



**EXPERIMENTAL EVALUATION OF HOT MIX ASPHALT
MODIFIED WITH DIFFERENT ADDITIVES**

TAMANNA JERIN

(B.Sc. Engg., MIST)

A THESIS SUBMITTED FOR THE DEGREE OF MASTER OF
SCIENCE IN CIVIL ENGINEERING

**DEPARTMENT OF CIVIL ENGINEERING
MILITARY INSTITUTE OF SCIENCE AND TECHNOLOGY**

2020

The thesis titled “*Experimental Evaluation of Hot Mix Asphalt Modified with Different Additives*” submitted by Tamanna Jerin, Roll No: 1014110027 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering (Transportation) on July 09, 2020.

BOARD OF EXAMINERS

Lt Col Mohammed Russedul Islam, PhD

Associate Professor
Department of Civil Engineering
Military Institute of Science and Technology (MIST)
Dhaka 1216, Bangladesh

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Md. Hadiuzzaman, PhD

Professor
Department of Civil Engineering
Bangladesh University of Engineering and Technology (BUET)
Dhaka 1000, Bangladesh

Member
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I hereby declare that this thesis entitled “Experimental Evaluation of Hot Mix Asphalt Modified with Different Additives” submitted to the department of Civil Engineering, Military Institute of Science and Technology (MIST) in partial fulfillment of the requirement for the degree of Master of Science in Civil Engineering (Transportation), is my original work and it has been written by me entirely. I have duly acknowledged all the sources of information which have been used in the thesis. This thesis (fully or partially) has not been submitted for any degree in any other university or institute previously.

Tamanna Jerin

July 09, 2020

ACKNOWLEDGEMENT

All praise to Almighty Allah, the most beneficent and merciful who gave me enough courage and patience in this endeavor.

The author also expresses her humble gratitude to her supervisor, Lt. Col. Mohammed Russedul Islam, Department of Civil Engineering, MIST for his vital guidance, encouragement, suggestions and continuous support for a successful completion of the thesis.

Sincere thanks to the faculties and office personnel of MIST for helping with various suggestions, active cooperation during the research and also for allowing access to the resourceful libraries.

The author also acknowledges the cooperation of Nag Traders Limited for providing all the necessary materials as per requirement. This continuous supply of materials made all the experimental works more efficient.

Finally, the author would like to thank the inseparable part of her life, her beloved parents, her sister, her husband who endured this long process with her, always offered affectionate support and encouragement. Their patient love and sacrifice enabled the author to complete the study.

ABSTRACT

Premature failures, including the development of early cracks, potholes are the major causes of the high annual road maintenance cost of Bangladesh. Modification of traditional bitumen by different types of polymers could be an effective solution to reduce this huge maintenance cost of pavement. To incorporate this modification in the conventional flexible pavement of our country, this study investigated the effect of Pyrolysis Carbon Black (PCB) and Polypropylene (PP) on both bitumen and bituminous mix. Pyrolysis Carbon Black (PCB), an elastomer and one of the by-products of the scrap tire pyrolysis process, had been recognized as one of the most efficient modifiers in several studies. Being a waste product, modification of asphalt with PCB could contribute to waste management problems as well. 2%, 3%, 5%, 10% and 15% PCB of total bitumen content was used for modification. Another modifier used for modification was polypropylene (PP). For polypropylene, the percentages used were 1 %, 2%, and 3%. Based on the results of two individual polymers, two combinations consisting of both PP and PCB were prepared as well. To ensure a homogeneous blending, all the modified bitumen was prepared through the wet process by using a mechanical blending device. Penetration, softening point, ductility, specific gravity tests were performed on unmodified and modified bitumen for evaluating the physical properties. The penetration and ductility values showed a decreasing trend with increased polymer content for all types of modified bitumen. But an increasing trend had been observed in the case of a softening point. The mechanical properties of the bituminous mix

were investigated through Marshall, Indirect Tensile Strength (ITS) test. To investigate the resistance to moisture damage, the retained Marshall stability test was performed on some specific bituminous mix. The stability of the bituminous mix with 3% PCB was approximately 51% greater than that of the unmodified mix. In the case of PP modified bitumen, a 22 % increase was found in stability value for the incorporation of 3 % PP in neat bitumen. The stability of the two combinations of PCB and PP increased by 29% from that of the unmodified bituminous mix. Significant improvement was observed in retained Marshall stability and ITS value for polymer modification. The retained stability increased from 74% to 90% for a combination of 3% PCB and 2%PP. The highest ITS and retained Marshall stability was observed for combined modified bitumen consisting of 3% PCB and 2%PP. From this study, it was confirmed that modification of bituminous mixes with PCB and PP could decrease the premature failure problem of Hot Mix Asphalt (HMA) pavement to some extent by increasing resistance to moisture damage, high-temperature susceptibility, load-bearing capacity. The findings of this study would motivate the road agencies of the country to use the modified bitumen instead of conventional bitumen to enhance the performance of the flexible pavement.

Keywords: Pyrolysis Carbon Black, Polypropylene, waste by-product, scrap tires, Retained Stability, Indirect Tensile Strength

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LIST OF ