth of Bangladesh. To meet the necessity of economic development of Bangladesh, day by day the demands of transporting goods, equipment, fuel etc. and frequent movement of human being are being increased through roadway transport system notably. Bangladesh has around 3,75,000 km road network comprising National highway, Regional highway, Zila road, Upazila road, Union road, and Village road [1]. RHD is the road authority in Bangladesh which is responsible for the management of major road network that includes National Highways, Regional Highways and Zilla Roads. Total RHD paved road network is around 19,387 km (91 % of total length) of which 3,759 km is National Highway, 4,043 km is Regional Highway and the rest 11,584 km is Zilla Roads. This infrastructure development is necessary to enhance economic growth, business opportunities, international trade and increased agricultural production. At the same time this infrastructure needs investment for repair and rehabilitation taking account of increased level of traffic.

In Bangladesh, flexible pavements make up about 90% of all paved roadways. When building flexible pavements, bitumen is an essential component. Because of its special qualities, it is the perfect binding agent for the aggregates used in road building, ensuring that the road will be strong and long-lasting and able to tolerate both severe weather and high traffic volumes. However, traditional bituminous pavements require regular maintenance and are extremely vulnerable to moisture damage and temperature fluctuations. Water intrusion, heavy vehicle stress, seasonal temperature fluctuations that promote expansion and contraction, oxidation, aging, and sun exposure are some of the factors that lead to bituminous pavement failure. Bituminous roads are susceptible to a wide range of faults, such as deep and shallow potholes, surface deterioration, edge failure, cracking, rutting, and subsidence [2]. So, properties of bitumen and bituminous mixes are required to be improved with the incorporation of certain additives or blend of additives. These additives are called modifiers and the bitumen premixed with these modifiers is known as "Modified Bitumen". Polymer modified bitumen (PMB) and waste crumb rubber modified bitumen (CRMB) can be taken as modified binder to evaluate their comparative preference with respect to neat 60/70 bitumen.

The economic advantages and desirable physical and rheological characteristics of asphalt binders and asphalt mixes make crumb rubber (CR) modifier one of the most widely used asphalt binder modifiers [3]. CRMB represents an innovative approach to enhancing the performance and longevity of asphalt pavements by incorporating recycled rubber derived from discarded tires into bituminous binders. This recycled rubber is processed into fine particles, known as crumb rubber, which are then blended with bitumen to form a modified binder with unique properties. The use of rubber crumb as additives has been reported to improve the service life of pavements, require less maintenance, and drive comfort [4].

According to BRTA Annual Report 2022-2023 [44], the total number of registered vehicles since 1987 is 1,75,000. As on 30th June 2023, the total number of registered vehicles has increased to 57,59,353. The BRTA has approved 4,69,167 registered vehicles during the year 2022-2023. Therefore, disposal of waste tires is increased due to increased vehicles and mobility of people in Bangladesh. The total yearly generation of scrap tires is around 90,000 tons in 2008 [5] and 150,000 tons in 2016 [6].

50,400 tons of discarded tires are recycled annually at Bangladesh's 35 tire recycling facilities, which primarily employ pyrolysis technology. The tires are broken down into their four main components using pyrolysis: (i) oil (a diesel fuel and furnace oil substitute), (ii) carbon black, (iii) steel, and (iv) gas. As fuel and industrial materials are becoming more affordable and tire recycling helps to minimize pollution, industries are becoming more interested in using pyrolysis oil and other by-products of recycling facilities [6]. In addition to the pyrolysis process, discarded tires are used on a modest scale for tire retreading and for the production of products obtained from tires. After recycling and reusing of the waste tires though said purposes, large number of discarded tires are remained unused every year which are thrown in the landfill.

The recycled rubber from used car and truck tires is referred to as crumb rubber. Tires that are no longer fit for use on automobiles because of wear or irreversible damage can be recycled to gather waste crumb rubber. These waste tires are harmful to the environment as they are not biodegradable, large space is required for landfilling, difficult to extinguish in the event of fire, accumulate harmful gases and leachate. Leachate contains harmful and carcinogenic substances which contaminates the soil, groundwaters, and farmland. On the other hand, the rain water trapped in waste tire helps to propagate pests, specially mosquitoes. These mosquitos transmit diseases such as malaria, yellow fever, chikungunya and dengue fever.

Recycling efforts are encouraged and landfill waste is decreased by using used tires to make asphalt. Therefore, the incorporation of recycled waste rubber into bituminous mixtures presents an environmentally sustainable solution for managing scrap tires, which pose significant challenges in terms of reduction of waste and environmental pollution [7]. Conversely, by lowering the demand for new materials and increasing road resilience, crumb rubber asphalt helps to reduce carbon emissions throughout the course of the road's lifecycle. Using CRMB can assist reduce the carbon footprint of asphalt production in terms of sustainable development because using recycled rubber requires less energy and emits fewer emissions than standard manufacturing methods. A product's carbon footprint is a combination of the embodied carbon emissions associated with manufacturing, installing, and maintaining the product over its full life cycle and the operational emissions during use of the product [8].

The rising loading requirements for asphalt pavements are driving a steady increase in the use of polymer-modified asphalt. The addition of polymers has been found to noticeable change the rheological properties at high temperatures or low rates of loading. The civil engineers and polymer scientists have tried numerous times to enhance the performance of asphalt pavements by altering the characteristics of asphalt binders in order to reduce certain pavement failures. By changing the failure properties, a polymer modifier causes the binder to produce greater stresses and strains prior to failure [9].

Hence, in this investigation, it has been tried to compare the various modified binder properties & their performance in the bituminous mixes through laboratory evaluation.

1.2 BACKGROUND OF THE STUDY

Bangladesh is a rain prone country, from March to September in a year, people are suspectable to flooding. This flooding has adverse effect on pavement. In case of neat bitumen stripping may occur and damage the road pavement.

Bitumen is a vital component in road construction and maintenance, plays a significant role in providing durability and strength to asphalt pavements. However, conventional bitumen often exhibits limitations in terms of its properties, such as permanent deformation, temperature susceptibility, aging, cracking and water sensitivity. Most flexible pavements break down too soon as a result of high temperatures and heavy loads [2]. Because of moisture induced damage, high temperature and heavy traffic, conventional bitumen based bituminous surface of the flexible pavement often deteriorates at early stage of its life time. To overcome these challenges, modification of conventional bitumen is necessary. Use of modified bitumen enhances the performance characteristics of bitumen by improving its elasticity, rut resistance, water sensitivity and aging resistance.

Rapid urbanization and population growth in Bangladesh have led to a significant increase in use of motor vehicles. Being used, tires of these vehicles become waste which causing adverse effects on human health and the environment due to the lack of recycling program. Crumb rubber is a material found from waste tires and can be effectively recycled for use in binder modification. The use of waste tires in road construction provides economic and ecological sustainability [10].

However, the asphalt industry has a long history of modifying asphalt binders by adding a polymer to enhance their rheological and physical characteristics. A swallowed polymer network is created when the polymer and asphalt binder are appropriately combined, and this network helps to alter the viscoelastic behaviour [9]. The required viscoelastic equilibrium is frequently absent from neat asphalt binders. It is suggested that using polymeric additives to add molecular complexity to asphalt will help attain this equilibrium. Polymer modification is both practical and economically reasonable, according to a life cycle cost analysis of several changed combinations [11].

The purpose of this study is to find the best modified binder with adequate stability and durability to support the expected traffic loads and to withstand the negative effects of air, water, and temperature changes while building roads. It also aims to reduce waste from the landfill where waste tires are disposed of after being discarded from motor vehicles.

1.3 PROBLEM IDENTIFICATION

Premature failure and deterioration of flexible pavement due to temperature fluctuations, moisture induction and heavy traffic loads are common issues in Bangladesh. Fatigue and rutting failure of pavement are often caused by poor bonding of bitumen to aggregate. A few instances illustrating pavement failures are depicted in Fig. 1.1.

Conventional bitumen has the lack of necessary properties to withstand these challenges, lead to frequent road repairs and increased maintenance costs. While penetration grade bitumen is commonly used in road construction, it has certain limitations and performance drawbacks. Understanding these limitations is crucial for developing more effective and sustainable road materials. Investigating the performance of neat 60/70 bitumen, such as its susceptibility to cracking, rutting, and temperature sensitivity, is an important aspect to address.

Besides, Due to increased human mobility, waste tire rubbers have been disposed of in landfills more frequently in recent years. People's mobility grew as a result of population growth. As a result, contamination in the environment has increased [12].



Rutting at Jessore-Jhenaidah Road



Rutting at Dhaka-Chittagong Road



Potholes at Dhaka-Sylhet Road



Fatigue Crack at Dhaka-Sylhet Road

Fig. 1.1 Various Flexible Pavement Failures in Bangladesh

As the rubbers are non-biodegradable, it pollutes lands. Burning of waste crumb rubber causes air pollution. Disposed tires contribute to waterlogging issues. It becomes breeding grounds for mosquitos in wet season and increases insect infestation during dry season. Diseases like dengue fever, chikungunya, yellow fever, and malaria are spread by these mosquitoes. The deposition of waste tires in Bangladesh are shown in Fig. 1.2 & Fig. 1.3. SBS Polymer and waste crumb rubber must be added to conventional penetration grade bitumen to improve the binder's ability to withstand fatigue, thermal cracking, pavement deformation, and moisture-induced damage. In order to minimize environmental risks, discarded crumb rubber must be used to create crumb rubber modified bitumen.

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Fig. 1.2 Waste Tire Deposited in Signboard, Siddhirganj, Dhaka



Fig. 1.3 Discarded Tire Disposed in a Landfill in Kadamtali, Chittagong

1.4 OBJECTIVES OF THE PRESENT INVESTIGATION

The objective of this study is to determine an appropriate modified binder for flexible pavement construction in terms of sustainability, performance, and durability. This investigation will be on the basis of laboratory test evaluation.

Based on the discussion above, the following objectives are as follows:

- To evaluate the properties of neat & modified binders (by SBS polymer and waste crumb rubber).
- To determine the optimum binder content based on Marshall properties.
- Water sensitivity analysis of neat and modified bituminous mixes to identify the best suitable binder.
- To compare the cost of bituminous mixes using various binders in pavement construction.

1.5 SCOPE OF THE RESEARCH

First, a survey of the literature and the basis in methodology have been done in order to reach the objectives set for this investigation. This study investigates the suitability of modified binders on the performance of flexible pavements under varying climatic conditions.

For this investigation, various types of materials have been collected from a number of reliable sources. The coarse aggregate and fine aggregate have been collected from materials laboratory of CUET where the source of coarse aggregate is Dubai, UAE and the source of fine aggregate is Sylhet, Bangladesh. The stone dust as filler material has been collected from the stone crusher of a project maned "SASEC, Dhaka-Sylhet Corridor Road Investment Project". Neat 60/70 penetration graded bitumen is collected from Eastern Refinery located in

North Patenga, Chittagong. The waste crumb rubber is collected from the tire retreading shops, Kadamtali, Chittagong where the waste tires are used. The polymer modified bitumen (SBS PMB PG 70-40) is collected from the materials laboratory of a bituminous surface treatment project named "Performance Based Operation and Maintenance of 4-Lane Dhaka-Chittagong National Highway (N1), Cumilla Part, Daudkandi to Dhumghat Bridge (Ch. 39+267 Km to 165+183 Km)". In order to prepare crumb rubber modified bitumen (CRMB), 7% by weight of passing sieve no. 50 (0.3 mm) crumb rubber has been blended with 60/70 penetration graded bitumen in the transportation laboratory, CUET. Various laboratory analyses have been carried out in the transportation laboratory, CUET, following the collection of aggregates, filler, 60/70 bitumen, and PMB, as well as the preparation of CRMB. The mechanical properties of various binders and aggregates have been evaluated in the laboratory. The Marshall mix design according to Marshall criteria specified by Asphalt Institute [31], for various bituminous mixes have been conducted to determine the optimum bitumen content (OBC) of respective binders. The performance of the bituminous mixes using various binder at OBC have been conducted in the laboratory through retained Marshall stability (RMS) and tensile strength ratio (TSR). TSR's have been determined through indirect tensile strength (IDT) of both the sample without freeze – thaw condition and with freeze – thaw condition.

Eventually, the cost associated with production, laying and compaction of asphalt for various bituminous mixes have been compared in order to establish a cost benefit analysis. Based on the above results, a comparison between neat 60/70 bitumen, polymer modified bitumen (PMB) and crumb rubber modified bitumen (CRMB) is conducted.

1.6 ORGANIZATION OF THE THESIS

There are six chapters in all that describe the research activities. The following are the contents of the chapters:

- Chapter 1 contains the study on importance of asphalt binders in flexible pavement construction in Bangladesh. The problem statement is given here. This chapter addressed the goals and scope of this study.
- In Chapter 2 the types of pavements, layers of flexible pavement, types of pavement distress, binders of flexible pavement, method of mix design are reviewed.
- The research methodology is discussed in Chapter 3.
- Physical properties of aggregate and bitumen, optimum bitumen content, Marshall properties, water sensitivity analysis to evaluate bitumen performance, Investigation result and discussion are representing in Chapter 4.
- Chapter 5 contains a cost comparison of bituminous mixes using various binders.
- Finally, Chapter 6 summarizes the findings, limitations, and suggestions of this study.

Chapter 2: LITERATURE REVIEW

This chapter begins with a general (section 2.1) discussion about the chapter, details about pavement (section 2.2) and type of pavements (section 2.3). This chapter also describes common flexible pavement distresses (section 2.4), distress modes (section 2.5) of the pavement, pavement surface coarse bituminous material (section 2.6) consisting of neat 60/70 bitumen, PMB & CRMB, preparation of CRMB (section 2.7), preparation of PMB (section 2.8), asphalt mix design methods (section 2.9), Marshall mix design (section 2.10), water sensitivity analyses of bituminous mixes (section 2.11). Section 2.12 represents previous investigations on various bituminous binders. The conceptual foundation for the study is developed in Section 2.13, which also underlines the implications from the literature.

2.1 GENERAL

This chapter comprehensively examines previous research relevant to the characterization and analysis of crumb rubber modified bitumen (CRMB) and polymer modified bitumen (PMB) in pavement engineering. It begins by explaining the basic characteristics of bitumen, highlighting its vital role in the construction of pavements as well as the inherent difficulties it faces with regard to durability and environmental impact. The chapter then explores the steps of a novel technique of crumb rubber modification and talking about how effective both the modified bitumen are improving bituminous mixture performance. Utilizing knowledge from previous research, it assesses the critical factors that go into defining CRMB and PMB, such as aging patterns, resistance to rutting & cracking and rheological characteristics. In addition, the review includes comparisons between CRMB, PMB and neat bitumen,

emphasizing the latter's better performance and long-term advantages. Material sources, availability and economic issues are also investigated to provide a comprehensive picture of PMB and CRMB utilization.

2.2 PAVEMENTS

Pavement refers to a hard surface constructed with resilient materials, designed to support the movement of vehicles or pedestrians. The primary purpose of the system is to disperse the vehicle loads that are applied to the subgrade over many strata. The road surface should offer adequate traction, optimal smoothness, desirable light-reflecting properties, and minimal noise emissions. The objective is to decrease the load transferred by the vehicle to ensure it does not exceed the subgrade's bearing capability. Road pavements are essential part of the progress of any building project.

2.3 TYPES OF PAVEMENTS

The two primary forms of pavement that are commonly used. These are rigid and flexible pavements. Rigid pavements, which have a high structural strength and long lifespan, are often made of concrete. However, they can break and crumble in regions with wide soils or abrupt temperature swings, which are frequent in Bangladesh's tropical climate. Conversely, multiple layers of bitumen and aggregate make up flexible pavements. They are better suited to the country's climate since they are more resilient and adaptive. Building and maintaining flexible pavements can also be done at a lower cost.

2.3.1 Flexible Pavement

Flexible pavements are utilized in highway construction because they can disperse loads and withstand various pressures. Flexible pavements have

numerous layers of materials. Each layer distributes and transfers loads from the layer above to the layer below. The flexible pavement consists of surface course and binder course as bituminous road layers. The underlying layers of bituminous courses consist of the base course, sub-base course, compacted subgrade, and natural subgrade. The layers of flexible pavement are shown in Fig. 2.1.

The base course is made up of bigger pieces of gravel. The main course helps to get stronger and spread weight out. There is less chance for water to leak into the thicker layers, which could weaken the pavement's structure. The subbase is further down and is made up of rougher materials than the base course. It is thicker. The subbase is the layer between the pavement and the subgrade, or soil below. It spreads the weight of the pavement over a wider area. It makes the structure of the pavement more stable and stops the dirt below from expanding.

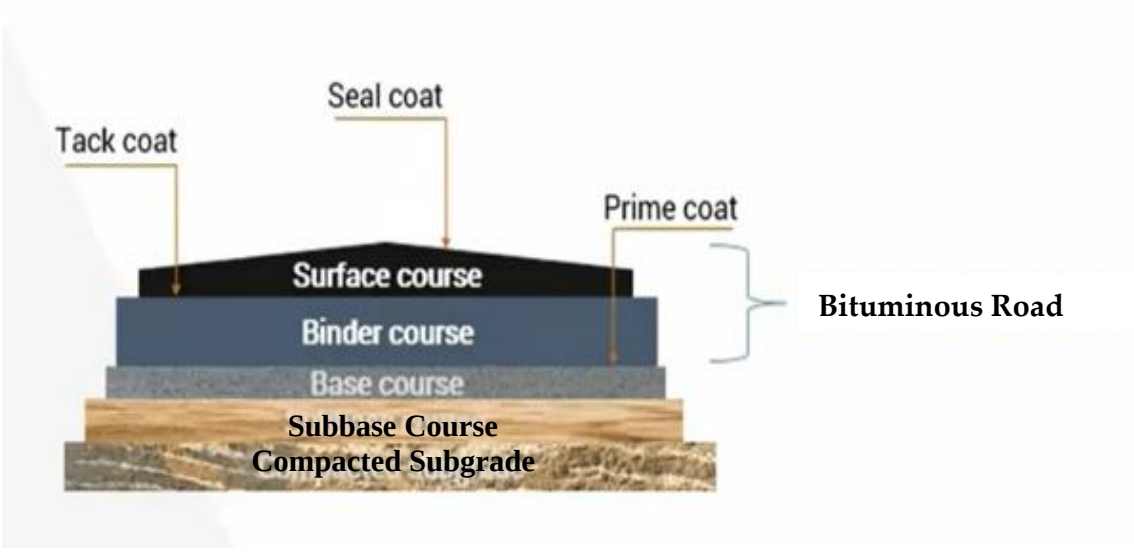


Fig. 2.1 Layers of Flexible Pavement (www.dreamcivil.com)

Over time, the surface course can get worse because of changes in traffic, leading to cracks, ruts, and other types of damage. Flexible pavements need to

be maintained often and resurfaced to keep them in good shape. When building roads, flexible pavements are the best choice because they are long-lasting, flexible, and cheap. They can handle a wide range of traffic and environmental conditions.

2.3.1.1 Seal Coat

Seal coat is applied to a worn bituminous pavement to restore its condition. The best method for applying a single layer of surface dressing on specific bituminous pavements that are not waterproof. Examples of open graded bituminous construction include: i) premixed carpet and ii) grouted macadam.

A protective layer is put on the surface of flexible pavement. It is occasionally called surface treatment or chip seal. The pavement surface is coated with a thin layer of asphalt emulsion, which serves as the seal coat. The purpose of employing a seal coat is to prevent the infiltration of water, as it has the potential to cause harm. Furthermore, it provides protection against oxidation, aging, and the adverse impacts of traffic such as abrasion and wear, which can cause the pavement surface to become slippery over time.

2.3.1.2 Surface Course

The layer that directly bears the weight of traffic is referred to as the surface course. Usually, dense graded asphalt concrete (AC) is used in their construction. It provides adequate drainage, a smooth surface, and optimal friction. Moreover, it will hinder the infiltration of excessive surface water into the base, sub-base, and subgrade of the substructure. It must possess strength to ensure a durable and non-slippery riding surface that can withstand traffic

without deformation. To prevent water from compromising the structural integrity of the foundation and subgrade, the material must be water-resistant.

2.3.1.3 Binder Course

This layer provides the majority of the asphalt concrete structure. Its main goal is to evenly distribute the load across the base course. By replacing a section of the surface course with the binder course, which generally consists of aggregates with less asphalt and lower quality standards, a more cost-effective design is accomplished.

2.3.1.4 Tack Coat

A tack coat is a layer of bituminous material applied over an existing pavement surface. This layer might be partially impervious, like cement concrete, or pervious, like WBM that has been treated by a prime coat. Tack coat is a thin coating of bituminous liquid asphalt, emulsion, or cutback that is put between layers of HMA pavement to enhance bonding. Ensuring proper adhesion between construction lifts, particularly between the current road surface and an overlay, is crucial for the pavement structure to function as a cohesive unit and offer sufficient strength. If adjacent layers fail to adhere to one other, they basically act as separate thin layers, none of which are intended to withstand the bending pressures caused by predicted traffic. Insufficient adhesion between layers can lead to the separation of layers, known as breakdown or debonding. This can subsequently cause longitudinal wheel path cracking, fatigue cracking, potholes, and other forms of damage, such as rutting, which significantly decrease the lifespan of the pavement.

2.3.1.5 Prime Coat

A prime coat refers to the initial application of a thin, low-viscosity liquid bituminous substance over a porous or absorbent pavement surface, such as the WBM base course.

2.3.1.6 Base Course

This layer constitutes the primary component of asphalt concrete construction. Its fundamental purpose is to evenly distribute load across the base course. A cheaper design is achieved by substituting part of the surface course with the binder course, which contains aggregates with less asphalt and lower quality.

2.3.1.7 Sub-Base Course

The sub-base course, located beneath the base course, has three primary purposes: enhancing drainage, offering structural reinforcement, and minimizing the infiltration of subgrade particles into the pavement structure.

2.3.1.8 Subgrade

The topsoil, or subgrade, is a natural soil layer hardened to withstand forces from above. Always avoid soil subgrade overextension. It needs the right wetness and density.

2.3.2 Rigid Pavement

Rigid pavements, also called concrete pavements, are road constructions that utilize a substantial layer of concrete as the primary load-bearing surface. Rigid pavements depend on the inherent strength and rigidity of the concrete to

bear the weight of traffic. Rigid pavements are constructed by employing a meticulously calculated blend of cement, aggregates and water to ensure structural soundness and minimize the possibility of cracking or faulting.

Rigid pavement has a substantial load-bearing capacity and exhibit exceptional resilience to environmental factors such as temperature variation, moisture, and chemical degradation. The stiffness of the concrete slab, a key advantage of rigid pavements, facilitates the uniform distribution of loads across a wide surface area. Moreover, it acts as a barrier against water and pollutants, effectively protecting the upper layers of the pavement and increasing its durability. Rigid pavements are particularly well-suited for high-traffic roadways, motorways, and airports that experience significant weights and frequent traffic movements. Repairing and replacing stiff pavement is a laborious and costly process. Construction activities cause traffic delays when concrete slabs are replaced over time, completely obstructing the flow of vehicles.

The rigid pavement consists of cement concrete slab as top layer of road on which vehicle moves. The underlying layers of concrete slab consist of the base course, sub-base course and natural subgrade. The layers of flexible pavement are shown in Fig. 2.2.

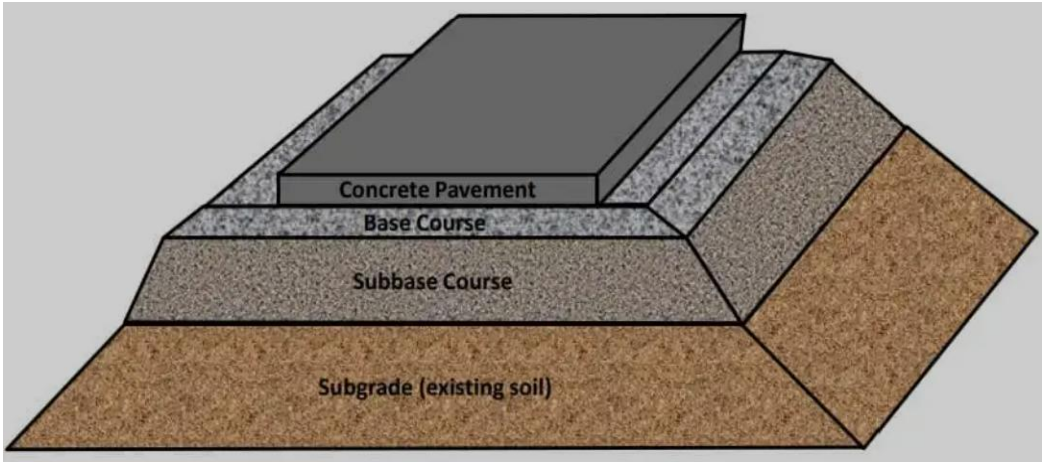


Fig. 2.2 Layers of Rigid Pavement (www.theconstructor.org)

2.3.2.1 Cement Concrete Slab

A concrete slab that directly supports vehicle loads makes up the surface course, the topmost layer of rigid pavement. The sub-grade or sub-base is covered with a concrete mix made of aggregate, sand, cement, and water in the proper proportions. It prevents water from penetrating the layers underneath. Vehicles are prevented from skidding by the concrete slab's friction.

2.3.2.2 Base Course

The base course is the second layer of pavement from the top, also called the granular base or stabilized base, is constructed using crushed aggregates. This layer gives the stiff pavement a strong base and permits more load distribution on the surface course. It is advantageous to install a subsurface drainage system, particularly in regions that are susceptible to frost, the stabilized base course reduces subgrade soil swelling and helps regulate frost activity.

2.3.2.3 Sub-Base Course

The third layer that comes into contact with the base course and subgrade soil is known as the granular subbase or stabilized subbase course. They are of higher quality than the subgrade soil, but its material quality is lower than that of the base coarse aggregates. Supporting the higher layers, regulating frost action, and preventing particles from the subgrade soil from penetrating the surface layers are its main purposes. The subbase course also enhances drainage capacities.

2.3.2.4 Subgrade

The current soil layer is formed by the subgrade soil, which is then compacted by machines to create a solid base for the rigid pavement. Because

stresses diminish with depth, subgrade soils are less stressed than the top layers. Texture, density, moisture content, and strength are some of the variables that affect how subgrade soils react to stresses from the top layers. In order to minimize the displacement of subgrade soil layers and lessen the strain on the subgrade soil, the layers above the subgrade should be built accordingly. Since approximately 90% paved road in Bangladesh are bituminous flexible pavement, in this study the details of flexible pavement are required to be analyzed.

2.4 COMMON FLEXIBLE PAVEMENT DISTRESSES

Pavement distresses fall into three categories: degradation, cracking, and deformations. The pavement's performance and potential lifespan can be determined by each of these distresses. Pavement cracks have the following negative effects: pumping and loss of fines from the base course; loss of load spreading ability of the cracked material; loss of water proofing of the pavement layers; loss of riding quality due to surfacing loss; and loss of appearance. The pavement condition typically deteriorates more quickly when spreading ability and water proofing are lost. A sustainable flexible pavement construction addresses the potential mitigation of pavement deterioration brought on by water intrusion, severe vehicle stress, seasonal temperature variations, and expansion and contraction. The primary cause of cracking and deformations that result in pavement deterioration is a decline in the bituminous surface's quality [13]. Types of pavement deterioration are as follows:

2.4.1 Potholes

One of the most well-known forms of asphalt damage, potholes are seen in Fig. 2.3 and arise when the area beneath the asphalt's surface has been

weakened, left unfixed, and eventually failed. This ultimately results in a pothole, which is a depression in the pavement. Potholes are hazardous and have the potential to cause both car damage and injuries.



Fig. 2.3 Schematic Diagram of Pothole (www.truegridpaver.com)

2.4.2 Fatigue Cracks

fatigue fractures brought on by the asphalt concrete surface's fatigue failure from repeated traffic loads. As seen in Fig. 2.4, the cracking starts near the bottom of the asphalt surface, where tensile stress and strain are greatest under wheel weight. These fissures frequently resemble broken glass or a spiderweb in their layout. They may result from a subsurface that was installed incorrectly or from water damage. Inappropriate weight distribution across the asphalt surface causes cracking as a result of traffic and heavy loads that are applied repeatedly.



Fig. 2.4 Schematic Diagram of Fatigue Crack (www.truegridpaver.com)

2.4.3 Blowouts

A blowout is just a huge pothole. A blowout, which is similar to a shallow sinkhole and frequently stretches several feet across and lengthwise, is much larger than a pothole. Similar to potholes, they are caused by a failed base beneath the paved area's surface.

2.4.4 Reflection Cracks

A reflection crack in flexible pavements occurs when an existing crack or joint in an underlying layer (like an old asphalt) propagates through to a new overlay placed above it. This type of cracking is caused by the movement of the underlying layers due to temperature changes, traffic loads, or moisture variations.

2.4.5 Block Cracks

It manifests as haphazardly spaced linear cracks, frequently spaced a few feet apart. They appear when there is little traffic on an asphalt lot, and as the

asphalt ages, the surface shrinks horizontally. They will result in water penetration and other asphalt problems if not filled which is shown in Fig. 2.5.



Fig. 2.5 Schematic Diagram of Block Crack (www.truegridpaver.com)

2.4.6 Rutting

Ruts are caused by vehicle traffic which is shown in Fig. 2.6. Usually, the same size and shape as vehicle tracks, they show up as depressions in the direction and form of frequently driven places. They appear when the asphalt is unable to support the weights being carried on it.



Fig. 2.6 Schematic Diagram of Rutting (www.truegridpaver.com)

2.4.7 Ravelling

As seen in Fig. 2.7, asphalt deterioration happens when the gravel in the asphalt stretches and becomes loose. If the asphalt's surface has oxidized, this will occur gradually. If left untreated, ravelling destroys the asphalt's surface and causes more serious problems.



Fig. 2.7 Schematic Diagram of Ravelling (www.truegridpaver.com)

2.4.8 Shoving

On asphalt, shoving manifests as elevated patches or lumps. It is typically located where large loads of vehicles frequently start and stop, particularly in areas where braking, turning, or accelerating frequently take place, causing excessive asphalt distress in these areas. Shoving is typically a sign of shear failure within the pavement layers, where the mix is unable to resist the applied forces, leading to material movement.

2.4.9 Upheaval

It appears as a raised, often broken-open area of asphalt and is caused by an underlying swelling of the subsurface, which can be caused by frost or expanding soils which is shown in Fig. 2.8.



Fig. 2.8 Schematic Diagram of Upheaval (www.truegridpaver.com)

2.4.10 Peeling

The term peeling over flexible pavement describes the loss of surface material from the top layer of asphalt, which is frequently brought on by the bitumen binder and aggregate not adhering well to one another. It is the gradual breakdown of a flexible pavement's outer layer. It happens as the asphalt's top layer dries up over many years and starts to peel off. Additionally, it is occasionally referred to by phrases like flaking or ravelling.

2.4.11 Linear Cracks

As seen in Fig. 2.9, they are lengthy cracks that mostly appear when water can penetrate the asphalt pavement's surface. They need to be addressed right away because they have a high probability of becoming open holes.

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Fig. 2.9 Schematic Diagram of Linear Crack (www.truegridpaver.com)

2.5 DISTRESS MODES

Distressed pavement is often a result of a combination of factors, rather than just one root cause. The factors affecting pavement distress are reflected as different distress modes. There are five distress modes appear on the pavement. These are:

2.5.1 Permanent Deformation

Permanent deformation is irreversible, meaning that it persists even after the applied pressures are removed. One of the main distresses affecting pavement performance is permanent deformation, commonly referred to as rutting. This pavement distress, which is evident in the surfacing layer of a pavement, is longitudinal deformation, deformation, or depression in the wheel tracks that results from repeated applications of axle loading conditions. It is the outcome of the buildup of load-induced, long-lasting deformation from each layer of pavement, including the subgrade. Under repeated stresses, it is typically ascribed to the plastic flow of the underlying foundation or asphalt

layers. In addition, longitudinal cracking and rutting were caused by the deterioration of asphalt brought on by diesel spills on roadways.

2.5.2 Fatigue Crack

Bituminous pavement can develop a sequence of interconnected cracks called fatigue cracking, sometimes referred to as alligator or crocodile cracking. The fatigue failure of the asphalt concrete surface under repeated traffic loading is what causes fatigue fractures. The bottom of the asphalt surface (or stable base), where tensile stress and strain are greatest under wheel load, is when the cracking starts. At first, the cracks appear as a sequence of parallel cracks that spread to the surface. Repeated traffic loading causes the fissures to join, creating sharply angled, multi-sided fragments. If alligator cracking is not adequately fixed, the damage may spread quickly, threatening your pavement's overall sustainability and aesthetic appeal.

2.5.3 Thermal Crack

The low temperature environment is the main cause of thermal cracking. The fracture that is roughly perpendicular to the pavement's center line is known as thermal cracking in hot mix asphalt (HMA) pavements. As the temperature drops, tensions form in the pavement, causing it to compress. The produced strains are greater than the pavement strength at very low temperatures. The pavement may ravel if water seeps into the fissure. The pavement's rideability is greatly reduced as a result.

2.5.4 Oxidative Aging

Oxidative aging causes chemical changes in asphalt that enhance the binder's viscosity and elasticity, which causes the substance to harden, or stiffen. Throughout the life of asphalt binders, oxidative aging takes place in two primary stages: i) short-term aging, which happens during the production,

transportation, and compaction of asphalt mixtures, and ii) long-term aging, which happens during the asphalt mixtures' service period in a pavement structure. Cracks form under cyclic traffic stresses as a result of the aggregate and asphalt binder losing cohesiveness and adhesion due to the increased stiffness.

2.5.5 Moisture Damage

The loss of strength and durability in asphalt mixtures as a result of moisture's impacts is known as moisture damage. The loss of the link between the fine and coarse aggregate and the asphalt cement might result in moisture damage. Additionally, moisture degradation happens when moisture seeps through and degrades the binder, increasing its susceptibility to moisture during cyclic loading. Stripping, or the vulnerability of asphalt mixtures to moisture, has been identified as the primary performance issue affecting the longevity of asphalt pavements. A very complex form of distress, moisture-induced degradation to asphalt pavement results in the mixture's loss of stiffness and structural strength, which ultimately necessitates expensive pavement structure repair.

2.6 SURFACE COARSE BITUMINOUS MATERIALS

In light of above discussion on various pavement distresses and modes of distress it is apparent that, the bituminous surface is most important part of flexible pavement. As this surface layer directly receives traffic loads and transfers load to the underling layers, it requires sufficient strength and durability to withstand rutting, creaking, aging and moisture damage. Bituminous material plays important role as it binds the aggregates. Therefore, the binding and water proofing properties of bitumen are required to be

studied in this research. Bituminous materials include penetration grade bitumen and modified bitumen which are commonly used in road construction.

2.6.1 Penetration Grade Bitumen

The favourable engineering features of penetration grade bitumen, a binder frequently employed in asphalt mixtures, make it an essential component in pavement construction. Because of its unique rheological and physical characteristics, penetration grade bitumen can be used in a variety of climates and traffic volumes. Because of its relatively high penetration value, it can withstand mild temperatures and still be workable during construction, providing sufficient resistance to deformation under traffic loads. Bangladesh's tropical environment, with its high temperatures and intense monsoon rains, makes 60/70 grade bitumen qualities extremely important rather than 80/100 grade bitumen for pavement performance. Because of its comparatively high penetration value, which guarantees sufficient flexibility at moderate temperatures, asphalt pavements can endure the dynamic loads brought on by a variety of traffic situations. Therefore, in this research, 60/70 grade bitumen has to be used for laboratory investigation.

2.6.2 Modified Bitumen

The addition of specific additives or a combination of additives can improve the properties of bitumen and bituminous blends. These additions, which include plastic and rubber, are referred to as modifiers. The bitumen premixed with such modifiers in order to improve its operational capabilities and long-term durability is known as modified bitumen. Ideally, modified bitumen has a higher adhesion than pure bitumen, a reduced thermal sensitivity in the range of service temperatures, and a viscosity that is adequate at the temperature at which it is being executed. Furthermore, its sensitivity to

the time of loading is low, and its strength to plastic deformation, fatigue, and fractures is strong. Therefore, modified bitumen's are the better choice as asphalt binder.

Some bitumen modifiers have been presented in Table 2.1 with their performance against various distress modes [14] [15] [16].

Table 2.1 Some Bitumen Modifiers used in Paving Applications (Michele et al., 2019; Honarmand et al., 2019; Farhana et al., 2019)

Group	Modifiers	Distress Condition Affected				
		PD	FC	LTC	MD	AG
Fillers	Carbon Black	√				√
	Mineral: Hydrated Lime	√			√	√
	Fly Ash	√				
	Portland Cement	√				
Extenders	Sulfur	√	√	√	√	
Rubbers	Styrene Butadiene Diblock (SB)	√		√	√	
	Styrene Butadiene Triblock (SBS)	√	√	√		
	Styrene Isoprene (SIS)	√				
	Styrene Butadiene Rubber Latex (SBR)	√		√		
	Polychloroprene Latex	√	√	√		
	Crumb Rubber (Reclaimed)	√	√	√	√	√
Plastics	Ethylene Vinyl Acetate (EVA)	√	√			
	Ethylene Propylenediene Monomer (EDPM)	√				
	Polysobutylene	√				
	Polyethelene	√		√		
	Polypropylene	√				
Oxidants	Manganese Compounds	√				
Fibers	Polypropylene	√	√	√		
	Polyester	√		√		
	Reinforcement	√	√	√		
	Natural: Cellulose	√				
	Minerals	√				

Note: PD – Permanent Deformation, FC – Fatigue Cracking, LTC – Low Temperature Cracking, MD – Moisture Damage, AG – Oxidative Aging

2.6.2.1 Common Modified Bitumen

Asphalt performance is enhanced by a variety of chemical and polymer additions. Generally speaking, the most often used kind of asphalt additive is polymer modifier. Elastomers and plasterers are the two types of polymer asphalt modifiers. Waste crumb rubber, styrene-butadiene, and styrene-butadiene-styrene (SBS) block copolymers are elastomers that are frequently used to modify asphalt. Low-density polyethylene and ethylene vinyl acetate (EVA) are often used plasterers as asphalt additives. Well-known modified bitumen comes in four varieties, which are explained below.

2.6.2.1.1 Polymer Modified Bitumen (PMB)

By adding particular polymers to the mix, a class of road bituminous binders known as Polymer Modified Bitumen (PMB) is created and produced with the express purpose of enhancing asphalt longevity and road traffic safety. Polymer modified bitumen is often utilized in the construction of road pavements, particularly those that are designed to handle heavy-duty traffic and severe weather conditions. Polymer modified bitumen, also known as PMB, is a type of bitumen that has been specifically created and constructed to be used in the production of pavement, roads that are meant to handle heavy traffic, and roofing solutions for homes that are designed to survive extreme heat and cold. Such bitumen that enhances the cohesiveness of the mixture, resulting in significantly increased strength and improved resistance to factors such as fatigue and permanent deformations in road pavements. This is achieved by modifying the properties of regular bitumen by including a polymer, which might be either elastomeric or of a different composition altogether.

Bitumen was mixed with various thermoplastic polymers, such as ethylene-vinyl acetate (EVA), ethylene-butyl acrylate (EBA), styrene-butadiene-styrene

(SBS), and styrene ethylene butylene styrene (SEBS), to make polymer-modified bitumen. When bitumen modification is being done, two types of plastic are used: thermosetting polymers and thermoplastic polymers.

2.6.2.1.2 Crumb Rubber Modified Bitumen (CRMB)

In the 1800s, it was common to mix bitumen and rubber, but more as a replacement for rubber than as a way to change asphalt. In the early 1900s, researchers started to think about and then write down the particle structure of bitumen. In the 1940s, patents were issued for bitumen that had been changed by adding polyisobutylene. In the 1950s, more and more neoprene rubber was used to change asphalt in North America. In the 1960s, the concept of bitumen modified with crumb rubber was developed. The first transportation engineer to include crumb rubber into asphalt mixtures to improve road performance was Charles McDonald.

The advantages of bitumen and rubber are combined in crumb rubber modified bitumen (CRMB), a modified bitumen compound that creates a flexible and long-lasting road building medium. It is an environmentally friendly way to recycle used tires and lessen the negative effects of road construction. CRMB is produced by combining crumb rubber modifier with a specific grade of bitumen. The modifier acts as an agent that enhances the binding material's resistance to deformation when exposed to low temperatures & fatigue.

2.6.2.1.3 Natural Rubber Modified Bitumen (NRMB)

It has been demonstrated that using natural rubber as a bio-modifier for bitumen and asphalt mixtures has some advantages. Natural rubber is made up of polymers of the chemical molecule isoprene, water, and trace amounts of other organic compounds.

2.6.2.1.4 Chemical Modified Bitumen

Bitumen is often modified with various chemicals and additives to enhance its properties, making it more suitable for specific applications such as road construction, roofing, or waterproofing. Some of the common chemicals and materials used for bitumen modification include (a) Sulfur: it is sometimes used to cross-link polymer chains in bitumen, creating a network structure that enhances the strength and durability of the material. (b) Anti-Stripping Agents: Chemicals like hydrated limes are used to improve the adhesion between bitumen and aggregates, preventing stripping in the presence of water. (c) Phosphoric Acid: It is used as a binder modifier to enhance the high-temperature performance of bitumen. (d) Amine-based Additives: These are used to improve the adhesion between the bitumen and the aggregates, enhancing moisture resistance.

2.6.2.2 Mostly Used Modified Bitumen

Among the different group of modifiers extender and rubbers are appreciated based on performance against five distress condition. The use of sulfur in asphalt modification is very limited as it is not available abundantly, emits harmful gases to environment, involves careful mixing with asphalt. Among the rubbers, crumb rubber appears to have caught the attention of the researchers more than any other type of rubber because of the beneficial effects of modifying bitumen with crumb rubber (CR). Some of the beneficial effects are noted [17] as follows:

- CR enhances bitumen's rheological and physical characteristics.
- It increases paving mixes' strength and decreases their sensitivity to temperature changes.
- At higher temperatures, fatigue life and resistance to irreversible deformation are enhanced.

- It increases the aggregate and binder's adherence.
- Reflection cracking is lessened.
- The long lifespan, lower maintenance, and usage of less material result in cost savings.
- An 80% reduction in traffic noise.
- Relief from the pollutants that tires that have been scraped or dumped give to the environment.
- A decrease in asphalt oxidation and aging.

SBS (styrene-butadiene-styrene) is also the polymer mostly used to modify asphalt. This polymer modified bitumen (PMB) is widely used worldwide due to its excellent properties such as enhanced performance, durability and longevity of flexible pavement. Following are the beneficial properties of PMB:

- To reduce rutting, make the combination more rigid.
- To reduce cracking, soften and improve the mixture's elasticity.
- Increase the mixture's resistance to exhaustion.
- Enhance asphalt aggregate binding to lessen moisture sensitivity or peeling.
- To lessen ravelling, increase abrasion resistance.
- Increase resistance to oxidation or aging.
- Reduce the pavement layer's structural thickness.
- Lower the HMA pavements' life cycle costs.

Therefore, both the SBS and CR modified bitumen are required to be taken in this study work to compare their properties and performance.

2.7 PREPARATION OF CRUMB RUBBER MODIFIED BITUMEN

Disposal of waste tire are increased due to increased mobility of people. Because tires are non-biodegradable and have a long lifespan, disposing of

waste tires can be difficult. Tire waste is traditionally managed by illegally dumping, landfilling, or storing. Crumb rubber is a term used for recycled rubber from automotive and truck scrap tires [18] as shown in Fig. 2.11.



Fig. 2.10 Dumping of Waste Tires (www.ecomena.org)

2.7.1 Components of Crumb Rubber

Crumb rubber is obtained from the scrapping industry of scrap tires of vehicle and available in tire re-treading shops in Bangladesh. In the re-treading process only tread component of waste tire is generally scraped. Tread is that part of tire which comes in contact to the road and provides sufficient friction with the pavement. Schematic diagram of a tire with different component is shown in Fig. 2.12. Crumb rubber is a mixture of SBR and NR with polybutadiene as elastomer, petroleum oil as processing oil, fatty acid as processing aid, carbon black as filler and sulfur as volcanizing agent [17].

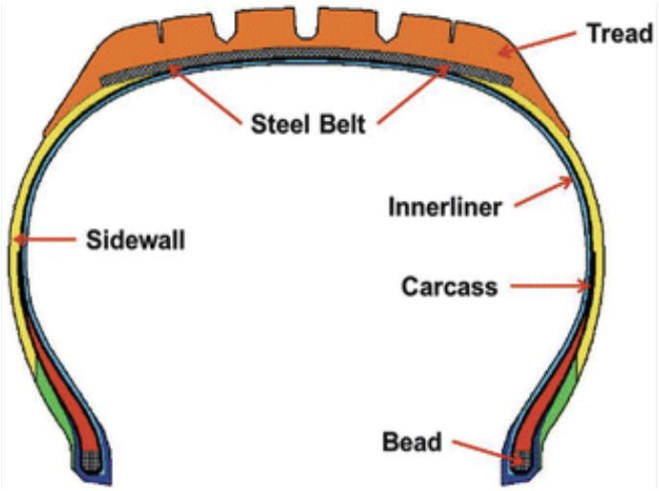


Fig. 2.11 Schematic Diagram of a Tire with Different Components (www.link.springer.com)

2.7.2 Scrap Tire Grinding Process

As illustrated in Fig. 2.13, discarded tires are shred to create crumb rubber, a substance devoid of steel and fiber. The mesh screen or sieve size that crumb rubber passes through during manufacture is typically used to identify it. Reducing the tire powder's size to the necessary extent is crucial for producing high-quality crumb rubber. Cryogenic grinding and ambient mechanical grinding are the two main methods used to create crumb rubber [19].



Fig. 2.12 Schematic Diagram of Crumb Rubber (www.ecomena.org)

2.7.2.1 Ambient Mechanical Grinding

A scrap tire breaks apart during an ambient mechanical grinding process at room temperature or higher. Using complete or pre-treated automobile or truck tires in the form of shreds or chips, ambient grinding is a multi-step process. Rubbers, metals, and textiles are separated out in a systematic manner. Tires are broken up into chips by passing them through a shredder. The chips are put into a granulator, which reduces their size and extracts the fiber and steel. Any leftover steel is eliminated using a combination of wind sifters and shaking screens, as well as magnetic and fiber methods. Additional grinding in high-speed rotary mills and secondary granulators can produce finer rubber particles. Most crumb makers employ ambient grinding as their production method.

2.7.2.2 Cryogenic Grinding

Applying liquid nitrogen to the scrap tire at -80°C solidifies it so that it may be easily ground into powder is known as cryogenic grinding. Although cryogenic grinding produces fine mesh size more quickly and cleanly, the high expense of the method is a drawback because liquid nitrogen is required. Because it involves handling liquid nitrogen, the procedure is also risky. In the industry that produces crumb rubber, ambient grinding is more common.

2.7.3 Blending of Crumb Rubber

The wet process and the dry process are the two ways that CRMB can be produced. In both cases, heated bitumen and crumb rubber are combined in a high-speed mixer. The wet process employs wet crumb rubber, whereas the dry process uses dry crumb rubber ground into a fine powder. The specifications developed by [17] are used for blending crumb rubber with asphalt. In this process, 60/70 penetration grade bitumen is heated to 160°C in the mixing

machine before crumb rubber is added. 7.0% (by weight) of 50 mesh (0.3mm) crumb rubber is mixed at low speed for about 5 min [20]. The mixture was heated to 170°C to 180°C and agitated vigorously for about 60 minutes using a mechanical stirrer operated at 1400 rpm. After 60 minutes, the developed modified bitumen is removed from the mixing machine and kept in a sealed container after cooling to room temperature.

2.7.4 Interactions between Crumb Rubber and Bitumen

The chemical interactions between crumb rubber and bitumen significantly contribute to the enhanced performance of Crumb Rubber Modified Bitumen (CRMB). These chemical reactions primarily involve the devulcanization and depolymerization of the rubber and interaction with the aromatic components in bitumen. The key mechanisms are as following:

- **Devulcanization and Depolymerization:** Crumb rubber contains vulcanized rubber with sulfur cross-links. At elevated temperatures (160 - 180°C), thermal and thermo-oxidative reactions cause partial devulcanization, breaking the sulfur cross-links and producing smaller, reactive rubber molecules. Depolymerization also breaks down rubber chains into oligomers, which can diffuse into the bitumen matrix [21].
- **Swelling and Absorption:** Bitumen contains aromatic oils, which are absorbed by crumb rubber particles, causing them to swell. This physical change is often accompanied by chemical absorption, leading to changes in the microstructure and mechanical interlock within the bitumen [22].
- **Chemical Interaction with Bitumen Components:** Reactive groups from rubber (like unsaturated C=C bonds and sulfur-containing fragments) interact with polar asphaltenes and resins in bitumen, improving compatibility and stability. Oxidative coupling reactions between rubber

and bitumen functional groups can form chemical bridges, increasing elasticity [23].

The improvement in the properties of CRMB is due to both physical and chemical interactions, with chemical reactions such as devulcanization, depolymerization, and functional group interaction playing a key role. These reactions enhance the compatibility and durability of the binder.

2.8 PREPARATION OF POLYMER MODIFIED BITUMEN

Styrene-Butadiene-Styrene (SBS) is a type of thermoplastic elastomer that, at room temperature, is just as elastic as rubber. At high temperatures, it may melt and flow like plastics, also known as plastic material. As a result, the SBS modified asphalt is described as having a high degree of flexibility and age resistance, without becoming brittle or viscous when heated. The most popular and successfully applied modified asphalt at the moment is SBS. SBS is typically applied to asphalt in amounts ranging from 5% to 10% [24] [25].

2.8.1 Components of Styrene-Butadiene-Styrene (SBS)

SBS (Styrene-Butadiene-Styrene) is a thermoplastic elastomer commonly used as a polymer modifier in bitumen to improve the performance of asphalt pavements. SBS consists of a polybutadiene segment in the middle with polystyrene blocks at the ends, which contains the C=C bonds in the unsaturated carbon chains and benzene rings respectively as shown in Fig. 2.14 [25]. SBS is a thermoplastic elastomer produced by solution-living polymerization using styrene and butadiene as main components and an anionic initiator.

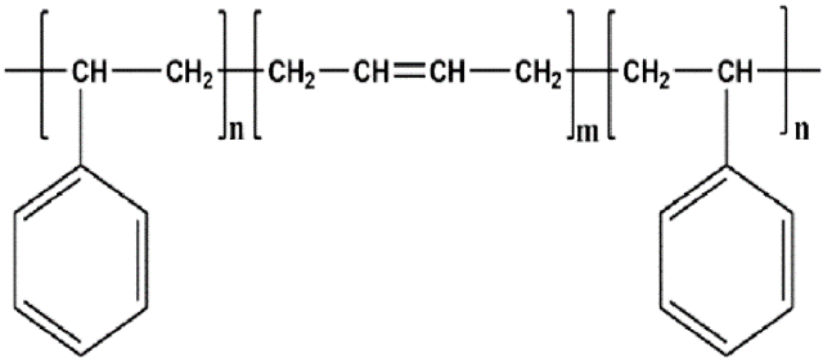


Fig. 2.13 Chemical Structure of Linear SBS Polymer (www.segroup.cn)

2.8.2 Blending of Styrene-Butadiene-Styrene

Blending bitumen 60/70 with a particular grade of SBS (styrene-butadiene-styrene) under extremely specific pressure and temperature conditions is known as polymer modified bitumen. In order to create a homogenous mixture of bitumen and block copolymer, it involves adding a block copolymer composition to the bitumen component while stirring it at 2000 ± 10 rpm. The temperature is kept between 180°C and 190°C for two hours, creating a cured polymer modified bitumen binder composition [26].

2.8.3 Interactions between SBS and Bitumen

Styrene-Butadiene-Styrene (SBS) improves bitumen properties primarily through physical interaction, but some chemical interactions may also occur, contributing to enhanced performance. The key mechanisms are as following:

- **Physical Network Formation:** It is a primary mechanism where SBS is a thermoplastic elastomer, composed of two polystyrene blocks (S) and one butadiene block (B) and when mixed with bitumen, polystyrene domains form rigid microphases, polybutadiene chains form a flexible matrix. This creates a three-dimensional network that enhances elasticity and high-temperature performance [27]. Lu and Isacsson demonstrated that SBS-modified bitumen shows improved elasticity, softening point, and temperature susceptibility due to this network.

- **Chemical Reactions:** Some studies indicate minor chemical reactions take place between SBS and bitumen components, especially during high-temperature mixing and aging. Butadiene units in SBS may react with asphaltenes and maltenes in bitumen via oxidative crosslinking and sulfur bridging. This leads to improved thermal stability and storage stability by reducing phase separation [28].
- **Role of Sulfur in Crosslinking:** When sulfur is added during modification, it chemically crosslinks the polybutadiene chains in SBS. This crosslinking Increases storage stability, prevents polymer segregation during storage, enhances mechanical properties at high temperatures [23]. Airey reported improved performance due to both physical swelling and chemical crosslinking with sulfur.

While the dominant improvement in SBS-modified bitumen arises from physical interactions, there is evidence of chemical reactions, particularly in the presence of sulfur or under oxidative conditions, that contribute to the improved rheological and thermal properties.

2.9 ASPHALT MIX DESIGN METHODS

The goal of bituminous mix design is to keep the stresses that traffic causes to the pavement to a safe level where road surface deformation is negligible while also making sure that the road surface doesn't deteriorate significantly over a certain amount of time. Since it is difficult to create a bituminous mix that does not deteriorate with time and with traffic due to the nature of the ingredients used, the goal of mix design is to minimize pavement distress, which is gauged by riding quality, rut depth, and cracking. The bituminous surfacing layer is the most important layer of the pavement, and it requires the best material. Where thick bituminous surfacing is required, they are normally constructed with a wearing course laid on a base course (also

called a binder course) which can be made to slightly less stringent specifications. To perform satisfactorily as road surfacing, bitumen aggregate mixes need to possess the following characteristics [29]:

- Excellent deformation resistance.
- They must be flexible in order to endure severe strains and have a high resistance to fatigue.
- Enough rigidity to lessen the forces transferred to the pavement layers underneath.
- Good durability, or high resistance to environmental deterioration.
- Low permeability to stop air and water intrusion.
- Good workability, which makes it possible to achieve sufficient compaction when building.

Considering sustainable development of bituminous surfaced road, recycled crumb rubber from scrap tires can be used in modification of asphalt mixes. Tires contain up to 54% natural and synthetic rubber. Therefore, following the removal of steel reinforcement and recycling, they may constitute a considerable supply of rubber [30]. In addition, polymer modification of asphalt mixtures reduces the quantity of conventional asphalt binder requirement. Therefore, modified asphalt binders can be a good choice in bituminous pavement construction in terms of durability and sustainability.

This study aimed at using waste crumb rubber and polymer separately as partial replacement of bitumen binder to have modified asphalt binders i.e., Crumb Rubber Modified Bitumen (CRMB) and Polymer Modified Bitumen (PMB) for the preparation of asphalt specimen using these modified binders. Different properties of modified asphalt pavement will be tested and compared with reference specimen which will be made by unmodified bitumen. Then the suitability of modified binders for sustainable flexible pavement will be determined properly.

When it comes to black top surfaces, bituminous concrete is the best construction material. The bituminous mixes are appropriately built to meet the stability and durability design requirements despite their high cost. Coarse and fine aggregates are densely graded in the mixture, together with mineral filler that has been bitumen-bound. In a hot mix factory, the mixture is made. Traffic and quality have an impact on the bituminous concrete layer's thickness. Bituminous mix design involves carefully determining the appropriate amounts of different aggregate sizes and bitumen composition. There are five popular methods of mix design. These are Marshall method, Hubbard-Field method, Hveem method, Smith tri-axial method and Superpave method. Out of these methods, Marshall Method is widely used in the world.

2.9.1 Marshall Method

In 1939, Bruce Marshall of the Mississippi Highway Department created the Marshall Mix Design process. As per ASTM D6926, this procedure involves using the Marshall method to prepare and compact cylindrical bituminous pavement mixture specimens that are 102 mm (4 in.) in diameter and nominally 64 mm (2.5 in.) high. This procedure is designed to compact asphalt pavement samples and work with bituminous mixtures made in laboratories and plants that contain aggregates up to 25 mm (1 in.) in size.

The Marshall Mix Design method's primary concept is choosing an asphalt binder content with an appropriate density that meets minimal stability and flow value range requirements. A stability-flow test of the compacted test specimens and a density-voids study are the two main components of the Marshall method of mix design. The density-voids analysis includes determination of bulk specific gravity, % air voids, VMA and VFA. Marshall did not include the VMA, but he did include the Hubbard-Field air void calculation. Rather, he employed asphalt-filled voids as a criterion. Norman

McLeod promoted the use of VMA in the mix design approach in the 1950s. He presumably thought VMA should apply to the Marshall approach as he was aware of it in the Hubbard-Field method.

The maximum load resistance in Newtons that the standard test specimen will acquire at 60°C is the test specimen's stability. Test procedures ASTM D6927/AASHTO T 245 outline stability and flow testing. Before being put in a head, the compacted asphalt specimen is conditioned in a water bath. During the test, the specimen assembly and breaking head are placed within a Marshall stability tester that is equipped with parts to gauge flow and stability. The performance of the trial mixtures is predicted by this test. When loaded at a rate of 2 inches (50.8 mm) per minute, stability is the mix's maximum strength. The Marshall Method is used in pavement design to determine the Optimum Binder Content (OBC) in asphalt concrete. According to asphalt institute, Marshall method is not valid for size of maximum aggregate larger than 25mm.

2.9.2 Hubbard Field Method

Together with the newly established Asphalt Association (later the Asphalt Institute), Charles Hubbard and Frederick Field produced the Hubbard Field Method of Design in the middle of the 1920s. The surface combination, the sand asphalt-wearing course, was the initial focus of the Hubbard Field technique. A manual rammer was used to condense the specimens, which had a diameter of two inches. For asphalt concrete, a modified Hubbard-Field variant was created. It used 6-inch diameter specimens that were compacted with two different rammers. The Hubbard Field method built upon Richardson's process. Specimens were made in the laboratory but instead of using a paper stain test, they developed an evaluation method to determine design asphalt content. Bulk specific gravity of the compacted specimens was measured. Maximum

theoretical specific gravity was computed using aggregate bulk specific gravity. Air voids were calculated as were voids in the aggregate skeleton (VMA by today's terminology). Thus, the qualities employed today were comparable to the volumetric analysis. The Hubbard Field method included a stability test in addition to the volumetric analysis, in which the compacted mix is forced through a ring that is marginally smaller than the diameter of the specimen. The Hubbard Field stability was the maximum load maintained prior to the mix beginning to flow through the orifice. In theory, this is the same as Marshall Stability, in which the specimen is put on its side, and the Marshall stability is the highest load. The Hubbard Field method used stability and air voids to determine the amount of asphalt. To help modify the stability of the combination, voids in the aggregate were assessed.

2.9.3 Hveem Method

Francis Hveem designed hot mix asphalt using the same methodology as oil mixes. By 1932, he had created a technique that used surface area to calculate the amount of asphalt. He created a procedure to evaluate asphalt absorption using motor oil and kept adjusting the surface area variables. Surface area factors created by Hveem for the California Department of Highways in the 1940s are used in the Asphalt Institute's MS-2 guidebook for Hveem mix design today.

Hveem got to work creating a stability test. He created the Hveem stabilometer, a pseudo-triaxial test, after realizing the importance of the mix's mechanical strength. A restricted specimen is subjected to a vertical load, and the resulting horizontal pressure is measured. Hveem exploited this characteristic to distinguish between stable and unstable pavements: the horizontal pressure rises as the asphalt content beyond a threshold. He created stability threshold

values based on oil blends and applied them to HMA. According to Hveem's mix design philosophy, there must be enough asphalt binder to ensure aggregate absorption and a minimum film thickness on the aggregates' surface. The aggregates have to have a minimum tensile strength to withstand turning movement (measured by the cohesiometer) and a sliding resistance (measured by the Hveem stabilometer) in order to support load. The amount of asphalt binder and aggregate characteristics affected stability and cohesiveness. Hveem created the moisture vapor sensitivity test and the swell test to gauge the mix's response to water in order to assess durability. Liquid water was used in the swell test, while moisture vapor was employed in the vapor sensitivity test. Following conditioning, the impact on Hveem stability was quantified. Hveem discovered that thicker asphalt coatings were more moisture-resistant. The mix design system developed by Hveem does not include air spaces.

He believed that film thickness and mechanical properties as described by stability were most important.

2.9.4 Smith Tri-axial Method

The Smith triaxial method requires an 8-in specimen to be statically compacted. The compaction procedure for Hveem stability specimens is used as a model. Six roughly equal-thickness layers make up each 8-inch specimen. Hveem's specimen required 150 applications of 500 psi pressure for densification, while the triaxial specimens required 450 applications of 500 psi pressure in total (because to their roughly three times larger mass). All specimens are cooled after molding, removed from the mold, and allowed to cure for 48 hours in a dedicated container. The specimens are put in the triaxial cell and loaded after curing at 25 °C. From the triaxial test, values of friction and cohesion are obtained, both of which contribute to the strength of bituminous concrete under load.

2.9.5 Superpave Method

Superior Performing Asphalt Pavements is referred to as Superpave. The Superpave mix design method was one of the main outcomes of the Strategic Highway Research Program (SHRP). The Hveem and Marshall procedures were intended to be replaced with the Superpave mix design process. In order to enhance materials selection and mixture design, the Strategic Highway Research Program (SHRP) developed:

- A novel mix design approach that takes environmental (climate) conditions and traffic loading into account.
- A novel approach to evaluating asphalt binder.
- Novel approaches to mixture analysis.

Superpave establishes the classification gradations and a common set of sieves to use for the classification. Additionally, the Superpave system specifies the drawing of the Maximum Density Line. From the FHWA 0.45 power chart's origin to its greatest aggregate size, the maximum density line is depicted. Gradations are categorized by Superpave according to their nominal aggregate size, which is "one size larger than the first size to retain more than 10% by weight of aggregate." The definition of the maximum aggregate size is "one sieve size larger than the nominal aggregate size." Additionally, the Superpave system creates a restricted area that a gradation mapped on the FHWA 0.45 chart shouldn't cross.

The area indicated on the maximum density line, usually between the 0.03 mm sieve and the 2.36 mm size, is known as the Restricted Zone. The purpose of the limited zone was to discourage the production of gradations that plot directly on the maximum density line and to restrict the quantity of natural sands that may be utilized in a mix. To get the best mixture qualities, the aggregates and binder for the asphalt mixture must be mixed together after they have been chosen. To find the ideal mixture, a number of experimental blends are

assessed. This is accomplished via the Superpave Gyratory Compactor (SGC).The SGC is a mechanical compaction device comprised of a reaction frame, rotating base, and motor; loading system, loading ram, and pressure gauge; height measuring and recordation system, mould and base plate. The SGC produces 150 mm diameter by 115 mm high cylindrical specimens. Gyratory compaction produces with a kneading motion is used that better replicates what happens beneath the rollers during compaction on the road surface.

2.10 MARSHALL MIX DESIGN

The Marshall mix design approach is straightforward, small, and affordable. It generates densities that are rather nearer to field density. The fundamental idea behind it is to select an asphalt binder content with a suitable density that satisfies the flow values and minimal stability criteria. The ASTM and Asphalt Institute [31] have standardized the test techniques.

2.10.1 Marshall Specification

The Marshall Criteria for bituminous mix samples as per Asphalt Institute [31] is represented in Table 2.2

Table 2.2 Marshall Specification According to Asphalt Institute [31]

Marshall Specification	Light Traffic Surface and Base		Medium Traffic Surface and Base		Heavy Traffic Surface and Base	
	Min	Max	Min	Max	Min	Max
Compaction, No. of blow each end of specimen	35		50		75	
Stability, lb (kN)	750 (3.34)		1200 (5.34)		1800 (8.00)	
Flow, 0.25mm (0.01in)	8	18	8	16	8	14
% Air Voids	3	5	3	5	3	5
% Voids in Mineral Agg, VMA	Referred to Table 2.3					
% Air Void filled with Asphalt, VFA	70	80	65	78	65	75

Table 2.3 Minimum Percent Voids in Mineral Aggregate [31]

Nominal Maximum Aggregate Size (NMAS)		Minimum VMA (%)		
		Design Air Voids (%)		
mm	inch	3.0	4.0	5.0
1.18	No. 16	21.5	22.5	23.5
2.36	No. 8	19.0	20.0	21.0
4.75	No. 4	16.0	17.0	18.0
9.5	3/8	14.0	15.0	16.0
12.5	1/2	13.0	14.0	15.0
19.0	3/4	12.0	13.0	14.0
25.0	1.0	11.0	12.0	13.0
37.5	1.5	10.0	11.0	12.0
50	2.0	9.5	10.5	11.5
63	2.5	9.0	10.0	11.0

2.10.2 Density Void Analysis

Density and voids are used in all mix design techniques to establish fundamental physical properties. Theoretical maximum specific gravity (G_{mm}), Bulk specific gravity (G_{sb}) and are two commonly used metrics of densities. The volumetric characteristics of the samples are then determined using these densities. Percent volume of bitumen (V_b) in mix, Percent air voids (V_a), Percent voids filled with asphalt (VFA) and Percent voids in the Mineral Aggregate (VMA) are the typical measured void expressions. Effective specific gravity of combined aggregate (G_{se}), Absorbed asphalt percent by total weight of aggregate (P_{ba}), Effective asphalt percent by weight of total mixture (P_{be}), Fines to asphalt ratio (F/A) are also the measurement of effective void and absorbed asphalt content. All the parameters are determined by the expressions from eq. (i) to eq. (xii). The respective data of Bulk specific gravity, Percent air voids, Percent voids filled with asphalt and Percent voids in the Mineral Aggregate are plotted in graph against the bitumen content which uses to determine optimum bitumen content [31].

2.10.3 Stability Flow Analysis

When the test specimen is cured at 60°C for 30 minutes, positioned in a suitable test head, and subjected to a continuous strain (50.8 mm/minute), the maximum load needed to cause failure is known as the Marshall stability of the test specimen. A dial gauge is used to gauge the specimen's vertical deformation throughout the stability test. The Marshall flow value is the amount of deformation measured in units of 0.25 mm at the specimen's failure point. To measure flow, a dial gauge is attached to the testing device. The stability and flow value are measured after the load is applied. The actual stability of the specimens is calculated by test stability multiplied with stability factor as described in ASTM D 6927. The respective data of Stability and Flow are plotted in graph against the bitumen content which uses to determine optimum bitumen content [31].

2.10.4 Optimum Bitumen Content

The phrase "Optimal Bitumen Content (OBC)" describes the recommended quantity of bitumen, sometimes referred to as "Asphalt Binder" that should be used in asphalt mixtures to produce the necessary performance characteristics. Designing long-lasting, high-quality asphalt pavements requires knowing the optimum bitumen content. Graphs are plotted using the density-void and stability-flow analyses. The plotted graphs are used to calculate four bitumen content. The formulas for obtaining optimum bitumen content are given below:

According to IS, OBC = Bitumen Content at (Max. Stability + Max. Density + Avg. Air Void) / 3

According to ASTM, OBC = Bitumen Content at (Max. Stability + Max. Density + Avg. Air Void + 80% VFA) / 4

According to Asphalt Institute [31], OBC = Bitumen Content at 4% Air Void.

2.11 WATER SENSITIVITY ANALYSIS OF ASPHALT MIXES

Water sensitivity of asphalt mix refers to the degree to which the mechanical properties of asphalt concrete, such as strength and durability, are affected by water infiltration. This is a key concern in road construction because water can weaken the bond between the bitumen (asphalt binder) and the aggregates in the mix, leading to issues such as stripping, potholes, cracking, and overall deterioration of the pavement. The main points of concern regarding the water sensitivity of asphalt mix are:

- Stripping: it refers to the separation of the asphalt binder from the aggregate surface due to water infiltration. When water penetrates into the pavement structure, it can disrupt the adhesive bond between the binder and the aggregates, leading to failure.
- Moisture susceptibility: it indicates the likelihood of an asphalt mix experiencing loss of strength or durability when exposed to moisture. This is often tested in the laboratory using methods like the Retained Marshall Stability & Tensile Strength Ratio (TSR), which compares the strength of conditioned (moisture-exposed) specimens to that of unconditioned specimens.

2.11.1 Retained Marshall Stability

Retained Marshall stability refers to the ability of an asphalt mix to maintain its strength and stability after being subjected to conditioning that simulates long-term exposure to environmental factors like water, temperature changes, and traffic loads. This test is typically conducted by measuring the stability of a Marshall specimen before and after immersion in water, which helps assess the mixture's resistance to moisture damage. In this context, Marshall Stability is a measure of the strength of asphalt concrete in resisting deformation under load. Retained Marshall Stability (RMS) indicates the

percentage of the original Marshall stability that is retained after the asphalt sample is conditioned, such as through immersion in water for a specified period (often 24 hours at 60°C) (ASTM D 1075). A higher retained Marshall stability percentage suggests better moisture resistance and long-term performance of the asphalt pavement.

2.11.2 Tensile Strength Ratio (TSR)

The Tensile Strength Ratio (TSR) is a key indicator used to assess the moisture susceptibility of asphalt mixtures. It is a comparison of the tensile strength of asphalt samples under wet and dry conditions. The purpose of the TSR test is to determine how well an asphalt mix resists damage caused by water, particularly stripping, which is the loss of bond between the asphalt binder and the aggregates due to water infiltration. The TSR test typically follows the procedure outlined in AASHTO T 283, which includes the Tensile strength of both the conditioned (wet) and unconditioned (dry) samples is measured by conducting an Indirect Tensile Strength (IDT) test, where a compressive load is applied along the vertical diametrical plane of a cylindrical specimen until failure. The TSR is determined under the two circumstances mentioned below:

- TSR without Freeze-Thaw Condition: IDT conduct on conditioned (wet) and unconditioned (dry) samples without the use of freezing-thawing action.
- TSR with Freeze-Thaw Condition: IDT conduct on conditioned (wet) and unconditioned (dry) samples with use of freezing-thawing action.

The TSR is expressed as a percentage. A higher TSR value indicates better resistance to moisture damage, meaning the asphalt mix is less likely to suffer from water-induced damage such as stripping. Most specifications require a TSR of at least 80% to ensure adequate moisture resistance.

2.11.2.1 Indirect Tensile Strength (IDT)

Indirect Tensile Strength (IDT) is a crucial mechanical property of asphalt mixes that evaluates their tensile strength and resistance to cracking. This test follows the procedure outlined in ASTM D 6931, involves loading a cylindrical specimen of asphalt horizontally until failure, using a compressive force applied along its vertical diametral plane. The stress generated in the horizontal direction induces tensile failure at the centre of the specimen, simulating the tensile forces that occur under traffic loading. Higher IDT values typically indicate better resistance to cracking and improved durability of the asphalt pavement.

2.11.2.2 Moisture Induced Damaged Test

Moisture-induced damage in asphalt mixes, commonly referred to as "stripping," occurs when water infiltrates the asphalt-aggregate bond, weakening the pavement and leading to premature failure. To assess moisture susceptibility, various laboratory tests are used, such as the Tensile Strength Ratio (TSR) test, outlined in AASHTO T 283. In this test, conditioned (wet) and unconditioned (dry) specimens of asphalt mix are subjected to indirect tensile strength testing. The ratio of the tensile strength of the conditioned to unconditioned specimens is used to evaluate the mix's resistance to moisture damage. A higher TSR indicates better resistance. The test helps predict the pavement's performance in wet conditions, guiding improvements in material selection and mix design.

2.12 PREVIOUS INVESTIGATIONS

Since bituminous pavements in transportation systems deal with issues like economic, environmental, and social factors, they face significant hurdles in terms of performance, durability, and sustainability. Sustainable development

requires sustainable construction. One of the primary concerns of a sustainable transportation system is undoubtedly the sustainability of bituminous pavement. In addition to achieving its goals in an eco-friendly way, a sustainable pavement also meets human needs, prudently preserves natural resources, and preserves and/or restores ecosystems [30]. A durable and sustainable flexible pavement construction deals with possible reduction of pavement deterioration caused by expansion and contraction from seasonal temperature variation, water intrusion, stress from heavy vehicle etc. CRMB and PMB provide effective solutions to the limitations of neat bitumen in terms of performance and durability. Also, CRMB minimizes environmental effects of waste tires. Much research has been conducted to understand the suitability of such CRMB and PMB. These researches are reviewed below:

2.12.1 Crumb Rubber Modified Bitumen

[4] conducted an investigation on the influence of Crumb Rubber in bituminous mixture. They added Crumb rubber (5, 10 and 15% by asphalt weight) with bitumen (80/100 grade) using the wet method. They concluded that the degree of penetration of the modified bitumen was significantly decreased with the addition of Crumb Rubber. Additionally, it was found that the inclusion of Crumb Rubber in bitumen lead to an increase in the ideal amount of asphalt and improved the volumetric characteristics of asphalt mixtures, specifically in terms of Marshall stability and Marshall flow. Notably, the utilization of 10% Crumb Rubber demonstrated the most significant impact on the Marshall stability of the mixture.

[20] examined the properties of Crumb Rubber modified bitumen using crumb rubber particles measuring 30 micrometres in size (6% to 14%). They observed that as the content of crumb rubber increased, the penetration and ductility values decreased, while the softening point increased. The highest level of

Marshall stability is achieved when the crumb rubber percentage is at 10%, however, the ductility is significantly reduced. Based on the results of the penetration, softening, and ductility tests, it is recommended to use 8% rubber content for 80/100 grade bitumen.

[32] It was found that adding crumb rubber to bitumen raises the binder's viscosity, which raises the asphalt mixes' manufacturing temperature. A 60/70 penetration grade asphalt binder treated with CR (at dosages of 15, 18, and 21% via the wet method) and WMA chemical additives (Evotherm M1 and Iterlow T) was examined for its mechanical and rheological characteristics. Permeation, softening point, rotational viscosity, frequency sweep using a dynamic shear rheometer (DSR), and multiple stress creep recovery (MSCR) tests were among the laboratory experiments.

According to the findings, CR makes the asphalt binder more rigid, which results in a better softening point and a lower penetration grade. Although it reduces fatigue performance, it also increases its resistance to rutting. Additionally, it has been demonstrated that, in the conditions under investigation, the asphalt binder's degree of stiffness and performance increases with the CR concentration. Conversely, WMA technology reduces the performance and stiffness of asphalt at high temperatures.

[33] used municipal refuse to make sustainable pavement. In this investigation, base bitumen (PG 64-10) was supplemented with crumb rubber and low and high density polyethylene. The fundamental parameters utilized to assess the behavior of the binder with regard to rutting and fatigue cracking are the complex modulus (G*) and phase angle (δ), which are acquired from the Dynamic Shear Rheometer (DSR). It was determined that the rheological properties of the binder were significantly improved by the use of Low Density Polyethylene (LDPE), High Density Polyethylene (HDPE), and Crumb Rubber (CR) modified binder. Various percentage of crumb rubber from waste tire were used in this investigation and found that increasing percentage of crumb rubber

(CR) has a significant effect on the elastic behaviour of the modified binder. Additionally, recycling this municipal trash will help address the environmental issues in the Kingdom of Saudi Arabia that arise from their accumulation in landfills.

[34] noted that employing crumb rubber has the potential to improve the qualities of traditional bitumen, protect the environment, and provide industrial-economic benefits. Investigating the impact of varying crumb rubber contents and blending circumstances (temperature and time) on bitumen binders' characteristics is the primary goal of this study. The softening point test and the dynamic shear rheometer (DSR) test were used for testing. The results demonstrated that while blending time had an insignificant impact on modified binder properties, varying crumb rubber contents and blending temperature had substantial effects. The interaction of bitumen-rubber blends was found to be influenced by higher blending temperature and crumb rubber content. These factors also increased the rate at which rubber particles swelled, which led to a decrease in phase angle (δ) and an increase in complex shear modulus (G*), storage modulus (G'), loss modulus (G''), and softening point. After stress was removed, the modified bitumen became less prone to deformation, proving that bitumen's properties are improved and its resistance to high and low temperatures is increased when crumb rubber is added.

[35] conducted an experiment where they mixed 5% and 10% of CR with 60/70 bitumen. After modifying the bitumen, they saw a decrease in the penetration value of the modified bitumen. This indicates that the modified asphalt binder became harder and had improved resistance to deformation. The elevated softening point indicates an enhancement in the softening temperature of asphalt binder, leading to an improvement in high temperature stability.

An environmentally friendly method of dealing with crumb rubber to asphalt pavement and the excellent rheological performance of reclaimed rubber modified asphalt (RRMA) are introduced in the work. Rubber reclamation

resulted in a notable decrease in viscosity and an improvement in storage stability for rubber-modified asphalt. Rotational viscosity, the linear amplitude sweep test, the multi-stress creep recovery test, and the bending beam rheological test were used to examine the rheological characteristics. The rheological performance of RRMA improved as the amount of rubber that was reclaimed grew, according to the results [36].

[12] examined the physical and rheological properties of bitumen. The assessment revealed that adding crumb rubber into the neat bitumen resulted in decreased penetration and increased softening point. Consequently, this leads to a reduction in the temperature sensitivity of the binder. This is achieved by elevating the penetration grade and increasing the softening point. Furthermore, it was shown that the viscosity of the binders that include crumb rubber experiences a substantial increase.

In the study conducted by [37], bitumen was modified with three additives (Crumb Rubber, SBS, F.T. Paraffin). The results indicated that the CR adjustment reduced the non-recoverable creep compliance (Jnr) more effectively than the SIS adjustment, and that the bitumen maintained its flexibility better as the temperature increased. Furthermore, this effect became evident when additives were utilized in conjunction.

A mixture of polymers and crumb rubber additives was used to modify the bituminous binder. The mixed modified binder was created in the refinery using the terminal blend method. Characterizing the qualities of the 45/80-55 CR binder in relation to the reference 50/70 and traditional polymer-modified 45/80-55 bitumen was the main goal of the laboratory testing. Rheological properties were examined using BBR (bending beam rheometer) and DSR (dynamic shear rheometer) tests, as well as standard binder tests like penetration, softening point, and Frass breaking point. Using a modified bitumen tube testing method, the stability of the polymer and crumb rubber was assessed. The study of the results showed that bitumen treated with

polymer and crumb rubber had improved viscoelastic qualities. [38] discovered that bitumen treated with crumb rubber had good low and high temperature properties and a broad visco-elastic range.

[39] conducted an assessment on the low temperature characteristics of rubberized asphalt mixture. They found that a mixture containing crumb rubber had superior toughness at low temperatures and a lower overall cost compared to an asphalt mixture modified with Styrene-Butadiene-Styrene.

[40] examined the fatigue properties of asphalt mixes including varying amounts of waste tire powder as a modifier. They found that the addition of crumb rubber to the modified asphalt mixture improved its fatigue performance. The crumb rubber asphalt mixture exhibited an extended lifespan when the crumb rubber percentage reached 9%.

[41] conducted research on the performance of rubber powder modifiers in pavement. They suggested that increasing the amount of crumb rubber could enhance the stability of the mixture at high temperatures and in the presence of water. However, exceeding a specific threshold would diminish the performance of the mixture.

2.12.2 Polymer Modified Bitumen

The asphalt business has a long history of modifying asphalt binders by adding a polymer to enhance their rheological and physical characteristics. A swallowed polymer network is created when the polymer and asphalt binder are appropriately combined, and this network helps to alter the viscoelastic behavior. [9].

The rising loading requirements for asphalt pavements are driving a steady increase in the use of polymer-modified asphalt. Higher dosages are being utilized more frequently to improve the performance and durability of asphalt mixtures, even though the typical polymer modification doses fall between 2.5

and 3.5% by weight of asphalt binder. The resulting binders are known as highly or heavily modified asphalts (HiMA or HP), and these higher doses vary from 7 to 8% by weight of asphalt. Characterizing and contrasting various basic material characteristics as well as the anticipated mechanical performance of a standard polymer modified and a HiMA asphalt at the binder and mastic levels under various aging conditions is the aim of this investigation. The results confirm an enhanced expected long-term mechanical performance of the HiMA asphalt in road projects as compared to conventional polymer modified binders [42].

The correct viscoelastic equilibrium that often happens when an efficient elastic network is formed by molecular association is absent from neat asphalt binders. By using high molecular weight polymeric additives to create molecular entanglement in asphalt, it is theorized that the right viscoelastic balance can be achieved. In this study, a method for altering asphalt binders was created, along with standards to assess how well the polymer modification process worked. Arab asphalt binders were modified using the process and criteria to meet the Gulf countries' performance standards for rutting, fatigue, and low-temperature cracking. The information gathered made it abundantly evident that polymer modification works well to enhance the rheological characteristics of neat Arab asphalt binders in order to meet the performance standards of the Gulf nations. Moreover, polymer modification is both practical and economically justified, according to life cycle cost study of several polymer modified combinations [11].

The fracture temperature of the combination was generally lowered by 6–10°C using polymer modifiers. There is a strong correlation between the mixture's performance and the performance-based requirements (SHRP). Resistance to load-associated fatigue and low-temperature thermal cracking were most strongly correlated with the binder's theological properties [43].

According to lab tests, the performance characteristics of binders and mixes continue to improve as the amount of polymers increases. Without any construction-related problems, the evaluated field projects demonstrated promising early field performance. Furthermore, based on the information found in the literature, this paper discusses approaches that were investigated to determine a structural coefficient of High Polymer (HP) blends. According to this analysis, the HP mixtures that were devised have the potential to reduce the thickness of the asphalt layer by up to 40%, which would result in significant upfront cost savings [45].

2.13 CONCLUDING REMARKS

From the above discussions, the following salient features can be drawn

- Flexible pavement using conventional bitumen distresses due to stress from heavy vehicles, expansion and contraction from seasonal temperature changes, oxidation aging, sun exposure and water logging. There are numerous types of defects that has been identified on the conventional bituminous roads including deep potholes, shallow potholes, surface deterioration, edge failure, cracking, rutting and subsidence. So, properties of bitumen and bituminous mixes is required to be improved by modifiers to improve performance, durability and ensure long life span of the pavement.
- According to the earlier research, bitumen treated with waste crumb rubber (CR) and styrene-butadiene-styrene (SBS) polymer modified bitumen can perform better than conventional bitumen to resist bituminous pavement from permanent deformation, cracking, aging and moisture induced damages. Among them, PMB is the most common type modified bitumen using worldwide.

- Waste crumb rubber (CR) from discarded tires treated with conventional bitumen forms CRMB. Therefore, utilization of waste tires helps reducing environmental hazards and making sustainable pavements.
- It is vital to look at the mechanical properties of conventional and modified binders through laboratory evaluation helps ensure the binder performs as required under various loading, temperature, and environmental conditions.
- Marshall method has to be employed for making Marshall specimens with various bitumen content of both conventional and modified binders. Marshall properties i.e., stability, flow value, bulk density, % air void, void in mineral aggregate (VMA), void filled with asphalt (VFA) are to be evaluated from experimental analyses to determine the optimum binder content (OBC).
- Since Bangladesh is a rain prone country, it has adverse effect on flexible pavement. Therefore, water sensitivity analyses i.e., retained Marshall stability and TSR on indirect tensile strength (IDT) and moisture induces damage test have to be conducted for both neat and modified bituminous mixes to identify the best suitable binder.

Chapter 3: MATERIALS AND METHODOLOGY

This chapter begins with a general (section 3.1) discussion about the chapter and describes the work flow diagram in section 3.2. This chapter also represents the materials (section 3.3) used in the investigation, preparation of crumb rubber modified bitumen (section 3.4), gradation of aggregate (section 3.5), mechanical properties of binders (section 3.6). Marshall mix design of bituminous concrete explains in section 3.7. Section 3.8 outlines the procedure of water sensitivity analysis of bituminous mixes and section 3.9 discusses about the cost analysis of bituminous mixes. finally, the summary of this chapter discusses in section 3.10.

3.1 GENERAL

This chapter comprehensively reviews the different materials and techniques necessary for conducting the research. A well performed bituminous mixes should be capable of supporting high traffic volumes and the goal of this mix design is to produce a mixture strong enough to meet the standards of the paving surface. Several well-established methods have been used to assess bituminous mixtures and various sources are used to collect these materials. Here Marshall method is adopted for bituminous mixes. In the following chapter, the materials are examined using recognized methods.

The 60/70 neat bitumen, PMB and CRMB are utilized in this study. The laboratory is used to measure the bitumen's mechanical properties i.e., specific gravity, ductility, penetration, softening point, flash and fire points, loss on heating, elastic recovery, stripping of bitumen-aggregate mix, loss of mass in thin film oven (TFO) test, reduction in penetration in TFO residue, increase in softening point in TFO residue, elastic recovery of TFO residue, temperature susceptibility and determining Marshall properties.

3.2 WORK FLOW DIAGRAM

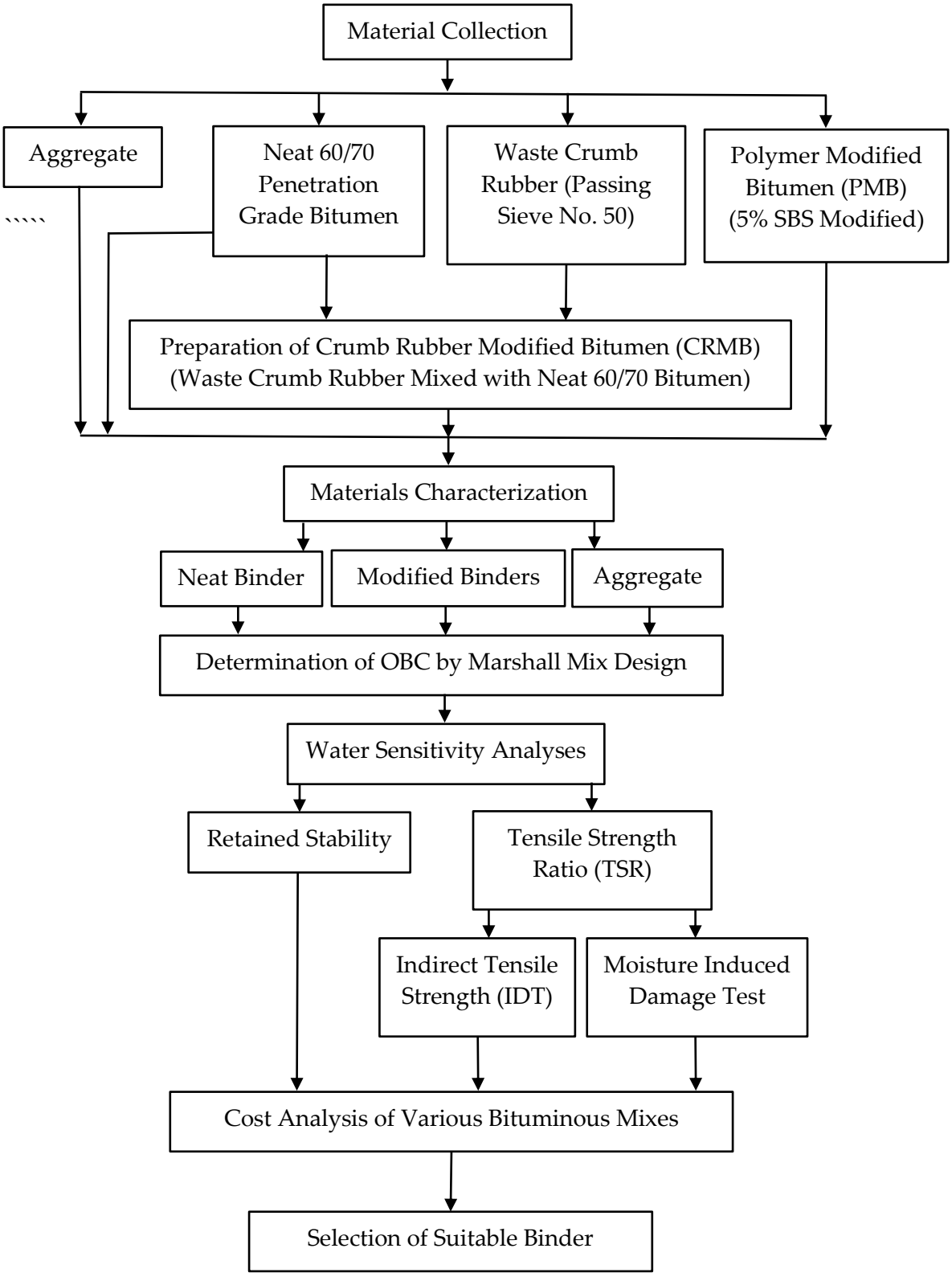


Fig. 3.1 Work Flow Diagram of the Present Investigation

A workflow diagram demonstrates the sequential steps or necessary tasks to complete a specific activity or process. The document offers a concise and organized representation of the work pattern, demonstrate the operations, decisions, and interrelationships among the various components. The workflow diagram by which our experiment has proceeded is represented in Fig. 3.1. Surface course mixes must be made to be stable and long-lasting enough to support the expected traffic loads and to resist the damaging effects of temperature, water, and air changes in order to build an appropriate asphalt pavement. As such, to get better performing asphalt mix in terms of stability and durability, activities (material collection, preparation of modified binders, laboratory analyses) involve in comparative experiments of different binders are important.

3.3 MATERIALS

The natural aggregates (coarse and fine aggregate), stone dust as a mineral filler, 60/70 neat bitumen, PMB, and crumb rubber (CR) powder are the ingredients utilized to create bituminous mixtures for the lab experiment.

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3.3.1 Coarse Aggregate

The selection of coarse aggregate is crucial in order to achieve maximum performance of asphalt concrete. The qualities of coarse aggregate, such as the distribution of particle sizes, shape, and surface roughness, have a significant impact on the mechanical capabilities and longevity of the asphalt mixture. Appropriate grading of the coarse aggregate allows sufficient interlocking within the asphalt binder matrix, hence improving stability and durability against permanent deformation caused by traffic loads. Furthermore, the angular shape and rough surface of large aggregate particles enhance the bonding between the aggregate and asphalt binder. This is important for

minimizing moisture damage and ensuring the long-term durability of the pavement. Thorough quality control procedures are essential during the process of selecting aggregates and designing mixtures to fulfill the standards of Marshall mix design. These steps are necessary to guarantee the manufacture of asphalt pavements of superior quality that can resist the demands of traffic and environmental conditions. For this investigation, coarse aggregate is collected from Materials Laboratory, CUET. The source of coarse aggregate is Dubai, U.A.E.

3.3.2 Fine Aggregate

The role of fine aggregate is essential as it significantly impacts the performance and characteristics of asphalt concrete. The fine aggregate, commonly made up of sand or crushed stone dust, serves a vital function in filling the empty spaces between the larger coarse aggregate particles. This contributes to the overall density and stability of the asphalt mixture. The size and form of the small particles in the fine aggregate have a considerable effect on how easy it is to work with, how well it sticks together, and how likely it is to be affected by moisture in the asphalt binder mixture. An ideal distribution of fine aggregate particles guarantees effective coverage and bonding with asphalt binder, resulting in increased resistance to road deformations and cracks caused by fatigue. Additionally, it enhances the overall durability and capacity to withstand moisture damage. For this investigation, fine aggregate is collected from Materials Laboratory, CUET. The source of fine aggregate is Sylhet.

3.3.3 Mineral Filler

Soil and stone dust are chosen as a mineral filler based on its particle size distribution, mineralogy, and plasticity index to ensure it is compatible with the

asphalt binder and aggregate components. The soil mineral filler has several roles, such as strengthening the workability and cohesion of the asphalt mixture, improving the adhesion between the asphalt binder and aggregate particles, and filling the empty spaces in the aggregate structure to enhance compaction and stability. In addition, the use of soil filler can help decrease the drainage of asphalt binder and its susceptibility to moisture, hence improving the pavement's resilience to rutting, fatigue cracking, and moisture damage. Stone dust used in this experiment is collected from a stone crusher of government road project named "SASEC, Dhaka-Sylhet Corridor Road Investment Project" under Roads and Highways Department (RHD).

3.3.4 60/70 Neat Bitumen

Bitumen is a thick, black crude oil which is composed of complex, heavy hydrocarbons. Bitumen used in flexible pavement construction should have the quality and performance to withstand surface deterioration, edge failure, cracking, rutting, and subsidence due to water intrusion, stress from heavy vehicles, expansion and contraction from seasonal temperature changes, and sun exposure. The grade of bitumen is named after the penetration test on bitumen. Among this bitumen 80/100 & 60/70 penetration grade bitumen are used in Bangladesh. In this research, 60/70 penetration grade bitumen is selected for further testing. This is collected from Transportation Laboratory, CUET. The source of 60/70 bitumen is Eastern Refinery Ltd. located in Chittagong.

3.3.5 Reclaimed Crumb Rubber (CR)

Crumb rubber is a type of rubber that is made by recycling used tires of vehicle. Crumb rubber is a polymer mostly consisting of rubber and carbon black. Crumb rubber primarily consists of vulcanized rubber, which is

predominantly composed of non-polar rubber hydrocarbon. Crumb Rubber is collected from tire re-treading shop located at Kadamtali, Chattogram. Being screened of the crumb rubber, the 50 mesh (0.30 mm size) CR powder is used as modifier to modify 60/70 grade bitumen.

3.3.6 Polymer Modified Bitumen (PMB)

One of the particularly created and developed bitumen grades used to create pavement and roads for heavy traffic is polymer modified bitumen (PMB). Blending bitumen 60/70 with a particular grade of SBS (styrene-butadiene-styrene) under extremely specific pressure and temperature conditions is known as polymer modified bitumen. Because polymer-modified bitumen is less sensitive to temperature, it will not flow in hot summer temperatures and will not break in cold winter temperatures because it retains its elasticity at low temperatures. Due to its high viscosity and excellent fatigue resistance, PMB will adhere to aggregates rather than separate. A cured polymer modified bitumen binder composition is created by adding a block copolymer composition to the bitumen component while the bitumen component is being stirred at 2000 ± 10 rpm to create a homogenous mixture of the bitumen and the block copolymer. The temperature is kept between 180°C and 190°C for two hours [26]. SBS modified bitumen (SBS PMB PG 70-40) is collected from a bituminous surface treatment project named "Performance Based Operation of 4-Lane Dhaka-Chattogram National Highway (N1), Cumilla Part, Daudkandi to Dhumghat Bridge (Ch. 39+267Km to 165+183Km)" under Roads and Highways Department (RHD). The PMB was brought to this project from Manufacturer: Dan-Bunkering (Middle East) DMCC located in Dubai, U.A.E. According to the project specification, 5% SBS was added with 60/70 neat bitumen to prepare modified bitumen.

3.4 PREPARATION OF CRUMB RUBBER MODIFIED BITUMEN

The waste crumb rubber (CR) is collected from tire re-treading shop which is used through following process to prepare CRMB in the Transportation Laboratory, CUET.

3.4.1 Processing of Crumb Rubber

The crumb rubber particles are screened by sieve no. 50 (0.30 mm particle size) and collected CR powder to modify 60/70 bitumen. Before blending, CR powder is cleaned and dried properly.

3.4.2 Blending of Crumb Rubber

The wet process and the dry process are the two ways that CRMB can be produced. In both cases, heated bitumen and crumb rubber are combined in a high-speed mixer. Wet crumb rubber is used in the wet process, while dry crumb rubber that has been finely powdered is used in the dry process. The guidelines developed by [17] are applied while mixing asphalt and crumb rubber. Before adding crumb rubber, 60/70 penetration grade bitumen is heated in a mixing machine to 160°C. About five minutes are spent mixing at a low speed with 7.0% (by weight) of 50 mesh (0.3mm) crumb rubber [20]. After that, a mechanical stirrer running at 1400 rpm is used to vigorously swirl the mixture for around 60 minutes while it is heated to between 170°C and 180°C. The generated modified bitumen is taken out of the mixing machine after 60 minutes and allowed to cool before being stored in a sealed container.

3.5 GRADATION OF AGGREGATE

The distribution of particle sizes in a given sample is described by the aggregate gradation, which also establishes the aggregate quality. There are

several distinct aggregate sizes in this gradation. Smaller rocks and particles fill the voids left by larger rocks.

The smallest sieve that 100% of the sample must pass through is known as the maximum aggregate size. The smallest sieve size that most of the material can flow through (up to 15% can be retained) is known as the nominal maximum aggregate size (NMAS). In this study, maximum aggregate size is 25mm and nominal maximum aggregate size is 19mm.

The natural aggregates are collected, sieved, and then kept individually based on size. In accordance with ASTM and RHD specifications, the following surface course gradation was chosen. Table 3.1 displays the aggregate gradation.

Table 3.1 Gradation of Aggregate (ASTM D 3515 & Technical Spec. of RHD)

Sieve Size (mm)	Percent (%) Passing (19mm Nominal Max. Aggregate Size, NMAS)	Mid Value	Weight in 100% (1100 gm) Mix (gm)
25	100	100	0
19	90-100	95	55
12.5	67-88	77.5	192.5
9.5	56-80	68	104.5
4.75	35-65	50	198
2.36	23-49	36	154
1.18	14-34	24	132
0.6	9-24	16.5	82.5
0.3	5-19	12	49.5
0.15	3-13	8	44
0.075	2-8	5	33
<0.075	-	-	55

3.6 MECHANICAL PROPERTIES OF BINDER

Bitumen, also known as asphalt, is a viscoelastic material commonly used in road construction. Its mechanical properties are crucial for determining its performance in pavements, waterproofing, and other applications. Key mechanical properties of bitumen are listed in the following Table 3.2.

Table 3.2 Mechanical Property Tests for Bitumen Binders

Sl. No.	Name of The Property Test	Reference(s)
1	Specific Gravity	AASHTO T228 / ASTM D70
2	Penetration	AASHTO T49 / ASTM D5
3	Softening Point (R&B)	AASHTO T53 / ASTM D36
4	Ductility	AASHTO T51 / ASTM D113
5	Loss on Heating for 5 hrs at 163˚C	AASHTO T179 / ASTM D6
6	Flash & Fire Point	AASHTO T48 / ASTM D92
7	Elastic Recovery, 10 cm elongation	AASHTO T301 / ASTM D6084
8	Striping of Bitumen-Aggregate Mix	AASHTO T182 / ASTM D1664
9	Thin Film Oven (TFO), Loss in Mass	AASHTO T240 / ASTM D1754
10	Penetration of Residue of TFO	AASHTO T49 / ASTM D5
11	Ductility of Residue of TFO	AASHTO T51 / ASTM D113
12	Softening Point (R&B) of Residue of TFO	AASHTO T53 / ASTM D36
13	Temperature Susceptibility	AASHTO T49 / ASTM D5

3.7 MARSHALL MIX DESIGN OF BITUMINOUS CONCRETE

The process of measuring the ratios of aggregates, bitumen, and other additives to be used in asphalt concrete or bituminous mixes is referred to as bitumen mix design. For this investigation, the Marshall mix design is used. This approach is straightforward, small, and affordable. It is the world's most popular method. It generates densities that are rather nearer to field density.

The fundamental idea behind it is to select an asphalt binder content with a suitable density that satisfies the flow values and minimal stability criteria. ASTM and other organizations have standardized the test technique. Bitumen and aggregate hot-mix designs with a maximum size of 25mm are suitable for the stability test.

The heated aggregates and bitumen are adequately blended. When the mixture temperature is between range specified, placed into a heated mould, and rammed 75 times on each side to crush it. It is possible to adjust the weight of the materials used to make the specimen in order to get a compacted thickness of 63.5±3 mm. In the following experiment, repeat the previous procedure while increasing the bitumen concentration by +0.5%. The bitumen percentage has been adjusted from 4.0 to 6.5%. Number 3 specimens are prepared for each bitumen percentage.

3.7.1 Mixing and Compaction Temperature

The Viscosity-Temperature relationship indicates the change in viscosity of the bitumen binder with temperature. Bitumen become less viscous (thinner) as temperature increases, while they become more viscous (thicker) as temperature decreases. Hence, it is necessary to develop a Temperature-Viscosity chart to establish mixing and compaction temperatures. This can be done by determining the viscosity in Pa-s at different temperatures - generally ranges from 110°C to 190°C. These viscosities are then plotted against temperature on the graph and a straight line is drawn between the points as shown in Fig. 3.3. The desired viscosity range for mixing temperature is in between 0.15 and 0.19 Pa-s, 0.25 and 0.31 Pa-s is for compaction temperature. Appropriate mixing and compaction temperatures are selected as the temperature where these viscosity requirements are met (ASTM D 6926).

3.7.2 Compaction of Specimens

A temperature of 90°C to 150°C is applied to the specimen mold assembly and the compaction hammer's face. Before the mixture is added, a piece of nonabsorbent paper that has been cut to size is inserted into the mold's bottom. A warm spatula is used to vigorously stir the mixture once it has been placed. Cut a second piece of non-absorbent paper to fit over the mixture. The mixture's temperature right before compaction is kept within the compaction temperature range. The mold assembly is set up on the pedestal and compacted by applying the necessary number of blows to each side using the designated compaction hammer. After compaction, the collar and base plate are removed and the specimen with mold is allowed to cool in room temperature (ASTM D 6926).

3.7.3 Marshall Properties of Compacted Mix

To assess the characteristics of the compacted mix, experimental investigations were carried out using Marshall specimens in accordance with ASTM D 6927. These are (i) Stability-Flow Analysis and (ii) Density-Voids Analysis. Density-Void Analysis is used to measure the bulk density of the compacted mix, the percentage of air void, the void in mineral aggregate (VMA), the void filled with asphalt (VFA), the percentage of absorbed asphalt by the total weight of aggregate (Pba), and the percentage of effective asphalt by the weight of the entire mixture (Pbe). Stability: The compacted mix's stability and flow value are provided by flow analysis. Fig. 3.2 illustrates the bituminous mix's volume-void relationship.

The standardized the test procedures have been explained by ASTM and Asphalt Institute [31]. According to MS-2, 2014, the test techniques involve following calculations:

- Specific Gravity of Asphalt (Binder), G_b is determined in laboratory.

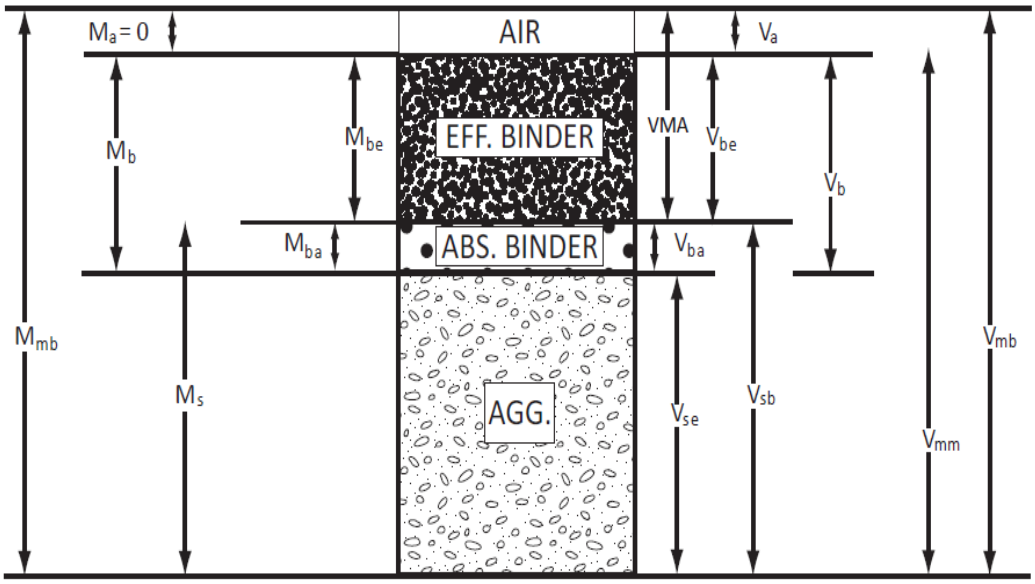


Fig. 3.2 Phase Diagram of Bituminous Mix [31]

- Bulk Specific Gravity of Combined Aggregate, G_{sb} = Dry (OD) Mass / Bulk Volume

$$= \frac{P_1 + P_2 + \ldots\ldots\ldots\ldots + P_n}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \ldots\ldots\ldots\ldots + \frac{P_n}{G_n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

Where, $P_1, P_2, \ldots . P_n$ = Individual Percentage by Mass of Aggregate

$G_1, G_2, \ldots . G_n$ = Individual Bulk Specific Gravity of Aggregate

The bulk specific gravity of mineral filler is difficult to determine accurately. However, if the Apparent Specific Gravity of the filler is substituted, the error is usually negligible.

- Effective Specific Gravity of Combined Aggregate, G_{se} = Dry (OD) Mass / Effective Volume

$$= \frac{P_{mm} - P_b}{\frac{P_{mm}}{G_{mm}} - \frac{P_b}{G_b}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(ii)}$$

Where, G_{mm} = Max. Specific Gravity of Paving Mix

P_{mm} = Percent by mass of total Loose Mixture = 100

P_b = Asphalt Content, percent by total Mass of Mixture

G_b = Specific Gravity of Asphalt

Apparent Specific Gravity of Combined Aggregate, G_{sa} = Dry (OD) Mass / Apparent Vol. . . . . (iii)

- Bulk Specific Gravity of Compacted Mix, G_{mb} = Mass of Asphalt and Aggregate / Vol. of Compacted Mix . . . . . .(iv)

- Theoretical Max. Specific Gravity of Paving Mixture, G_{mm} = Mass of Asphalt and Aggregate / Vol. of Uncompacted or Loose Mix = $\frac{P_{mm}}{\frac{P_s}{G_{se}}+\frac{P_b}{G_b}}$ . . . . . (v)

Where, G_{se} = Effective Specific Gravity of Combined Aggregate

P_{mm} = Percent by mass of total Loose Mixture = 100

P_b = Asphalt Content, percent by total Mass of Mixture

G_b = Specific Gravity of Asphalt

P_s = Aggregate (Stone) Percent by Total Weight of Aggregate

- Asphalt (Bitumen) Percent by Weight of Total Mixture, P_b = Total Asphalt Content of a Paving Mixture

- Effective Asphalt Percent by Weight of Total Mixture, P_{be} = Total Asphalt content of a paving Mixture - The Portion of Asphalt absorbed into the Aggregate Particles = $P_b - \frac{P_{ba}}{100} * P_s$ . . . . . (vi)

Where, P_{ba} = Absorbed Asphalt Percent by Total Weight of Aggregate

P_b = Asphalt Content, percent by total Mass of Mixture

P_s = Aggregate (Stone) Percent by Total Weight of Aggregate

- Absorbed Asphalt Percent by Total Weight of Aggregate, P_{ba} = The Portion of Asphalt absorbed into the Aggregate Particles = $100 * \frac{G_{se}- G_{sb}}{G_{se}*G_{sb}} * G_b$. . . . (vii)

Where, G_{se} = Effective Specific Gravity of Combined Aggregate

G_{sb} = Bulk Specific Gravity of Combined Aggregate

G_b = Specific Gravity of Asphalt

- Aggregate (Stone) Percent by Total Weight of Aggregate, P_s

$= P_{mm} - P_b = 100 - P_b$ . . . . . (viii)

Where, P_{mm} = Percent by mass of total Loose Mixture = 100

P_b = Asphalt Content, percent by total Mass of Mixture

- Air Void Percent by Total Volume of Compacted Mixture, P_a = Total Vol. of small pockets of air between the coated aggregate particles throughout a compacted paving mixture

$= 100 * \frac{G_{mm} - G_{mb}}{G_{mm}}$ . . . . . (ix)

- Voids in Mineral Aggregate, VMA = Air voids & Effective Asphalt Content, Percent by Volume of Compacted Mixture = $100 - \frac{G_{mb} * P_s}{G_{sb}}$ . . . . . .(x)

- Voids Filled with Asphalt, VFA = Vol. of Air Voids Occupied by Effective Asphalt, (VMA – V_a), Percentage of VMA = $100 * \frac{VMA - P_a}{VMA}$ . . . . . (xi)

- Fines to Asphalt Ratio, F/A = % Pass #200 / P_{be} . . . . . (xii)

The set of test samples are prepared for both modified and unmodified binders. The performance of these modified and unmodified binders is evaluated and compared according to guidelines specified in Table 2.2.

3.7.4 Optimum Bitumen Content (OBC)

The test results of various Marshall properties i.e., stability, flow value, bulk density, % air void, void in mineral aggregate (VMA), void filled with asphalt (VFA) found from experimental analyses are then plotted in graphs against different bitumen content as shown in Fig. 3.5. As per recommendation

of asphalt institute, MS-2, 2014, the optimum bitumen content (OBC) is determined at 4% air void from % air void vs. bitumen content graph.

3.8 WATER SENSITIVITY ANALYSES OF BITUMINOUS MIX

Bituminous samples are put through the moisture susceptibility test, also known as the water sensitivity test, to determine how resistant they are to harm brought on by moisture. A bituminous mixture's sensitivity to moisture is commonly evaluated using the performance tests known as Retained Marshall Stability and Tensile Strength Ratio (TSR). The mix is often performed well and be resistant to moisture damage if the Retained Marshall Stability and Tensile Strength Ratio (TSR) is greater.

3.8.1 Retained Marshall Stability

ASTM D 1075 determines the loss of stability caused by submersion of flexible pavement in water. A minimum of six Marshall compacted specimens—three for conditioned samples and three for unconditioned samples—are required for both neat and modified bitumen. The specimens are in the intended gradation and have the right binder content. Each specimen's density and air voids are measured. Three samples are placed in a water bath set at 60°C for a full day, and three samples are left at room temperature. After a 24-hour waiting period, the three standard specimens are conditioned. Every sample is subjected to standard stability tests, and the average findings for each set are calculated. The following equation was used to determine retained stability. Bitumen with a greater maintained stability value is more resilient to water immersion-induced road stability deterioration.

Retained Stability % = (Conditioned Stability / Unconditioned Stability) * 100

3.8.2 Tensile Strength Ratio

The following formula is used to determine the tensile strength ratio (TSR) for both neat and modified bitumen (ASTM D 4867). The conditioned subset's tensile strength divided by the unconditioned subset's is known as the TSR. Bitumen with a higher TSR value is more resilient to moisture-induced degradation. A bitumen's resistance to rutting and lower temperature cracking increases with its tensile strength.

Tensile Strength Ratio, TSR (%) = $S_{t\,(Conditioned)} / S_{t\,(Unconditioned)} * 100$

Where, TSR = Tensile strength ratio, %

$S_{t\,(Conditioned)}$ = Avg. tensile strength of the conditioned subset, kPa (psi)

$S_{t\,(Unconditioned)}$ = Avg. tensile strength of the dry subset, kPa (psi)

3.8.2.1 Indirect Tensile Strength

The degree of susceptibility to moisture damage is determined by preparing a set of laboratory compacted specimens conforming to the job mix formula. A total of 6 specimens of equal void content are prepared. The set of specimens are divided into two subsets. One subset (3 specimens) is immersed in a water bath at 60°C, for a period of 24 hours (conditioned samples). The samples are then removed from the water bath and kept at a temperature of 25°C for a period of 2 hours. Other subset (3 specimens) of samples (unconditioned samples) are kept at a temperature of 25°C for a period of 2 hours without soaking. The tensile strength of each subset is determined by the tensile splitting test. These specimens are then mounted on the conventional Marshall testing apparatus and positioned the loading strips so that they are parallel and centered on a vertical diametral plan. Diametral load is applied at a deformation rate of 51mm/min and the load at failure is recorded at each case

(ASTM D 6931). Split / Indirect tensile strength (IDT) is determined for bitumen by following equation:

Split Tensile Strength, $S_t = \frac{2000P}{\Pi Dt}$ (kPa) or

$$S_t = \frac{2P}{\Pi Dt} \text{ (psi)}$$

Where, S_t = Split tensile strength, kPa (psi)

P = Maximum load, N (lbf)

t = Specimen height immediately before tensile test, mm (in)

D = Specimen diameter, mm (in)

The potential for moisture damage is indicated by TSR i.e., the ratio of the tensile strength of the conditioned subset to that of the unconditioned subset.

3.8.2.2 Moisture Induced Damage Test

By performing freezing-thawing action on test samples, which is a measure of the asphalt mix's long-term stripping susceptibility, the AASHTO T 283 specification determines the moisture-induced degradation of flexible pavement. Two sets of Marshall samples with an air void of 7 ± 0.5% are used for the test. There are two subsets of the sample set. The first set consists of three unconditioned subset samples that were maintained at 25˚C for two hours without soaking. The second subset are conditioned by vacuum saturation by 70-80 percent (AASHTO T 283-03) with water and then placed in a freezer at 0ºF (-18ºC) for 24 hours. The conditioned specimens are then placed in a water bath at 25ºC for 24 hours. After the freeze-thaw conditioning is done, the indirect tensile strength (IDT) is measured. The tensile strength of conditioned sample St(Conditioned) is compared to the tensile strength of unconditioned sample St(unconditioned) to determine tensile strength ratio (TSR). Bitumen having more TSR value is more resistant to moisture induced damage including freezing thawing condition.

3.9 COST ANALYSIS OF BITUMINOUS MIXES

A cost analysis of bituminous mix (asphalt) involves evaluating the costs associated with the production, transportation, and laying of the asphalt mix on a road or project site. The purpose of cost analysis of asphalt mixes is to evaluate and compare the financial implications of using different asphalt materials, mixtures, or production processes in paving projects. The cost analysis ensures that the project remains within budget and identifies areas where cost savings may be possible. This analysis typically includes the following components:

A. Material Costs

Bitumen: The binder material used in asphalt mixes, requirements of which depends on the proportion of bitumen to aggregate. The cost of bitumen can fluctuate with oil prices.

Aggregates: Crushed stone, gravel, or sand, which serve as the bulk material in the mix. The cost of asphalt depends on type and quality of aggregates used.

Filler Material: Additional fine materials like stone dust, clay soil, lime or other additives used to improve the mix.

Modifiers: Polymers, rubber, or other modifier used to modify bitumen which included with conventional bitumen to enhance the performance characteristics. The cost of modified bitumen depends on the fact that whether the modifiers are locally available or not.

B. Production Costs

Heating and Mixing: The bitumen and aggregates must be heated and mixed in an asphalt plant, which requires fuel (natural gas, oil, or electricity) and labor.

Plant Operations: Overheads like plant maintenance, labor costs, equipment depreciation, and utilities.

C. **Transportation Costs**

Distance from Asphalt Plant to Site: Transportation costs depend on the distance from the production plant to the road construction site.

Fuel Prices: Higher fuel costs can increase the transportation cost.

Vehicle Availability: The number of trucks required for delivery and their availability impact costs.

D. **Labor and Equipment Costs**

Paving Equipment: The cost of operating and maintaining machinery such as pavers, rollers, and compactors.

Labor: Costs for the crew involved in leveling and grading of the site prior to laying the asphalt mix, laying of asphalt, spreading and compacting the bituminous mix.

3.10 CONCLUDING REMARKS

From the above discussion, the following salient features can be drawn:

- An experiment specific work flow diagram is established by which all the laboratory investigations are to be conducted to get suitable outcomes.
- ASTM and RHD specifications for aggregate gradation for the bituminous surface course is selected for this investigation. An aggregate gradation chart is developed based on the specifications.
- The coarse aggregate and fine aggregate are collected from materials laboratory of CUET. The stone dust as filler material are collected from a stone crusher mill of government road project named "SASEC, Dhaka

Sylhet Corridor Road Investment Project" under Roads and Highways Department.

- A binder, conventional 60/70 penetration grade bitumen is collected from transportation laboratory, CUET. Another binder, polymer modified bitumen (SBS PMB PG 70-40) is collected form from a bituminous surface treatment project named "Performance Based Operation of 4-Lane Dhaka-Chattogram National Highway (N1), Cumilla Part, Daudkandi to Dhumghat Bridge (Ch. 39+267Km to 165+183Km)" under Roads and Highways Department (RHD).
- The waste crumb rubber (CR) is collected from tire re-treading shop located at Kadamtali, Chattogram which is to be blended with Neat 60/70 bitumen for preparation of crumb rubber modified bitumen (CRMB). This is another modified bitumen required for the study.
- The mechanical properties of conventional and modified binders through various laboratory experiments are conducted to evaluate performance of binder.
- The volumetric properties, stability, flow and ideal binder content for the optimal amount of bitumen are determined by the Marshall method of bituminous mix design, mostly used and straightforward procedure out of five mix design approaches.
- Since bituminous surfaces are directly exposed to weather, water sensitivity analyses of bituminous mix are performed by Retained Marshall Stability and Tensile Strength Ratio to identify suitable binder.
- The costs of asphalt are analyzed to figure out the cost effectiveness of bituminous mixes using modified and unmodified binders.

Chapter 4: EXPERIMENTAL INVESTIGATION AND RESULT

This chapter begins with a general (section 4.1) discussion of the chapter and shows the test results (section 4.2) of various materials used in the investigation. The bituminous mix designs using various binders are explained in section 4.3. The results of bituminous mix performance are shown in section 4.4. finally, the summary of this chapter discusses in section 4.5.

4.1 GENERAL

This chapter covers the experiments outcomes and the laboratory activity. Polymer modified bitumen and neat 60/70 bitumen have been collected. Waste crumb rubber (CR) has also been collected and blended with neat 60/70 bitumen to prepare crumb rubber modified bitumen. Both the neat and modified bitumen have been used to make Marshall mix. The physical properties and optimum bitumen content of bituminous mix prepared by neat 60/70 bitumen, PMB and CRMB have been determined. Water sensitivity of various bituminous mixes have also been analysed.

4.2 MATERIAL USED IN THE INVESTIGATION

For the purpose of this experiment, natural aggregate has been utilized as both coarse aggregate, fine aggregate and mineral filler. Additionally, neat 60/70 penetration grade bitumen and modified bitumen have been used as binder materials.

4.2.1 Coarse Aggregate

Aggregates that are retained on a 4.75mm sieve are coarse aggregate. The coarse aggregate has been used in this investigation is originated from Dubai, UAE. The physical properties of coarse aggregates have been evaluated and presented in the Table 4.1.

4.2.2 Fine Aggregate

Sand retained on a 0.075mm sieve after passing through a 4.75mm sieve has been taken as fine aggregate. The fine aggregate has been used in this investigation is originated from Sylhet, Bangladesh. The specific gravity has been evaluated and presented in the Table 4.1.

4.2.3 Mineral Filler

Filler materials are those which pass standard No. 200 sieve (0.075mm) i.e., pan materials. The filler materials are either fly ash, soil, or stone dust. In this investigation, stone dust has been used as filler material in this investigation is originated from Meghalaya, India. The specific gravity has been evaluated and presented in the Table 4.1.

Table 4.1 Mechanical Properties of Aggregates and Mineral Filler

Properties	Result	Specifications Reference for Surface Course
Specific Gravity of Coarse Aggregate	2.67	-
Specific Gravity of Fine Aggregate	2.60	-
Specific Gravity of Filler (Stone Dust)	2.58	-
Los Angeles Abrasion Test (LAA)	13.36%	<30%, AASTHO T96 & RHD
Aggregate Impact Value (AIV)	9.39%	<20%, BS 812-112:1990

Aggregate Crushing Value (ACV)	16.93%	<25%, STP 7.7.1 & RHD
Elongation Index	26.89%	<45%, IS 2386: Part I
Flakiness Index	22.34%	<30%, STP 7.3.1 & RHD

4.2.4 Aggregate Gradation

According to ASTM D 3515 & Technical Specification, RHD, the aggregate gradation curve for coarse aggregate, fine aggregate and mineral filler are shown in Fig. 4.1.

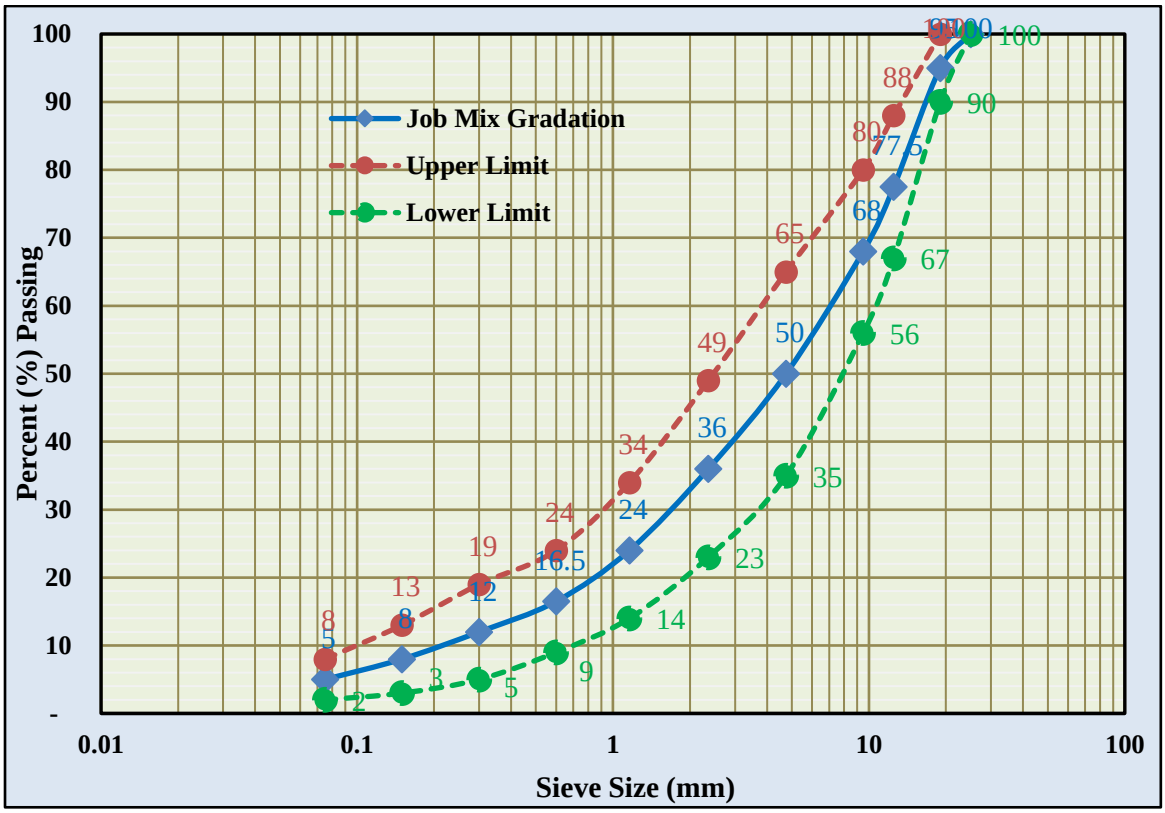


Fig. 4.1 Aggregate Gradation Curve (ASTM D 3515 & Tech. Spec. of RHD)

4.2.5 Crumb Rubber

Waste crumb rubber (CR) produce from scrap tires go through a multi-step grinding process at room temperature. The waste crumb rubber has been collected from Kadamtali, Chittagong. 7.0% by weight of passing sieve No. 50

(0.30mm) crumb rubber particle has been blended with neat 60/70 penetration grade bitumen pre-heated at temperature 180 °C to190°C to prepare crumb rubber modified bitumen (CRMB). The gradation of CR is shown in Fig. 4.2.

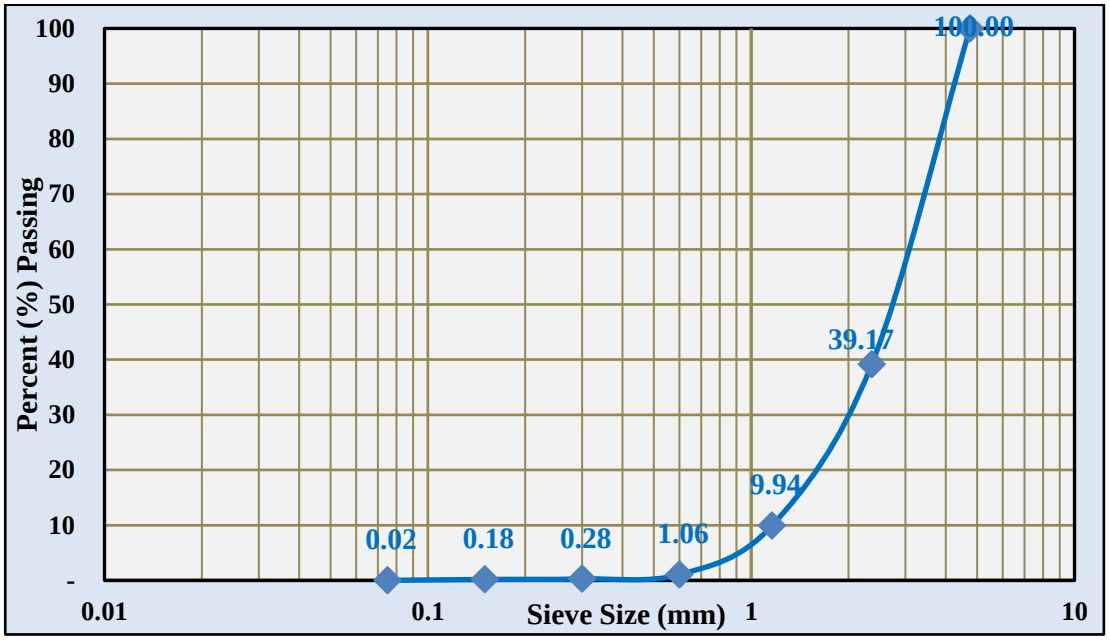


Fig. 4.2 Gradation of Crumb Rubber (CR)

4.2.6 Binders

Three binders have been utilized in bituminous mix design to evaluate the effectiveness of binders: Polymer Modified Bitumen (PMB), Crumb Rubber Modified Bitumen (CRMB), and the traditional 60/70 Penetration Grade Bitumen.

- The 60/70 Bitumen has been used in this investigation is originated from Eastern Refinery Ltd., Bangladesh.
- The PMB has been used in this investigation is originated from Dubai, UAE.
- The CRMB has been used in this investigation is prepared in Transportation Laboratory, CUET.

Laboratory analysis has established the mechanical characteristics of both neat and modified bitumen, which are shown in Table 4.2.

Table 4.2 Mechanical Properties of Various Binders

Name of The Test	Unit	60/70	PMB	CRMB	References	ASTM / AASHTO Specifications	RHD Specifications for Modified Bitumen
Specific Gravity @ 25˚C	-	1.024	1.015	1.037	AASHTO T228 / ASTM D70	ASTM: 1.0 ~ 1.2 AASHTO: 1.0 ~ 1.1	-
Penetration @ 25˚C & 100gm loading, 5 Sec	0.1 mm	68.5	42.5	32.5	AASHTO T49 / ASTM D5	60/70 Bitumen = 60 ~ 70	30 ~ 50
Softening Point (R&B)	˚C	48.5	67.5	68.5	AASHTO T53 / ASTM D36	Lower Grade Bit. = 40 ~ 60, Higher Grade Bit. = 60 ~ 70	Min. 60
Ductility	cm	100^{+}	100^{+}	32.8	AASHTO T51 / ASTM D113	Min. 100	-
Loss on Heating for 5 hrs. at 163˚C	% Loss	0.91	0.0	0.0	AASHTO T179 / ASTM D6	Max. 1	Max. 1
Flash Point	˚C	305	340	330	AASHTO T48 / ASTM D92	Min. 230	Min. 220
Fire Point	˚C	320	357	350	AASHTO T48 / ASTM D92	Min. 300	-
Elastic Recovery at 25˚C, 10cm elongation	%	17	61	70	AASHTO T301 / ASTM D6084	ASTM: Min. 60 AASHTO: 40 ~ 85	Min. 60
Stripping of Bitumen-Aggregate Mix	%	0.7	0.0	0.0	AASHTO T182 / ASTM D1664	Max. 5	-
Thin Film Oven (TFO) for 5 hrs. at 163˚C	% Loss	1.64	0.83	0.34	AASHTO T240 / ASTM D1754	Max. 1	Max. 1
Reduction in Penetration of TFO Residue	%	49	17	11.5	AASHTO T49 / ASTM D5	Max. 35	-
Increase in Softening Point of TFO Residue	˚C	5	2	2	AASHTO T53 / ASTM D36	Max. 5	-
Elastic Recovery of TFO Residue	%	12	52	67	AASHTO T51 / ASTM D113	Min. 50	-

The laboratory data suggests that almost all the properties of the bituminous material satisfy the conditions specified in the ASTM, AASHTO and RHD specification. In contrast to the traditional neat 60/70 bitumen, modified bitumen performs better. Based on the test results, an overview of the qualities of different types of bitumen are given below:

- **Penetration:** Bitumen with higher penetration value is softer and more susceptible to deformation at high temperatures whereas bitumen with lower penetration value is harder and may crack at low temperatures. Bangladesh has a tropical monsoon climate, characterized by high temperatures, heavy rainfall, and high humidity throughout the year. Since modified bitumen have a lower penetration value than conventional neat 60/70 bitumen, these are less sensitive to temperature changes. Among the modified bitumen, CRMB performs best.
- **Softening Point:** The softening point of bitumen is a crucial property that reflects how the material behaves under temperature variations, especially in pavement applications. A higher softening point implies lower temperature susceptibility, meaning the bitumen is more resistant to softening in hot climates. At elevated pavement temperatures, bitumen can soften and lose its ability to hold aggregate in place. Thus, pavement experiences permanent deformation or rutting under traffic loads. Modified binders have attained higher softening point which provides reduced risk of pavement deformation, rutting and bleeding, especially in hot climates and can withstands greater temperature variations, making it suitable for extreme weather conditions. Among the modified binders, softening point temperature of CRMB is higher.
- **Flash & Fire Point:** The flash point of bitumen provides safety threshold during heating and the fire point indicates absolute upper limit for safe heating. Higher flash and fire points of modified bitumen provide safety during heating and application, eliminating the possibility of an

accidental fire. The PMB holds highest temperatures at flash & fire points.

- **Loss on Heating:** It is a critical test that measures the volatilization and oxidation of bitumen when subjected to elevated temperatures. The percentage loss in mass of bitumen after being heated (usually at 163°C for 5 hours) in a thin film oven represents the amount of volatile components (light oils) lost due to heat exposure, reflects how bitumen will behave during mixing, storage, and paving. Over time, bitumen hardens and becomes brittle due to oxidative aging, which is less likely to occur in modified bitumen that does not lose mass when heated. As no loss identified for modified bitumen, its utilization in pavement applications increases its lifetime and durability.
- **Elastic Recovery:** High elastic recovery in bitumen refers to the material's ability to recover its original shape after being deformed, such as when subjected to traffic loads. It offers the following benefits: fatigue resistance to prevent fatigue damage over time under repeated traffic loads; improved crack resistance to withstand stress and strain caused by temperature fluctuations or repeated loading; improved rutting resistance to resist permanent deformation under heavy traffic loads; and self-healing properties that gradually restore minor cracks and deformations. Compared with neat 60/70 bitumen, the ability of elastic recovery of modified bitumen are high. The greatest value of elastic recovery has shown by CRMB.
- **Stripping:** It refers to the loss of adhesion between bitumen and aggregate in an asphalt mix, usually due to the presence of water, leading to ravelling, potholes, and cracks. Water ingress leads to loss of cohesion, reducing the load-carrying capacity, results in premature deformation, particularly under repeated loading. The zero-stripping results of modified binders indicate good adhesion between bitumen and

aggregates in the presence of water, which is significant for road construction and pavement performance. In addition, it assures that bitumen will adhere firmly to the aggregates and withstand water penetration, lowering the possibility of water-related damage like ravelling or potholes.

- **Ductility:** Ductile bitumen can better accommodate the expansion and contraction caused by temperature changes in pavements, reducing the chances of cracks forming. It measures the ability of bitumen to undergo significant deformation or stretching without breaking under specific conditions. Though 60/70 bitumen and PMB represent the ductility value more than 100 cm, CRMB shows poor ductility result.
- **Loss of Mass in Thin Film Oven (TFO) Test:** The Loss of Mass in the Thin Film Oven (TFO) test is a critical indicator of the volatility and oxidative stability of bitumen during short-term aging. It measures evaporation of volatile components (e.g., light hydrocarbons). A high loss indicates the binder contains excessive volatiles, which may evaporate during heating and affect performance and lower mass loss correlates with better durability and resistance to early aging. This test simulates the hardening of bitumen that occurs during the mixing and laying process in hot mix asphalt. In TFO test, the loss of mass of modified binders are less than 1.00% on the other side 1.68% loss of mass has been identified for neat 60/70 bitumen.
- **Reduction in Penetration, Increase in Softening Point & Elastic Recovery of TFO Residue:** The neat 60/70 bitumen has lost its properties after TFO test which have been identified while conducting Reduction in Penetration, Increase in Softening Point and Elastic Recovery tests on the residue of TFO test. The neat bitumen does not satisfy the criteria specified in ASTM and AASHTO. However, the modified binders perform well.

Therefore, as compared to pure 60/70 bitumen, modified bitumen—specifically crumb rubber modified bitumen, or CRMB—has demonstrated the best performance, durability, and stability. This indicates that the introduce of crumb rubber improves several characteristics of the bitumen such as,

- Excellent Rutting Resistance: rubber increases elasticity, reducing permanent deformation.
- Improved Fatigue Life: rubber particles absorb stresses, delaying cracking.
- Reduced Temperature Susceptibility: CRMB performs well in both hot and cold climates which reduced possibility of thermal cracking.
- Better Aging Resistance: rubber slows oxidation and hardening.
- High Elastic Recovery: more elastic due to rubber content.
- Stripping Resistance: better adhesion between aggregate and binder.

4.2.6.1 Temperature Susceptibility of Binders

The bitumen's sensitivity to temperature fluctuations, which impact its mechanical and rheological characteristics, is known as the binder's temperature susceptibility. This is a crucial feature since it affects bitumen's performance on pavements, particularly in different climates. Bitumen softens, loses viscosity, and becomes more vulnerable to rutting (permanent deformation) at high temperatures. Bitumen becomes more brittle and stiffer at low temperatures, increasing its vulnerability to thermal cracking. Bitumen's resistance to rutting at high temperatures and thermal cracking at low temperatures is directly impacted by temperature susceptibility. Bitumen's temperature susceptibility is increased by adding materials like polymers, crumb rubber, and other modifiers, which make it more resistant to both high and low temperatures. Figure 4.3 displays the temperature sensitivity of plain

60/70 and modified bitumen (PMB & CRMB). Appendix A-1 displays the penetration value (ASTM D 5) of different bitumen at various temperatures.

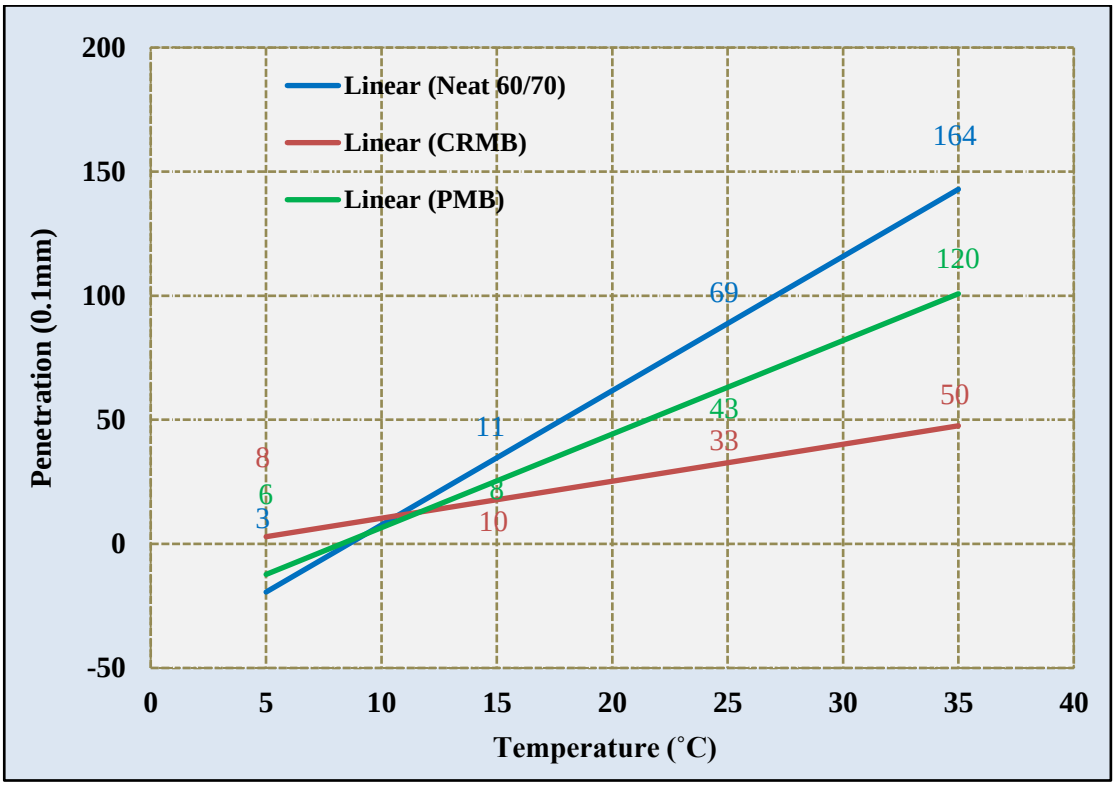


Fig. 4.3 Temperature Susceptibility of Various Binder

From the Fig. 4.3, when compared to unmodified bitumen, it has been found that polymer modified bitumen (PMB) and crumb rubber modified bitumen (CRMB) are less susceptible to temperature changes. This indicates that modified bitumen improves the bituminous mix's longevity and performance in pavement construction by decreasing thermal cracking and acting as a better binder. CRMB exhibits the best performance among modified bitumen.

4.2.6.2 Viscosity-Temperature Relationship of Binders

The Viscosity-Temperature Susceptibility (VTS) indicates the change in viscosity of the bitumen binder with temperature. Bitumen become less viscous (thinner) as temperature increases, while they become more viscous (thicker) as

temperature decreases. The viscosities in Pa-s at different temperatures (˚C) have been measured in the laboratory for both modified and unmodified bitumen to find the mixing and compaction temperatures of hot mix asphalt (HMA) for pavement construction. The viscosity vs. temperature relationship for Neat 60/70, PMB and CRMB binders are shown Fig. 4.4. The viscosity of Various Bitumen at Different Temperatures are shown in Appendix A-2.

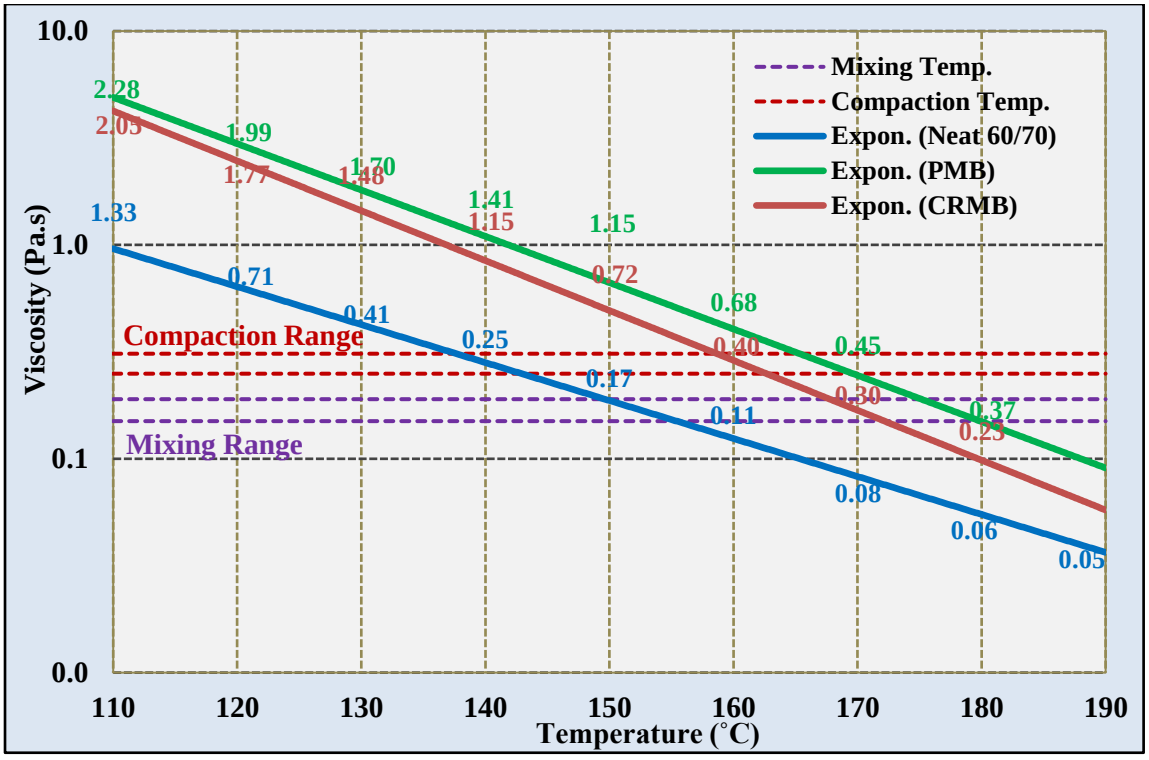


Fig. 4.4 Viscosity vs. Temperature Relationship of Various Binder

According to ASTM D 6926, the mixing and compaction temperatures for various binders found from the Fig. 4.4 (Viscosity - Temperature Relationship of Various Binder) which are shown in Table 4.3.

Table 4.3 Mixing and Compaction Temperature of Various Binders

Binder Name	Temperature (˚C) Range of HMA, ASTM D 6926	
	Mixing	Compaction
Neat 60/70 Bitumen	150 - 160	135 -145
PMB	175 - 180	160 - 170
CRMB	165 -175	150 - 160

4.3 MARSHALL METHOD OF BITUMINOUS MIX DESIGN

Among the five developed mix design methods, the Marshall Test is popular worldwide. Because of its simplicity and cost-effectiveness, performance predictability, standardization by ASTM D 6927 & AASHTO T 245 and global use it is a widely accepted and simple method for evaluating the strength and durability of asphalt mixtures used in road construction. In this investigation, 4%, 4.5%, 5%, 5.5%, 6%, and 6.5% by weight of binder content for both neat 60/70, PMB and CRMB have been applied to prepare the bituminous samples. The mechanical properties of these samples have also been determined. The work progress during preparation of bituminous mix and Marshall samples are shown in Fig. 4.5 and Fig. 4.6 respectively.



Fig. 4.5 Preparation of Bituminous Mix



Fig. 4.6 Marshall Samples before Testing

4.3.1 Determination of Marshall Properties

The Marshall test procedure has been followed to determine the Marshall properties of the samples prepared by both neat and modified bitumen. The bulk specific gravity, air voids (%), voids in mineral aggregate (VMA, %), voids filled with asphalt (VFA, %) have been calculated by the equations described in the article 3.7.3. The stability and flow test are conducted using a Marshall

Stabilometer (also known as a Marshall Test Apparatus), which applies load to a compacted asphalt specimen as shown in Fig. 4.7.



Fig. 4.7 Marshall Stability & Flow Testing

4.3.1.1 Marshall Properties and OBC for Neat 60/70 Bitumen

In this investigation, Marshall tests have been conducted in the laboratory for Neat 60/70 Bitumen to obtain the results of Marshall parameters. The results of Marshall parameters are shown in Table 4.4. The details of laboratory test data and determination of Marshall properties of the samples prepared by neat 60/70 bitumen at various binder contents are shown in Appendix B-1.

Table 4.4 Marshall Properties for Neat 60/70 Bitumen

Bitumen Content (%)	Bulk Spec. Gravity	Air Voids, Va (%)	VMA (%)	VFB (%)	Stability (kN)	Flow (mm)
4.0	2.38	6.11	13.25	53.91	17.48	1.51
4.5	2.39	4.99	13.34	62.61	18.31	1.67
5.0	2.40	3.87	13.43	71.18	21.11	2.92
5.5	2.39	3.56	14.24	74.97	17.30	4.05
6.0	2.38	3.27	15.03	78.27	16.50	5.77
6.5	2.37	2.87	15.89	81.94	15.00	7.80

The test results of various Marshall properties i.e., Stability, Flow value, Bulk density, % Air void, Void in mineral aggregate (VMA), Void filled with asphalt (VFA) found from experimental analyses are then plotted in graphs against different bitumen content as shown in Fig. 4.8.

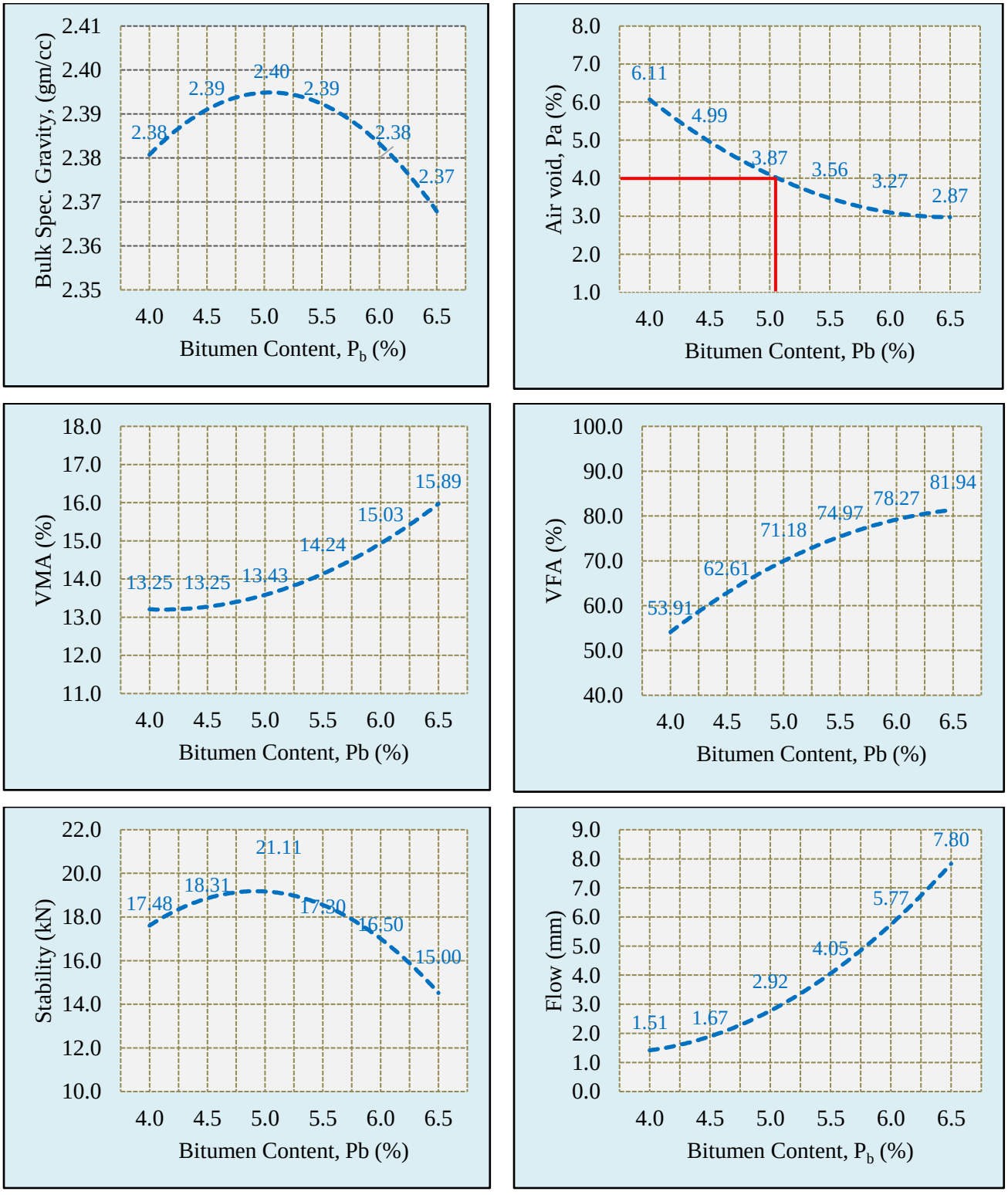


Fig. 4.8 Marshall Test Property Curves for Hot Mix Asphalt by 60/70 Bitumen

The Optimum Bitumen Content (OBC) has been determined at 4% air void from the Air void Vs. Bitumen content graph of Fig. 4.8. The OBC for neat 60/70 bitumen has been found 5.05%.

4.3.1.2 Marshall Properties and OBC for Polymer Modified Bitumen

In this investigation, Marshall tests have been conducted in the laboratory for Polymer Modified Bitumen (PMB) to obtain the results of Marshall parameters. The results of Marshall parameters are shown in Table 4.5. The details of laboratory test data and determination of Marshall properties of the samples prepared by polymer modified bitumen (PMB) at various binder contents are shown in Appendix B-2.

Table 4.5 Marshall Properties for Polymer Modified Bitumen

Bitumen Content (%)	Bulk Spec. Gravity	Air Voids, Va (%)	VMA (%)	VFB (%)	Stability (kN)	Flow (mm)
4.0	2.37	6.69	13.62	50.85	14.80	2.05
4.5	2.39	5.27	13.34	60.51	15.60	3.11
5.0	2.40	4.14	13.43	69.18	16.20	3.52
5.5	2.40	3.42	13.88	75.38	13.26	4.61
6.0	2.39	3.10	14.68	78.85	14.22	5.18
6.5	2.39	2.28	15.18	84.98	11.86	5.15

The test results of various Marshall properties i.e., Stability, Flow value, Bulk density, % Air void, Void in mineral aggregate (VMA), Void filled with asphalt (VFA) found from experimental analyses are then plotted in graphs against different bitumen content as shown in Fig. 4.9.

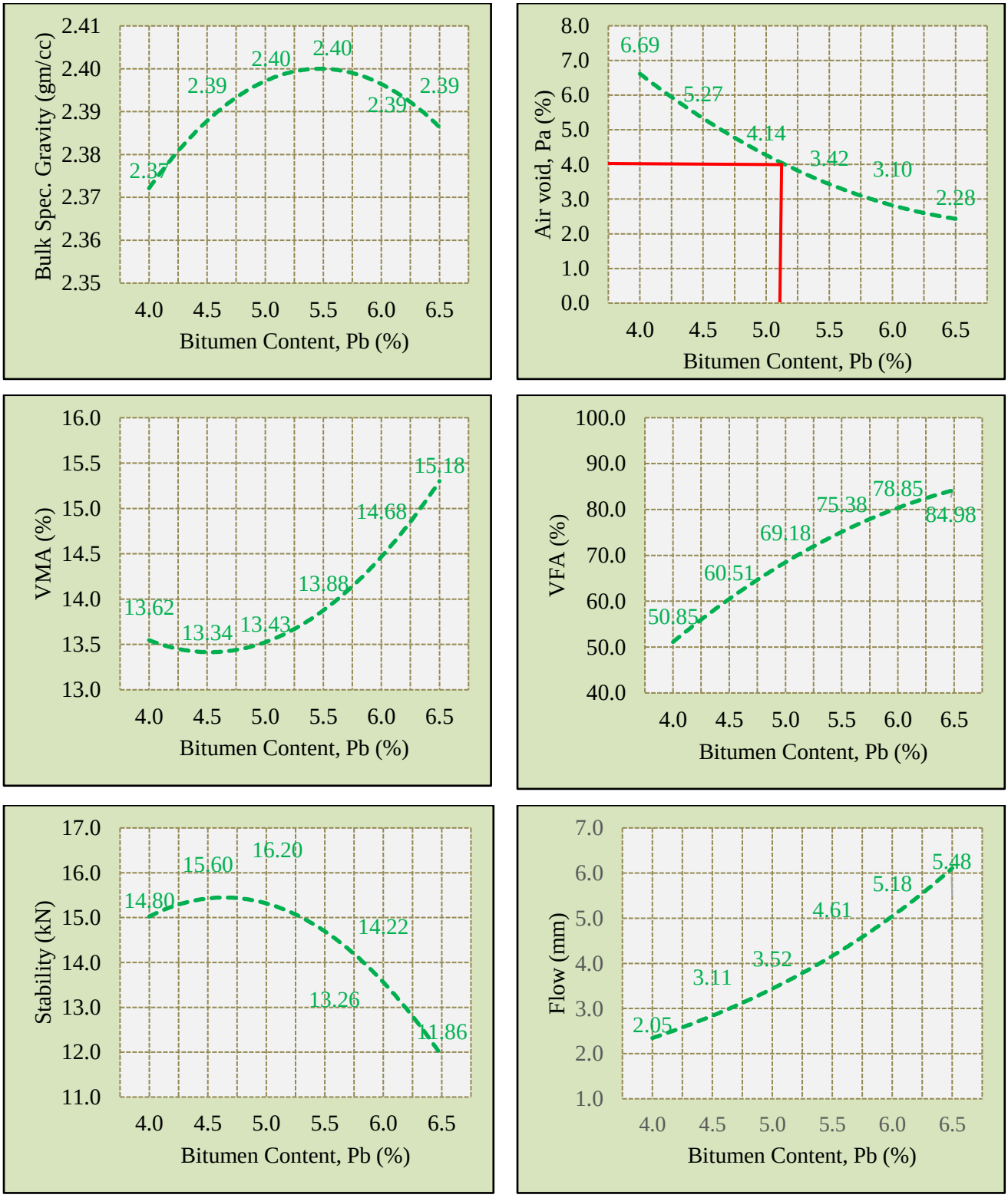


Fig. 4.9 Marshall Test Property Curves for Hot Mix Asphalt by PMB

The Optimum Bitumen Content (OBC) has been determined at 4% air void from the Air void Vs. Bitumen content graph of Fig. 4.9. The OBC for PMB has been found 5.10%.

4.3.1.3 Marshall Properties and OBC for Crumb Rubber Modified Bitumen

In this investigation, Marshall tests have been conducted in the laboratory for Crumb Rubber Modified Bitumen (CRMB) to obtain the results of Marshall parameters. The results of Marshall parameters are shown in Table 4.6. The details of laboratory test data and determination of Marshall properties of the samples prepared by crumb rubber modified bitumen (CRMB) at various binder contents are shown in Appendix B-3.

Table 4.6 Marshall Properties for Crumb Rubber Modified Bitumen

Bitumen Content (%)	Bulk Spec. Gravity	Air Voids, Va (%)	VMA (%)	VFB (%)	Stability (kN)	Flow (mm)
4.0	2.35	7.72	14.35	46.21	14.33	2.15
4.5	2.37	6.23	14.07	55.74	18.73	2.37
5.0	2.39	4.73	13.79	65.70	18.46	3.16
5.5	2.40	3.63	13.88	73.82	16.32	4.25
6.0	2.40	2.94	14.32	79.47	11.21	5.08
6.5	2.39	2.55	15.18	83.22	10.78	6.44

The test results of various Marshall properties i.e., Stability, Flow value, Bulk density, % Air void, Void in mineral aggregate (VMA), Void filled with asphalt (VFA) found from experimental analyses are then plotted in graphs against different bitumen content as shown in Fig. 4.10.

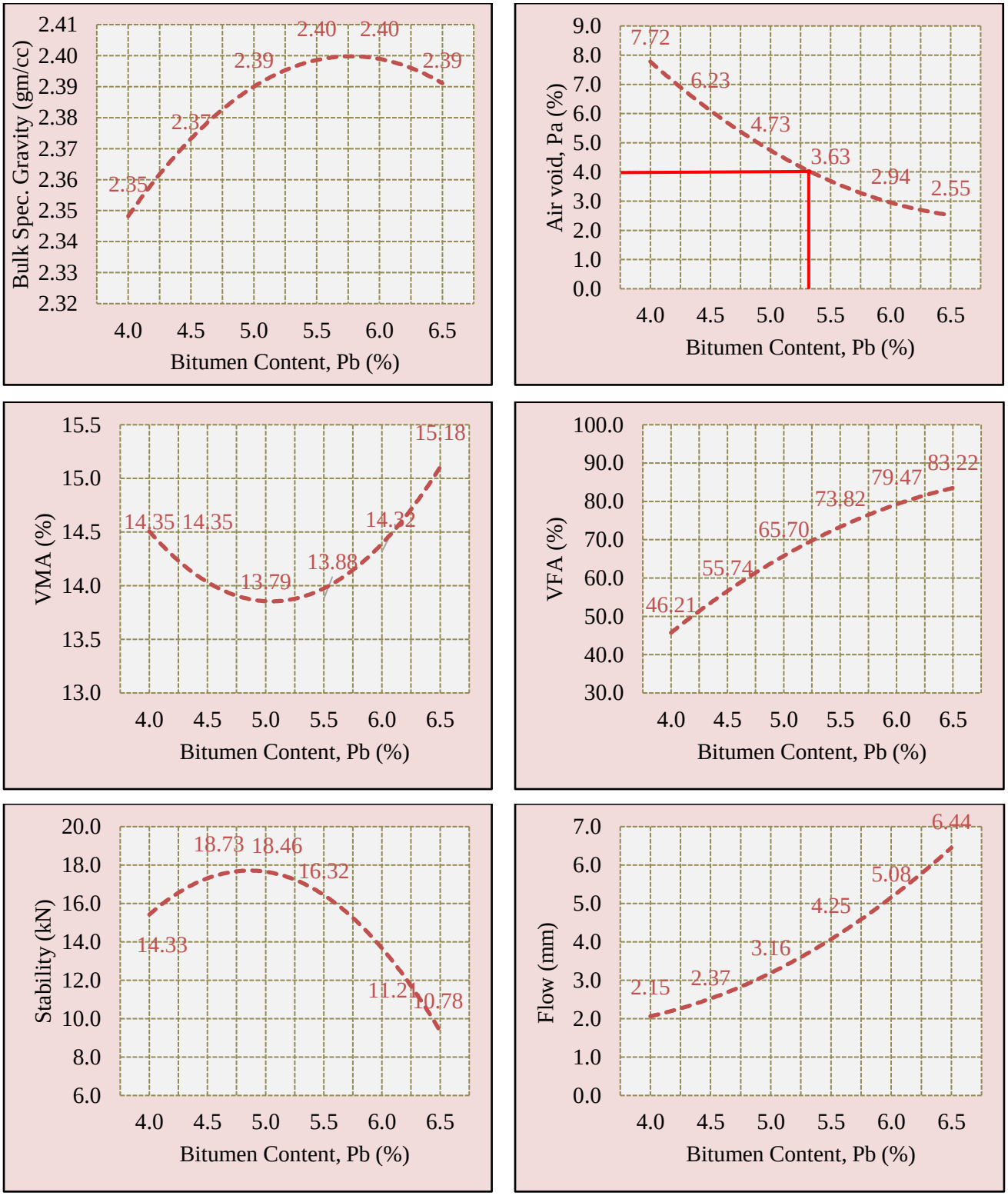


Fig. 4.10 Marshall Test Property Curves for Hot Mix Asphalt by CRMB

The Optimum Bitumen Content (OBC) has been determined at 4% air void from the Air void Vs. Bitumen content graph of Fig. 4.10. The OBC for CRMB has been found 5.30%.

4.3.2 Validation of Marshall Properties for Various Binders

The Marshall test samples are prepared using Marshall compaction method for heavy traffic road i.e., applying 75 blows on each side. It is essential to verify the Marshall properties of bituminous samples because these properties directly influence the performance and durability of asphalt mixes used in road construction. In this investigation, further, Marshall test samples have been prepared in the laboratory using optimum binder content (OBC) of Neat 60/70, CRMB and PMB to verify their Marshall properties with the pre-evaluated test results at OBC obtained from respective graphs. The comparative statement of test findings for both the neat and modified bitumen is shown in Table 4.7. The detail calculations are shown in Appendix B-4.

Table 4.7 Comparison of Marshall Properties at OBC for Various Binder

Marshall Properties	Neat 60/70 @ 5.05% OBC		PMB @ 5.10% OBC		CRMB @ 5.30% OBC		Marshall Criteria (Heavy Traffic, 75 Blows on each face)	
	From Graph	From Verification	From Graph	From Verification	From Graph	From Verification	As per MS-2, 2014	As Per RHD
Stability, kN	19.20	17.80	15.50	15.37	17.40	17.11	Min. 8	Min. 10
Flow, 0.25mm	3.00	3.80	3.90	3.98	3.70	3.96	2 ~ 4	3 ~ 4
Air Voids (%)	4.00	3.80	4.00	3.93	4.00	3.96	3 ~ 5	3 ~ 6
VMA (%)	13.80	13.36	13.60	13.34	13.85	13.62	Min. 13	Min. 13
VFA (%)	70.50	71.55	72.00	70.52	73.00	70.91	65 ~ 75	65 ~ 80
Bulk Density, gm/cc	2.395	2.400	2.398	2.402	2.396	2.399	-	-

The value of all Marshall parameters i.e., Stability, Flow, Bulk Density, %Air Voids, %VFA, %VMA for modified and unmodified bitumen are satisfy the criteria specified in MS-2, 2014 and RHD specification. The results of Marshall parameters for bituminous mixes produced at OBC show a variation of no more than ±10%. Therefore, it can be concluded that, OBC's of bitumen determined from respective graphs are acceptable. These OBC's in bituminous mixes provide an optimal balance between durability, flexibility, resistance to cracking, and stability.

4.4 BITUMINOUS MIX PERFORMACE

Bituminous samples are tested for moisture susceptibility test, which is also called the water sensitivity test, to see how well they can handle the damage that water can do. A bituminous mixture's sensitivity to moisture is commonly evaluated using performance tests known as the Retained Marshall Stability (RMS) and Tensile Strength Ratio (TSR) Indirect Tensile Strength (IDT) of both conditioned and unconditioned samples.

- The retained Marshall Stability refers to the percentage of stability of a sample that has been conditioned in a water bath at 60˚C for 24 hours, compared to that of the unconditioned sample. A greater retained stability denotes that the hot mix asphalt is less prone to moisture.
- Additionally, the Indirect Tensile Strength is measured for both conditioned and unconditioned samples to assess the Tensile Strength Ratio (TSR). The TSR represents the ratio of the tensile strength of the conditioned sample to that of the unconditioned sample. With a higher TSR grade, the likelihood increases that the combination will function effectively and resist water damage.

The arrangement of samples in water bath for water curing are shown in Fig. 4.11.



Fig. 4.11 Curing of Bituminous Samples in Water Bath

4.4.1 Retained Marshall Stability

The Retained Marshall Stability of Marshall specimens are measured in the laboratory according to ASTM D 1075 following a 24-hour curing period in a water bath set at 60˚C. Three samples are stored for 24 hours in a water bath at 60˚C, while the other three samples are kept at room temperature. After being gone through standard stability test of each mould, the results of Marshall Stability are then averaged. The results of retained stability of bituminous samples prepared from both neat bitumen and modified bitumen are shown in Table 4.8. The detail calculations are shown in Appendix B-4.

Based on the results shown in Table 4.8, it can be concluded that the retained Marshall stability of all bituminous mixes comprising of both neat and modified bitumen is satisfactory. The samples using PMB performs with highest retained

stability, and CRMB shows the result of retained stability higher than conventional bitumen. Higher retained stability of bituminous surface indicates

Table 4.8 Retained Stability of Various Bituminous Mixes

Name of Bitumen	Sample No.	Unconditioned Sample		Conditioned Sample		Retained Stability (%)	Standard Value (%) AASHTO T 165, ASTM D 1075 & RHD
		Stability (kN)	Avg. Stability (kN)	Stability (kN)	Avg. Stability (kN)		
60/70	1	16.77	17.80	12.96	14.07	79.05	≥75
	2	18.84		14.76			
	3	17.79		14.48			
PMB	1	13.78	15.37	14.23	14.23	92.58	
	2	16.95		13.47			
	3	15.38		14.97			
CRMB	1	17.94	17.11	16.26	16.25	94.97	
	2	16.28		15.45			
	3	17.10		17.04			

its better resistance to moisture damage (stripping), withstand traffic loads leading less rutting or deformation under heavy traffic, especially in high-temperature conditions, resistance to other distresses leading to better overall serviceability and user satisfaction. Among the

4.4.2 Indirect Tensile Strength

One indirect indicator of a flexible pavement's resilience to rutting issues and lower temperature cracking is its indirect tensile strength (IDT). The ASTM D 6931 specification is followed when performing this test in a lab. To assess the tensile properties of bituminous mixtures, a Marshall specimen is loaded along a diametric plane with a compressive force at a constant rate. This force acts parallel to and along the vertical diametrical plane of the specimen via two opposing loading strips. The compressive load indirectly creates a tensile load

in the horizontal direction of the sample. The peak load is recorded to obtain the indirect/split tensile strength. The tensile strength ratio (TSR), according to ASTM D 4867, has been determined from tensile strength of conditioned sample and unconditioned sample. The TSR of bituminous samples from both neat bitumen and modified bitumen are shown in Table 4.9. The detail calculations are shown in Appendix B-5.

Table 4.9 Tensile Strength Ratio of Various Bituminous Mixes

Name of Bitumen	Sample No.	Unconditioned Sample		Conditioned Sample		Tensile Strength Ratio, TSR (%)	Standard Value (%) ASTM D 6931, ASTM D 4867 & RHD
		Indirect Tensile Strength (kPa)	Avg. Strength (kPa)	Indirect Tensile Strength (kPa)	Avg. Strength (kPa)		
60/70	1	1291	1390	1162	1164	83.80	≥80
	2	1488		1254			
	3	1391		1077			
PMB	1	1404	1482	1416	1399	94.35	
	2	1561		1383			
	3	1481		1397			
CRMB	1	1336	1378	1317	1284	93.24	
	2	1419		1382			
	3	1380		1154			

According to the standard criteria specified in ASTM D 6931, ASTM D 4867 and the RHD specifications, the tensile strength ratio (TSR) of all bitumen mixes shown in Table 4.9 are acceptable. The samples having modified bitumen show higher TSR value and among the three type bitumen, polymer modified bitumen performs best. The TSR value is used to assess the moisture susceptibility of an asphalt mix i.e., its ability to resist damage from water infiltration. The bituminous mix is more resistant to moisture damage when its TSR value is higher. Specifically, it means the asphalt maintains a high

percentage of its strength even after being exposed to moisture. This implies that the mixture is resilient and less prone to problems like stripping.

4.4.3 Moisture Induced Damage

According to AASHTO T 283 the indirect tensile strength (IDT) is determined for conditioned and unconditioned sample to determine tensile strength ratio (TSR). Bitumen with a higher TSR value exhibits greater resistance to moisture-induced damage, including that caused by freezing and thawing conditions. The TSR of bituminous samples having freezing thawing condition from both neat bitumen and modified bitumen are shown in Table 4.10. The detail calculations are shown in Appendix B-6.

According to the standard value given in ASTM D 6931 and the RHD specification, the tensile strength ratio (TSR) of all bitumen mixes shown in Table 4.10 are acceptable.

Table 4.10 Tensile Strength Ratio of Various Bituminous Mixes having Freeze - Thaw Action

Name of Binder	Sample No.	Unconditioned Sample		Conditioned Sample		Tensile Strength Ratio, TSR (%)	Standard Value (%) AASHTO T 283 ASTM D 6931 & RHD
		Indirect Tensile Strength (kPa)	Avg. Strength (kPa)	Indirect Tensile Strength (kPa)	Avg. Strength (kPa)		
60/70	1	1045	1040	963	864	83.08	≥80
	2	1035		749			
	3	1041		881			
PMB	1	1116	1127	1030	1015	90.06	
	2	1138		1077			
	3	1126		938			
CRMB	1	1001	986	882	914	92.70	
	2	970		949			
	3	987		911			

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4.5 CONCLUDING REMARKS

The following findings can be stated from the experimental investigations:

- All testing standards have been correctly maintained throughout the experiment. The standard temperature has been maintained during mixing and compacting asphalt. The temperature of the water bath is also maintained properly as directed in ASTM, AASHTO specifications.
- The modified bitumen has been found to be less sensitive to moisture and temperature changes than clean 60/70 bitumen. It offers the following benefits: fatigue resistance to avert fatigue damage over time due to repeated traffic loads; enhanced crack resistance to endure stress and strain resulting from temperature changes or repeated loading; improved rutting resistance to resist permanent deformation under heavy traffic loads; and self-healing properties that gradually restore minor cracks and deformations.
- Furthermore, it reduces the likelihood of water-related damage like ravelling or potholes by guaranteeing that bitumen will stick securely to the aggregates and resist water penetration.
- The properties of Marshall samples using 60/70 bitumen, PMB & CRMB have been determined for different bitumen content ranging from 4.0% to 6.5% at intervals of 0.5%. The optimum bitumen content (OBC)'s of neat 60/70 bitumen, PMB & CRMB have been determined at 4% air voids, which are 5.05%, 5.10% & 5.30% respectively.
- The value of Marshall parameters i.e., Stability, Flow, Bulk Density, %Air Voids, %VFA, %VMA at OBC of modified (PMB & CRMB) and unmodified (60/70) bitumen have been satisfied the specifications specified in asphalt institute (MS-2, 2014) and RHD specifications. The

bituminous mixes produced at OBC have Marshall stability statistics that vary by no more than ±10%.

- The maintained Marshall stability and tensile strength ratio (TSR) results of water sensitivity studies of several bituminous mixtures have met the requirements outlined in AASHTO T 165, AASHTO T 283, ASTM D 6931, and RHD specifications. The results of modified bitumen (PMB & CRMB) are superior to those of neat bitumen, with CRMB demonstrating the greatest performance in the test for moisture-induced damage.
- Based on all the investigation results, it can be concluded that Crumb Rubber Modified Bitumen (CRMB) is the best binder in flexible pavement construction as it offers the best performance, durability, stability and longer service life in an economical manner.

Chapter 5: COST ANALYSIS OF ASPHALT MIX

This chapter begins with a general (section 5.1) discussion on cost analysis of asphalt mix. Section 5.2 constitutes a cost comparison of asphalt mixes using various bituminous binders. Finally, summary of this chapter concludes in section 5.3.

5.1 GENERAL

This chapter covers the outcomes of the various experiments and the laboratory activity. Polymer modified bitumen and neat 60/70 bitumen have been collected. Waste crumb rubber (CR) has also been collected and blended with neat 60/70 bitumen to prepare crumb rubber modified bitumen. Both the neat and modified bitumen have been used to make Marshall mix. The physical properties and optimum bitumen content of bituminous mix prepared by neat 60/70 bitumen, PMB and CRMB have been determined. Water sensitivity of various bituminous mixes have also been analysed. Eventually, cost analyses involved in production of bituminous mixes and construction of flexible pavements using different binders are required to be conducted to determine the suitable binder.

5.2 COST COMPARISON OF ROAD PAVEMENT

Beside the mechanical properties of bitumen, Marshall properties of HMA and water sensitivity analyses of bituminous mix, a cost comparison of per unit (1 Cum.) bituminous mix is necessary to identify a suitable bitumen in terms of cost-effective binder for more sustainable construction of road pavement. The primary goal of cost analysis of asphalt mixes is to choose the most cost-

effective option for pavement design, and construction in terms of their performance, durability, and sustainability factors. The material costs, labor and equipment cost for production and site compaction of HMA have been considered for evaluating cost of unit (1 Cum.) asphalt concrete for both neat bitumen and modified bitumen. The unit rates of required materials, production of HMA and compaction of asphalt mix are shown in Table 5.1.

Table 5.1 Unit Rate of Materials, Production and Compaction of HMA

Type of Item	Item Description	Unit	Rate (BDT)	Reference
Material	Coarse Aggregate (25 ~ 4.75mm)	1 cft	213	Table 3.4, BBS, Jun-24
	Fine Aggregate (4.75 ~ 0.075mm)	1 cft	65	Current Market Price
	Filler (0.075mm passing)	1 cft	14	Table 3.4, BBS, Jun-24
	Conventional Binder (60/70 Neat Bitumen)	1 M.ton	76,000	Bangladesh Petroleum Corporation, Jun-24
Material	Modified Binder (PMB)	1 M.ton	110,000	Bashundhara Oil and Gas Company, Apr-24
	Crumb Rubber (passing 0.30 mm sieve)	1 kg	60	Local Market, Chittagong, Price: Appendix C
	Blending of CR for Preparation of Modified Binder (CRMB)	1 kg	50	Based on Laboratory Work (assumed)
Production& Compaction of HMA	Equipment Cost	1 cum	660	Current Market Price
	Labor Cost	1 cum	105	Current Market Price

5.2.1 Requirement of Materials as per Job Mix Formula (JMF)

According to JMF, the materials required for the preparation of 1 Ton bituminous mixes by 60/70 penetration grade, PMB & CRMB binders have been presented in Table 5.2.

Table 5.2 Material required for Various Mixes as per JMF prepared with Various Binders

Materials per Ton HMA	Binders		
	60/70	PMB	CRMB
Coarse Aggregate (kg)	476	476	475
Fine Aggregate (kg)	428	427	427
Filler (kg)	48	48	47
Binder (kg)	48	49	51

5.2.2 Quantity of Materials Required for 1 Cum Bituminous Mixes

The required quantity of materials for the production of 1 Cum. of various bituminous mixes have calculated on the basis of JMF and presented in Table 5.3.

Table 5.3 Materials Required for 1 Cum. Bituminous Mixes

Materials per Cum.	Bituminous Mixes Prepared with (Unit Weight = 2.41 Cum/Ton)			
	60/70	PMB	CRMB	
Coarse Aggregate (M.ton)	1.147	1.147	1.145	
Fine Aggregate (M.ton)	1.031	1.029	1.029	
Filler (M.ton)	0.116	0.116	0.113	
Binder (M.ton)	0.116	0.118	CR (kg)	8.61
			60/70 (M.ton)	0.123

5.2.3 Cost Comparison of Different Bituminous Mixes

The neat 60/70 bitumen, PMB and CRMB are used as binder for preparation of three different types of bituminous mixes accordingly and an estimation has been made for 1 cum bituminous concrete to constitute a cost comparison among them. The cost of HMA's using various binders are shown in Table 5.4.

Table 5.4 Cost of Various Bituminous Mixes per Cum. using 60/70, PMB & CRMB Binders

Materials	Unit	Rate (BDT)	Bituminous Mixes Prepared with					
			60/70		PMB		CRMB	
			Qty.	Cost (BDT)	Qty.	Cost (BDT)	Qty.	Cost (BDT)
Coarse Aggregate	M.ton	7,520	1.147	8,625	1.147	8,625	1.145	8,610
Fine Aggregate	M.ton	1,430	1.031	1,474	1.029	1,471	1.029	1,471
Filler	M.ton	308	0.116	36	0.116	36	0.113	35
Binder (60/70)	M.ton	76,000	0.116	8,816	-	-	0.123	9,348
Binder (PMB)	M.ton	110,000	-	-	0.118	12,980	-	-
CR	kg	60	-	-	-	-	8.61	517
Equipment	Cum	660	1	660	1	660	1	660
Labor	Cum	105	1	105	1	105	1	105
Total Cost (BDT/Cum) of Asphalt Mix:				19,716		23,877		20,746

5.2.4 Cost - Benefit Analysis

From the above cost comparison of HMA shown in Table 5.4, using various binders, a cost – benefit analysis has been constituted as shown in Table 5.5 to identify the suitable binder in pavement construction.

Table 5.5 Cost - Benefit Analysis of Various Bituminous Mixes

Item Description	For Binders		
	Neat 60/70	PMB	CRMB
Construction Cost (BDT/Cum.)	19,716	23,877	20,746
Cost Increment (%) w.r.t. 60/70 Bitumen	-	17.22	5.22
Temperature Susceptibility	High	Medium	Low
Moisture Susceptibility	High	Low	Low
Performance & Durability	Low	High	High
Sustainability (based on test results)	Low	High	High

From the Table 5.5, it appears that cost of bituminous mix using modified bitumen become little bit higher than the neat 60/70 bitumen. It indicates the production cost get increased while using modified bitumen. However, modified bitumen shows much better performance and durability, not as sensitive to temperature and moisture as neat 60/70 bitumen which can be described as below:

- Temperature susceptibility of modified bitumen refers to the degree to which its physical properties, such as penetration, viscosity and stiffness, change with variations in temperature. Unlike 60/70 penetration graded bitumen, which becomes brittle at low temperatures and softens excessively at high temperatures, modified bitumen, incorporated with modifier like SBS or crumb rubber, exhibits improved thermal stability. These modifiers reduce the bitumen's sensitivity to temperature

fluctuations, resulting in better resistance to rutting in hot conditions and cracking in cold climates which in turns reduces maintenance and rehabilitation needs of pavements. Consequently, modified bitumen ensures enhanced performance and durability of pavements under a wide range of environmental conditions, making it particularly suitable for regions with significant temperature variations.

- Moisture susceptibility of modified bitumen refers to the binder's resistance to moisture-induced damage, which can significantly impact the durability and performance of asphalt pavements. Modified bitumen, enhanced with additives such as polymers or crumb rubber, generally exhibits improved resistance to moisture damage compared to unmodified binders. This improvement is attributed to the modified binder's better adhesion to aggregates and reduced permeability, which help prevent the stripping of the binder from the aggregate surface under wet conditions. A lower susceptibility ensures longer pavement life, reduced maintenance costs, and better performance under adverse environmental and traffic conditions.
- Modified bitumen exhibits enhanced performance and durability compared to conventional bitumen, making it highly suitable for modern pavement applications. By incorporating polymers such as SBS (styrene-butadiene-styrene), crumb rubber modified bitumen gains improved resistance to deformation, fatigue, and thermal cracking. This leads to better load-bearing capacity and longer service life, even under heavy traffic and extreme weather conditions. Its superior elasticity and flexibility allow pavements to withstand temperature fluctuations without deteriorating quickly. Additionally, modified bitumen enhances moisture resistance and reduces rutting and aging, resulting in reduced maintenance needs and overall lifecycle cost. These attributes make it a

preferred choice for high-performance and sustainable road infrastructure.

Thus, the asphalt pavement has a longer lifespan because asphalt mixes including modified bitumen are better able to withstand rutting, low temperature cracking, early aging and moisture induced stripping. Despite high initial cost of construction of flexible pavements using modified binders, because of its enhanced properties providing extended service period, modified bitumen may be a good choice as binder material for bituminous surface of the pavement. Out of two modified binders, CRMB exhibits lower cost in construction of bituminous surface and promotes sustainability by using waste material (CR) from the environment and conserving resources. Thus, CRMB might serve as an appropriate binder for constructing sustainable flexible pavements.

5.3 CONCLUDING REMARKS

The following findings can be stated from the cost analysis of asphalt mix:

- From the cost analysis of bituminous mixes in flexible pavement construction, it has been identified that production costs of asphalt concrete having PMB and CRMB are increased by 17.22% and 5.22% respectively with respect to neat 60/70 penetration grade bitumen.
- Although the cost of construction is higher, asphalt pavements by modified bitumen are more durable and sustainable due to their enhanced performance. The pavement surface built with modified bitumen has a longer life span than neat bitumen.

Chapter 6: CONCLUSION AND RECOMMENDATION

As outlined in the preceding chapters, please add a paragraph summarizing the chapter's structure at the beginning. Structure the chapter according to the study's objectives and the theoretical framework. Section 6.1 is the general discussion about this chapter. Previous chapter-based conclusions are shown in section 6.2 and section 6.3 represents the summary of conclusions. Finally, section 6.4 shows the limitations of the research and section 6.5 shows the recommendations for further study.

7.1 GENERAL

It is clear from the previous chapters that modified bitumen can significantly be utilized to construct pavement for high volume roads. The resources and methodology used for this inquiry are covered in Chapter 3. The results of various tests that are conducted in laboratory are displayed in Chapter 4. In chapter 5, an economic analysis is covered through the comparison among the costs associated with production, laying and compaction of various bituminous mixes. This chapter concludes by offering general conclusions about the work and making some suggestions for how to expand the future reach of this investigation.

7.2 CONCLUSIONS

An attempt has been made to improve the bitumen quality by mixing modifiers with the neat bitumen in order to reduce the imperfections in the roads, as conventional bituminous pavements in Bangladesh suffer from a

variety of flaws and are particularly susceptible to traffic loads, moisture damage, and temperature changes. Bangladesh produces a large quantity of non-biodegradable waste tires annually as a result of the country's fast growing automobile population, which poses a threat to the environment. Reclaimed crumb rubber (CR) has been gathered in order to combine it with regular bitumen to create Crumb Rubber Modified Bitumen (CRMB), which is environmentally friendly. In addition to CRMB, Polymer Modified Bitumen (PMB), which is used extensively throughout the world, has also been considered for further research as modified bitumen. The mechanical properties of various binders, Marshall properties and water sensitivity analyses of various bituminous mixes have been conducted to assess the efficacy and suitability of modified binder for flexible pavement construction in Bangladesh.

Based on the investigations and results presented in the previous chapters, the following conclusions have been reached.

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From the methodology chapter, the following conclusions can be drawn:

- An experiment specific work flow diagram has been established by which all the laboratory investigations are to be conducted to get necessary outcomes.
- ASTM & RHD specification of aggregate gradation for the bituminous surface course has been used in this investigation. An aggregate gradation chart is developed based on the specifications.
- The source of coarse and fine aggregates were Dubai, U.A.E and Sylhet, Bangladesh respectively. The aggregates are collected from Materials Laboratory of CUET.
- The stone dust was collected from the stone crusher of a government road project named “SASEC, Dhaka Sylhet Corridor Road Investment

Project" under Roads and Highways Department. The source of boulder stone using in crusher mill was from Meghalaya, India.

- The source of conventional 60/70 bitumen and polymer modified bitumen were Eastern Refinery Ltd., Chittagong and Dubai, U.A.E respectively. For this investigation, 60/70 penetration grade bitumen has been collected from Transportation Laboratory of CUET and The polymer modified bitumen (SBS PMB PG 70-40) has been collected form the bituminous surface treatment project named "Performance Based Operation of 4-Lane Dhaka-Chattogram National Highway (N1), Cumilla Part, Daudkandi to Dhumghat Bridge (Ch. 39+267Km to 165+183Km)" under Roads and Highways Department (RHD)
- The waste crumb rubber has been collected from tire retreading shop located at Kadamtali, Chattogram. For the preparation of crumb rubber modified bitumen (CRMB), neat 60/70 bitumen has been blended with waste crumb rubber powder that passes through a No. 50 sieve (0.30 mm) at a rate of 7% by weight. This is another variant of modified bitumen for the study.
- The Marshall method of bituminous mix design, which is one of the five mix design methodologies that is most commonly used worldwide, has been used to determine the Marshall properties, stability, flow, and optimum binder content of asphalt mix.

From the experimental investigation chapter, the following conclusions can be drawn:

- All testing standards have been correctly maintained throughout the experiment. The standard temperature has been maintained during mixing and compacting asphalt. The temperature of the water bath is

also maintained properly as directed in ASTM & AASHTO specifications.

- The mechanical characteristics of various binders indicate that modified binders are less susceptible to moisture and temperature fluctuations than 60/70 bitumen. They provide improved resistance to rutting, thereby averting permanent deformation from heavy traffic loads; enhanced resistance to cracking, capable of enduring stress and strain from thermal fluctuations or repeated loading; fatigue resistance, which stops fatigue damage from occurring over time due to repeated traffic loads; and self-repairing characteristics that enable the healing of small fractures and distortions as time passes. Moreover, it ensures that bitumen adheres firmly to the aggregates and withstands water intrusion, thus lowering the chances of water-related harm such as ravelling or potholes.
- The Marshall properties of various bituminous mixes using 60/70 bitumen, PMB & CRMB have been determined for different bitumen content ranging from 4.0% to 6.5% at intervals of 0.5%.
- The optimum bitumen content (OBC)'s of neat 60/70 bitumen, PMB & CRMB have been determined at 4% air voids and which are 5.05%, 5.10% & 5.30% respectively.
- For both modified and unmodified bitumen, the Marshall parameters (i.e., Stability, Flow, Bulk Density, %Air Voids, %VFA, %VMA) at OBC fall within the range given in MS-2, 2014, and the RHD specification. The bituminous mixes produced at OBC have Marshall stability statistics that vary by no more than ±10%.
- The Retained Marshall stability and tensile strength ratio (TSR) of several bituminous mixes in water sensitivity assessments have met the requirements outlined in AASHTO T 165, AASHTO T 283, ASTM D 6931, and RHD specifications. When compared to neat bitumen,

modified bitumen (PMB & CRMB) exhibits superior results. When it comes to water-sensitive circumstances, CRMB outperforms the other modified bitumen.

From the cost analysis of asphalt mix chapter, the following conclusions can be drawn:

- From the cost analysis of bituminous mixes in flexible pavement construction, it has been identified that production costs of asphalt concrete having PMB and CRMB are increased by 17.22% and 5.22% respectively with respect to neat 60/70 penetration grade bitumen.

Although the cost of construction is higher, asphalt pavements by modified bitumen are more durable and sustainable due to their enhanced performance. The pavement surface built with modified bitumen has a longer life span than neat bitumen.

7.3 SUMMARY OF CONCLUSIONS

The following is a summary of all the chapter-based conclusions:

- In Bangladesh, flexible pavements using conventional 60/70 bitumen show numerous types of defects in the roadway whereas CRMB reduces the possibility of pavement distresses as it provides enhanced properties.
- Based on the water sensitivity analyses, bituminous mixes prepared with CRMB achieves best performance which can be more sustainable in water prone area.
- The use of recycled crumb rubber (CR) in modification of conventional 60/70 promotes sustainability by reducing waste from the environment instead of looking for original sources.

- Though, initial costs of bituminous mix using modified binders are marginally high, yet it reduces the cost of repairs and maintenance of pavements due to its higher performance, durability and longevity. Crumb Rubber could be a cost-effective bitumen modifier as it is locally available. It can be a suitable alternative in reducing construction time and saving cost rather importing polymers.

Therefore, Crumb Rubber Modified bitumen (CRMB) is the suitable binder for sustainable flexible pavement construction in Bangladesh as it has shown best performance, durability, stability in comparison to both neat 60/70 bitumen and Polymer Modified Bitumen (PMB).

7.4 LIMITATIONS

While investigating bitumen modification, especially in the context of enhancing asphalt performance, the following limitations and challenges have been addressed:

- In this investigation, among the various modifiers, only SBS polymer and reclaimed CR as waste material were used for bitumen modification.
- The sieve No. 50 passed (0.30mm) particle size of waste crumb rubber (CR) was used in this experiment as sufficient amount of finer particles could not be gathered.
- A single percentage (7.0%) of CR was used for modification of conventional 60/70 bitumen.
- A simple cost comparison among the bituminous mixes of various binders was conducted where the Life Cycle Cost (LCC) analysis was required to be extensively studied.

7.5 RECOMMENDATIONS

The following is a list of recommendations for further research:

- In this investigation, waste crumb rubber was used as a bitumen modifier. Other waste materials should also be used for finding the effects on the bituminous mix properties.
- In this case, a particle of crumb rubber (CR) that had gone through no. sieve 50 size (0.30mm) was utilized only. Fine particles, which can pass through no. sieve 100, 200 etc., could be used in future research. Therefore, an appropriate and cost-effective grinding aid could be developed to have finer CR.
- Although 7% crumb rubber was employed in this inquiry, different percentages of CR could be used in future studies.
- A detailed life cycle cost analysis (LCCA) incorporating actual maintenance and rehabilitation cost can be carried out to establish actual net present value (NPV) of the bituminous mixes.
- Government should support bitumen modification with crumb rubber in pavement construction. This would encourage additional research into this topic.

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Appendices

Appendix A: [Test Data of Various Binders]

Table A-1: Penetration of Various Bitumen at Different Temperatures (ASTM D 5)

Temperature (˚C)	Penetration (0.1mm)		
	Neat 60/70 Bitumen	PMB	CRMB
5	3	6	8
15	11	8	10
25	69	43	33
35	164	120	50

Table A-2: Viscosity of Various Bitumen (ASTM D 4402)

Temperature	Neat 60/70		PMB		CRMB	
	Viscosity (cP)	Viscosity (Pa-s)	Viscosity (cP)	Viscosity (Pa-s)	Viscosity (cP)	Viscosity (Pa-s)
190˚C	46.15	0.05	--	--	--	--
180˚C	61.54	0.06	373.10	0.37	226.70	0.23
170˚C	80.77	0.08	453.80	0.45	301.90	0.30
160˚C	111.50	0.11	678.80	0.68	400.00	0.40
150˚C	167.30	0.17	1150.30	1.15	721.80	0.72
140˚C	253.80	0.25	1412.05	1.41	1146.00	1.15
130˚C	409.60	0.41	1704.20	1.70	1484.20	1.48
120˚C	705.80	0.71	1990.05	1.99	1771.50	1.77
110˚C	1333.00	1.33	2281.10	2.28	2054.00	2.05

Appendix B: [Test Data of Marshall Properties and Water Sensitivity Analyses of Various Bituminous Mixes]

Table B-1: Marshall Properties of Asphalt Concrete by Neat 60/70 Bitumen

% Bitumen in Total Aggregate	Sl. No.	Density - Void Analysis																Stability - Flow Analysis				
		Weight in Air (gm)	Weight in Water (gm)	SSD Weight in Air (gm)	Bulk Volume (cc)	Bulk Specific Gravity of the Compacted Mix (gm/cc)	Average Bulk Specific Gravity of the Compacted Mix (gm/cc)	Bulk Specific Gravity of Combined Aggregate	Theoretical Max Specific Gravity of Mix	Effective Specific Gravity of Combined Aggregate	Aggregate (Stone) Percent of Mix, Ps = 100-Pb	% Air Void Pa = 100*(Gmm-Gmb)/Gmm	Voids in Mineral Aggregate, VMA=100-(Gmb*Ps)/Gsb	Voids Filled with Asphalt, VFA=100*(VMA-Pa)/VMA	Absorbed Asphalt Percent by Total Weight of Aggregate, Pba=100*(Gse-Gsb)/(Gse*Gsb)*Gb	Effective Asphalt Percent by Weight of Total Mixture, Pbe=Pb-(Pba/100)*Ps	Fines to Asphalt Ratio, F/A=P200/Pbe	Stability kN	Avg. Stability (kN)	Flow mm	Avg. Flow (mm)
a	b	c	d	e	f	g'	g	h	i	j	k	l	m	n	o	p	q	J		K	
Pb					f = e - d	Gmb = c / f	Gmb(avg.)	Gsb = Gt	Gmm	Gse	k = 100-a	l = 100*(r-g)/r	m =100-(g*k)/h	n = 100*(m-l)/m	o = 100*(j-h)/(j*h)*Gb	p = a-(o/100)*k	q = P200/p	Y = 20.471 X + 0.7622			
4.00%	1	1147	670.60	1148	477.40	2.40	2.38	2.63	2.53	2.70	95.99	6.11	13.25	53.91	0.98	3.07	1.31	17.43	17.5	1.7	1.51	1.51
	2	1143	662.20	1145	482.80	2.37												18.1		1.50		
	3	1139	662.20	1140	477.80	2.38												16.9		1.33		
4.50%	1	1153	673.40	1154	480.60	2.40	2.39		2.52		95.49	4.99	13.34	62.61		3.58	1.33	20.00	18.3	1.05	1.67	
	2	1145	668.80	1147	478.20	2.39												17.46		2.26		
	3	1143	664.90	1144	479.10	2.39												17.48		1.7		
5.00%	1	1152	674.20	1153	478.80	2.41	2.40		2.50		94.99	3.87	13.43	71.18		4.08	1.16	19.67	21.1	2.21	2.92	
	2	1150	670.80	1151	480.20	2.39												20.19		3.33		
	3	1148	667.60	1149	481.40	2.38												23.48		3.21		
5.50%	1	1155	674.00	1156	482.00	2.40	2.39		2.48		94.50	3.56	14.24	74.97		4.57	1.03	17.95	17.3	4.09	4.05	
	2	1149	670.20	1150	479.80	2.39												16.75		4.37		
	3	1156	672.80	1157	484.20	2.39												17.21		3.68		
6.00%	1	1164	681.00	1165	484.00	2.40	2.38		2.46		94.02	3.27	15.03	78.27		5.06	0.93	16.36	16.5	4.45	5.77	
	2	1155	666.20	1156	489.80	2.36												16.67		6.75		
	3	1160	675.00	1161	486.00	2.39												16.48		6.11		
6.50%	1	1167	679.40	1168	488.60	2.39	2.37		2.44		93.46	2.87	15.89	81.94		5.63	0.83	15.06	15.0	8.42	7.80	
	2	1161	670.20	1163	492.80	2.36												14.66		6.36		
	3	1165	675.40	1166	490.60	2.37												15.28		8.62		

Table B-2: Marshall Properties of Asphalt Concrete by Polymer Modified Bitumen (PMB)

% Bitumen in Total Aggregate	Sl. No.	Density - Void Analysis																Stability - Flow Analysis			
		Weight in Air (gm)	Weight in Water (gm)	SSD Weight in Air (gm)	Bulk Volume (cc)	Bulk Specific Gravity of the Compacted Mix (gm/cc)	**Average Bulk Specific Gravity of the Compacted Mix (gm/cc)**	Bulk Specific Gravity of Combined Aggregate	Theoretical Max. Specific Gravity of Mix	Effective Specific Gravity of Combined Aggregate	Aggregate (Stone) Percent of Mix, Ps = 100-Pb	**% Air Void Pa = 100*(Gmm-Gmb)/Gmm**	**Voids in Mineral Aggregate, VMA=100-(Gmb*Ps)/Gsb**	**Voids Filled with Asphalt, VFA=100*(VMA-Pa)/VMA**	Absorbed Asphalt Percent by Total Weight of Aggregate, Pba=100*(Gse-Gsb)/(Gse*Gsb)*Gb	Effective Asphalt Percent by Weight of Total Mixture, Pbe=Pb-(Pba/100)*Ps	Fines to Asphalt Ratio, F/A=P200/Pbe	Stability kN	**Avg. Stability (kN)**	Flow mm	**Avg. Flow (mm)**
a	b	c	d	e	f	g'	g	h	i	j	k	l	m	n	o	p	q	J		K	
Pb					f = e - d	Gmb = c / f	Gmb(avg.)	Gsb = Gt	Gmm	Gse	k = 100-a	l = 100*(i-g)/i	m =100-(g*k)/h	n = 100*(m-l)/m	o = 100*(j-h)/(j*h)*Gb	p = a-(o/100)*k	q = P200/p	Y = 20.471 X + 0.7622			
4.00%	1	1134	659.21	1136	476.79	2.38	2.37	2.63	2.54	2.71	95.99	6.69	13.62	50.85	1.14	2.92	1.64	14.51	14.80	2.31	2.05
	2	1129	651.09	1130	478.91	2.36												14.67		1.85	
	3	1141	663.13	1143	479.87	2.38												15.22		2.00	
4.50%	1	1143	662.80	1144	481.20	2.38	2.39		2.52		95.49	5.27	13.34	60.51		3.43	1.39	17.69	15.60	3.28	3.11
	2	1123	653.40	1124	470.60	2.39												13.37		2.61	
	3	1152	675.00	1153	478.00	2.41												15.75		3.45	
5.00%	1	1152	674.40	1153	478.60	2.41	2.40		2.50		94.99	4.14	13.43	69.18		3.93	1.20	14.81	16.20	2.5	3.52
	2	1146	667.00	1147	480.00	2.39												17.10		3.46	
	3	1152	674.40	1153	478.60	2.41												16.69		4.59	
5.50%	1	1148	673.40	1150	476.60	2.41	2.40		2.48		94.50	3.42	13.88	75.38		4.42	1.07	13.35	13.26	4.1	4.61
	2	1154	675.80	1155	479.20	2.41												13.02		5.75	
	3	1150	668.60	1152	483.40	2.38												13.41		3.97	
6.00%	1	1158	674.40	1159	484.60	2.39	2.39		2.47		94.02	3.10	14.68	78.85		4.91	0.96	14.91	14.22	4.58	5.18
	2	1149	672.40	1150	477.60	2.41												13.47		5.6	
	3	1155	669.20	1156	486.80	2.37												14.27		5.35	
6.50%	1	1160	674.00	1161	487.00	2.38	2.39		2.45		93.46	2.28	15.18	84.98		5.48	0.85	12.41	11.86	6.45	5.48
	2	1158	671.40	1159	487.60	2.37												12.55		4.32	
	3	1161	681.80	1162	480.20	2.42												10.63		5.67	

Table B-3: Marshall Properties of Asphalt Concrete by Crumb Rubber Modified Bitumen (CRMB)

% Bitumen in Total Aggregate	Sl. No.	Density - Void Analysis																Stability - Flow Analysis			
		Weight in Air (gm)	Weight in Water (gm)	SSD Weight in Air (gm)	Bulk Volume (cc)	Bulk Specific Gravity of the Compacted Mix (gm/cc)	Average Bulk Specific Gravity of the Compacted Mix (gm/cc)	Bulk Specific Gravity of Combined Aggregate	Theoretical Max. Specific Gravity of Mix	Effective Specific Gravity of Combined Aggregate	Aggregate (Stone) Percent of Mix, Ps = 100-Pb	% Air Void Pa = 100*(Gmm-Gmb)/Gmm	Voids in Mineral Aggregate, VMA=100-(Gmb*Ps)/Gsb	Voids Filled with Asphalt, VFA=100*(VMA-Pa)/VMA	Absorbed Asphalt Percent by Total Weight of Aggregate, Pba=100*(Gse-Gsb)/(Gse*Gsb)*Gb	Effective Asphalt Percent by Weight of Total Mixture, Pbe=Pb-(Pba/100)*Ps	Fines to Asphalt Ratio, F/A=P200/Pbe	Stability kN	Avg. Stability (kN)	Flow mm	Avg. Flow (mm)
a	b	c	d	e	f	g'	g	h	i	j	k	l	m	n	o	p	q	J		K	
Pb					f = e - d	Gmb = c / f	Gmb(avg.)	Gsb = Gt	Gmm	Gse	k = 100-a	l = 100*(i-g)/i	m =100-(g*k)/h	n = 100*(m-l)/m	o = 100*(j-h)/(j*h)*Gb	p = a-(o/100)*k	q = P200/p	Y = 20.471 X + 0.7622			
4.00%	1	1141	658.20	1142	483.80	2.36	2.35	2.63	2.55	2.71	95.99	7.72	14.35	46.21	1.13	2.93	1.37	15.1	14.3	2.09	2.15
	2	1145	662.20	1147	484.80	2.36												14.2		2.20	
	3	1138	650.80	1140	489.20	2.33												13.7		2.15	
4.50%	1	1151	671.80	1153	481.20	2.39	2.37		2.53		95.49	6.23	14.07	55.74		3.43	1.39	19.45	18.7	2.31	2.37
	2	1146	662.40	1147	484.60	2.36												19.43		2.22	
	3	1142	657.10	1143	485.90	2.35												17.30		2.58	
5.00%	1	1153	672.40	1154	481.60	2.39	2.39		2.51		94.99	4.73	13.79	65.70		3.93	1.20	19.92	18.5	3.17	3.16
	2	1149	666.60	1150	483.40	2.38												18.38		3.12	
	3	1150	669.50	1151	481.50	2.39												17.09		3.18	
5.50%	1	1156	671.20	1157	485.80	2.38	2.40		2.49		94.50	3.63	13.88	73.82		4.43	1.07	17.15	16.3	4.61	4.25
	2	1154	676.10	1155	478.90	2.41												16.77		4.02	
	3	1158	676.60	1159	482.40	2.40												15.03		4.12	
6.00%	1	1163	682.00	1164	482.00	2.41	2.40		2.47		94.02	2.94	14.32	79.47		4.92	0.96	12.43	11.2	5.09	5.08
	2	1157	675.20	1158	482.80	2.40												11.77		5.15	
	3	1153	670.60	1154	483.40	2.39												9.44		5.01	
6.50%	1	1165	680.20	1166	485.80	2.40	2.39		2.45		93.46	2.55	15.18	83.22		5.48	0.85	11.57	10.8	6.13	6.44
	2	1159	676.20	1161	484.80	2.39												9.56		5.96	
	3	1160	673.40	1161	487.60	2.38												11.20		7.24	

Table B-4: Retained Marshall Stability (Immersion Test) at OBC for Various Bituminous Mixes
(Min. 75% as per RHD Specification, AASHTO T-165)

Bitumen	Specimen Subset	% Bitumen in Total Aggregate	Sl. No.	Density - Void Analysis																Stability - Flow Analysis				
				Weight in Air (gm)	Weight in Water (gm)	SSD Weight in Air (gm)	Bulk Volume (cc)	Bulk Specific Gravity of the Compacted Mix (gm/cc)	Average Bulk Specific Gravity of the Compacted Mix (gm/cc)	Bulk Specific Gravity of Combined Aggregate	Theoretical Max. Specific Gravity of Mix	Effective Specific Gravity of Combined Aggregate	Aggregate (Stone) Percent of Mix, Ps = 100-Pb	% Air Void Pa = 100*(Gmm-Gmb)/Gmm	Voids in Mineral Aggregate, VMA=100-(Gmb*Ps)/Gsb	Voids Filled with Asphalt, VFA=100*(VMA-Pa)/VMA	Absorbed Asphalt Percent by Total Weight of Aggregate, Pba=100*(Gse-Gsb)/(Gse*Gsb)*Gb	Effective Asphalt Percent by Weight of Total Mixture, Pbe=Pb-(Pba/100)*Ps	Fines to Asphalt Ratio, F/A=P200/Pbe	Stability kN	Avg. Stability kN	Retained Stability (%)	Flow mm	Avg. Flow mm
		a	b	c	d	e	f	g'	g	h	i	j	k	l	m	n	o	p	q	J			K	
		Pb					f = e - d	Gmb = c / f	Gmb(avg.)	Gsb = Gt	Gmm	Gse	k = 100-a	l = 100*(i-g)/i	m =100-(g*k)/h	n = 100*(m-l)/m	o = 100*(j-h)/(j*h)*Gb	p = a-(o/100)*k	q = P200/p	Y = 20.471 X + 0.7622				
60/70	Uncond.	5.05%	1	1146	671.00	1147	476.00	2.41	2.400	2.63	2.495	2.69	94.95	3.80	13.36	71.54	0.87	4.23	1.20	16.77	17.80	79.05	3.67	3.80
			2	1139	672.00	1148	476.00	2.39												18.84			3.93	
			3	1140	671.00	1146	475.00	2.40												17.79				
	Cond.	5.05%	1																	12.96	14.07		4.78	4.97
			2																	14.76			4.97	
			3																	14.48			5.16	
PMB	Uncond.	5.10%	1	1156	676.60	1157	480.40	2.41	2.402	2.63	2.500	2.71	94.90	3.93	13.34	70.52	1.14	4.02	1.27	13.78	15.37	92.58	4.43	3.98
			2	1153	672.00	1153	481.00	2.40												16.95			3.53	
			3	1151	670.80	1150	479.20	2.40												15.38				
	Cond.	5.10%	1								*									14.23	14.23		5.05	5.43
			2																	13.47			4.84	
			3																	14.97			6.41	
CRMB	Uncond.	5.30%	1	1159	676.80	1160	483.20	2.40	2.399	2.63	2.498	2.71	94.70	3.96	13.62	70.91	1.16	4.23	1.26	17.94	17.11	94.97	4.12	3.96
			2	1158	676.40	1159	482.60	2.40												16.28			3.80	
			3	1156	675.90	1158	482.10	2.40												17.10				
	Cond.	5.30%	1																	16.26	16.25		5.85	4.97
			2																	15.45			4.80	
			3																	17.04			4.26	

Table B-5: Indirect Tensile Strength (IDT) at OBC for Various Bituminous Mixes (Min. 80% as per RHD Specification, AASHTO T283, ASTM D 6931)

Bitumen	Specimen Subset	% Bitumen in Total Aggregate	Sl. No.	Specimens Dimension					Weight of Specimens in Air (gm)	Load at Failure, P (N)	Indirect Tensile Strength (kPa) St=2000*P/pi*D*t	Average Strength, St (kPa)	**Tensile Strength Ratio, TSR (%)**
				Thickness, t (cm)				Dia, D (cm)					
				t1	t2	t3	Avg. t						
		a	b	c	d	e	f=(c+d+e)/3	g	h	i	j	k	l
60/70	Uncond.	**5.05%**	1	5.90	6.10	6.00	6.00	10.00	1139	12165	1290.70	1390	**83.80**
			2	6.10	5.90	6.00	6.00	10.00	1131	14027	1488.35		
			3	6.00	6.10	6.00	6.03	10.00	1130	13175	1390.96		
	Cond.	**5.05%**	1	5.80	5.90	6.00	5.9	10.00	1134	10773	1162.37	1164	
			2	5.90	6.00	6.00	5.97	10.00	1140	11755	1253.53		
			3	5.90	5.90	6.00	5.93	10.00	1138	10036	1077.38		
PMB	Uncond.	**5.10%**	1	6.00	5.90	6.10	6.00	10.00	1133	13229	1403.64	1482	**94.35**
			2	5.90	6.00	6.00	5.97	10.00	1140	14642	1561.32		
			3	5.95	6.10	6.00	6.02	10.00	1142	14008	1481.36		
	Cond.	**5.10%**	1	5.90	5.90	6.00	5.93	10.00	1133	13188	1415.82	1399	
			2	5.90	5.90	5.90	5.90	10.00	1137	12820	1383.26		
			3	5.90	5.80	5.90	5.87	10.00	1130	12881	1396.99		
CRMB	Uncond.	**5.30%**	1	6.10	6.00	6.00	6.03	10.00	1134	12656	1336.15	1378	**93.24**
			2	6.000	6.000	6.000	6.000	10.00	1124	13372	1418.85		
			3	5.900	6.100	6.000	6.000	10.00	1128	13005	1379.87		
	Cond.	**5.30%**	1	5.90	5.70	6.00	5.87	10.00	1134	12144	1317.06	1284	
			2	6.10	5.90	6.00	6.00	10.00	1130	13024	1381.92		
			3	5.90	6.00	5.90	5.93	10.00	1128	10752	1154.29		

Table B-6: Moisture Induced Damage - Long-term Stripping Susceptibility (Freezing-Thawing Condition) at OBC for Various Bituminous Mixes (Min. 80% as per RHD Specification, AASHTO T283, ASTM D 6931)

Bitumen	Specimen Subset	% Bitumen in Total Aggregate	Sl. No.	Specimens Dimension					Specimens Volume (cc)	Avg. Specimens Volume (cc)	Volume of Air Void, Va (cc)	Weight of Specimens in Air (gm)	SSD Weight of Specimens in Air (gm)	Volume of Absorbed Water, J (cc)	Average Volume of Absorbed Water, J (cc)	Degree of Saturation, S (70% ~ 80%)	Load at Failure, P (N)	Split Tensile Strength (kPa) St=2000*P/pi*D*t	Average Strength, St (kPa)	Tensile Strength Ratio, TSR (%)
				Thickness, t (cm)				Dia, D (cm)			7% Air Void									
				t1	t2	t3	Avg. t													
		a	b	c	d	e	f=(c+d+e)/3	g	h	i	j = i*7%	k	l	m = l - k	n	o = n*100/j	p	q	r	s
60/70	Uncond.	5.05%	1	6.00	6.10	6.20	6.10	10.00	479.09	508.68		1142					10015	1045.21	1040	83.08
			2	6.10	5.90	6.20	6.07	10.00	476.74			1136					9872	1035.35		
			3	6.00	6.00	6.00	6.00	11.00	570.20			1135					10790	1040.78		
	Cond.	5.05%	1	5.90	5.90	6.00	5.93	10.00	465.74	474.64	33.22	1136	1160	24.00	25.00	75.26	8971	963.10	864	
			2	6.20	6.20	6.00	6.13	10.00	481.45			1143	1168	25.00			7214	749.20		
			3	6.10	6.10	6.00	6.07	10.00	476.74			1143	1169	26.00			8398	880.77		
PMB	Uncond.	5.10%	1	6.10	6.00	6.20	6.10	10.00	479.09	477.52		1152					10691	1115.72	1127	90.06
			2	6.10	6.10	6.00	6.07	10.00	476.74			1150					10854	1138.41		
			3	6.20	6.10	5.90	6.07	10.00	476.74			1148					10739	1126.30		
	Cond.	5.10%	1	6.00	6.20	6.10	6.10	10.00	479.09	481.71	33.72	1145	1170	25.00	25.00	74.14	9872	1030.26	1015	
			2	6.00	6.10	6.20	6.10	10.00	479.09			1155	1181	26.00			10322	1077.26		
			3	6.00	6.30	6.30	6.20	10.00	486.95			1142	1166	24.00			9135	937.97		
CRMB	Uncond.	5.30%	1	6.00	6.00	6.10	6.03	10.00	473.60	509.85		1135					9483	1001.16	986	92.70
			2	6.20	6.10	6.00	6.10	10.00	479.09			1145					9299	970.44		
			3	6.10	6.00	6.10	6.07	11.00	576.85			1141					10352	987.01		
	Cond.	5.30%	1	5.90	6.00	6.20	6.03	10.00	473.60	477.26	33.41	1151	1175	24.00	24.33	72.82	8357	882.29	914	
			2	6.20	6.20	6.00	6.13	10.00	481.45			1144	1169	25.00			9135	948.68		
			3	6.10	5.90	6.20	6.07	10.00	476.74			1148	1172	24.00			8684	910.83		

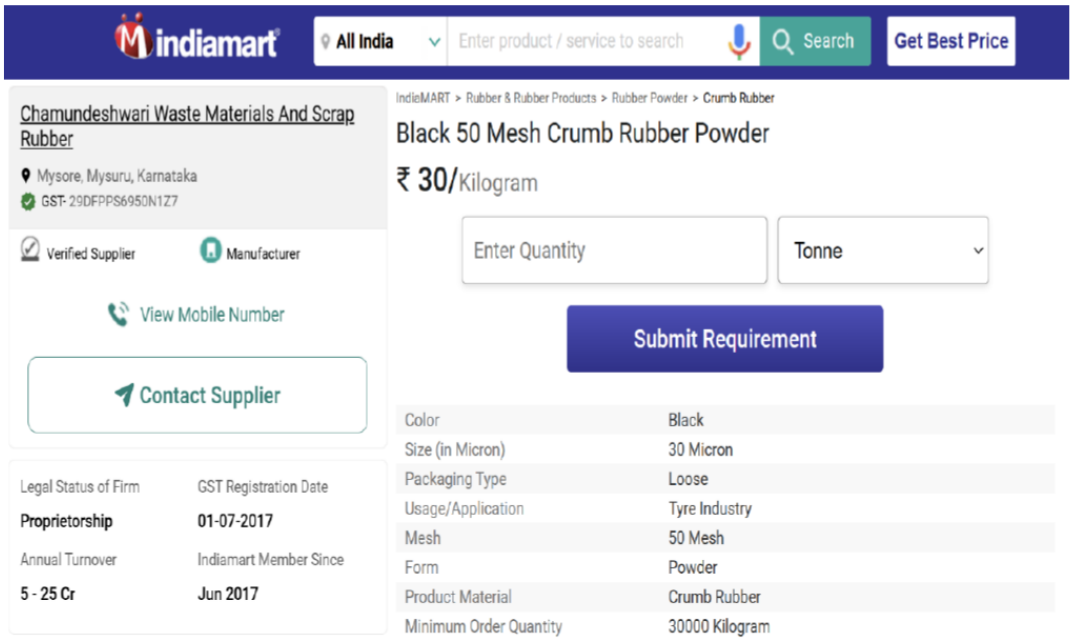
Appendix C: [Pricing of Crumb Rubber]

C-1: Price Calculation (including Custom Duty and Conveyance)

50 mesh (0.3mm) Crumb Rubber (CR) Price in India, (a)	= 30.00 INR/Kg [www.indiamart.com]
Crumb Rubber Price in BDT, (b) = (a)*1.41	= 42.30 TK/Kg [1 INR = 1.41 BDT in 2024]
Custom Duty (CD) to Import CR from India, (c) = (b)*31%	= 13.11 TK/Kg [CD = 31%]
Coveyance in Bangladesh, (d)	= 5.00 TK/Kg
Total Cost of 50 mesh Crumb Rubber, (e) = (b) + (c) + (d)	= 60.41 TK/Kg

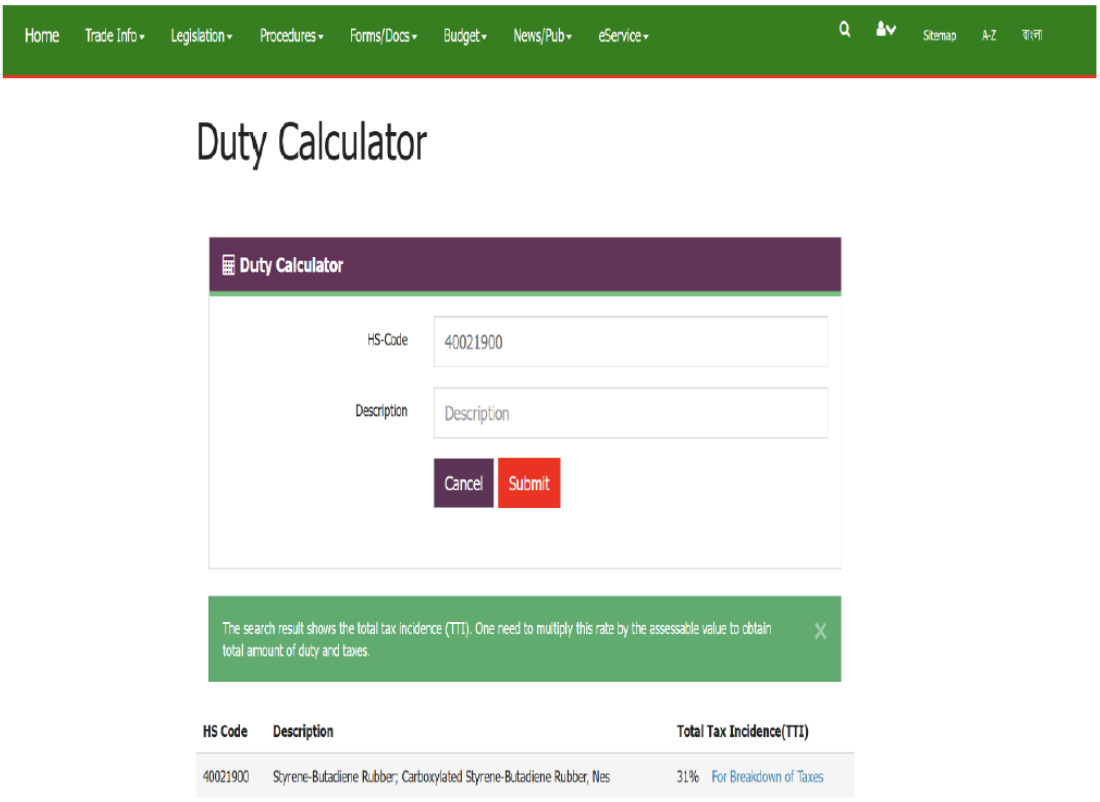
Say, 60.00 TK/Kg

C-2: Price of Crumb Rubber at Source (India)



C-3: Duty Calculator by Bangladesh Customs

https://bangladeshcustoms.gov.bd/trade_info/duty_calculator?hscode=03024910



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Crumb Rubber Modified Binder may More Sustainable than Other Binders for Pavement Construction in Rain Prone Area.

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Abstract- Flexible pavement gets less durable using conventional binders, whereas modified binders may provide higher performance, specially using waste crumb rubber modified binder (CRMB) in pavement construction. The CRMB was produced by incorporation of crumb rubber which was collected from discarded tires. This waste tires are increasing significantly with the increasing of vehicles day by day. With this era of strategy, an attempt has been tried to compare various binders like neat 60/70 bitumen, polymer modified bitumen (PMB) and CRMB in terms of their mechanical properties, Marshall properties and water sensitiveness. Mechanical property tests indicated that modified bitumen exhibit higher softening point, higher elastic recovery, lower temperature susceptibility and better resistance to stripping compared to neat bitumen. The performance of asphalt mixes at OBC prepared by neat 60/70 bitumen, PMB and CRMB were met the mix design criteria specified in the Marshall mix design approach. Both neat and modified bituminous samples undergone water sensitivity analysis. The retained stability of various bituminous mixes was found to be 79.0%, 92.6%, and 95.0% for the respective mixtures. The tensile properties of asphalt mixtures and their resistance to cracking, stripping due to frost and thawing action were also investigated by TSR based on moisture induced damage test and were found to be 83.1%, 90.1% and 92.7% for the bituminous mixes prepared by 60/70 bitumen, PMB, and CRMB respectively. Overall, the modified bitumen, especially CRMB, performed better than neat 60/70 bitumen as they are less susceptible to temperature variations and moisture, leading to reduced maintenance and hence the lifespan of pavement may increase. Therefore, taking into account both the performance and the environment, CRMB can be considered as sustainable alternative for durable and effective pavement construction in rain prone country like Bangladesh. Moreover, using CRMB in pavement construction, environmental hazard will be reduced to some extent.

Keywords – Flexible Pavement, Crumb Rubber, Water Sensitivity, Sustainable Development

I. INTRODUCTION

Nationwide connectivity is becoming a prerequisite for developing social, economic, industrial & cultural aspects of a country. So, a sufficient, sustainable, safe & efficient road network is very essential for rapid development of the same as it significantly reduces maintenance cost, vehicle operating cost, travel time cost etc. Approximately 90% of paved roads in Bangladesh are flexible pavements where bitumen is the main binding material on which pavement life is mainly dependent. However, conventional bituminous pavements in Bangladesh experience numerous types of defects which require frequent maintenance and are extremely vulnerable to traffic loading, moisture damage and temperature fluctuations. Thus, bitumen quality must be enhanced in order to minimize the imperfections in the roadways. Hence, an effort has been made to enhance the bitumen quality by adding modifiers with the neat bitumen.

In Bangladesh, vehicles are increasing approximately 0.5 million [1] per year with the increase of life standard, country development, economic zones, population and road network. Hence, every year, a significant amount (90,000 tons) [2] of non-biodegradable waste tires is produced in Bangladesh, out of which as major consumptions, 50,400 tons [3] are used in pyrolysis process to produce liquid fuel (Furnace Oil & Diesel). Remaining discarded tires, one of the main sources of municipal solid waste, may take up large space in the landfill, produce harmful gases, contaminates the soil, groundwater, and farmland, trap the rain water helps to propagate pests, specially mosquitoes, and many other environmental hazards if not properly recycled. Whereas it may be advantageous for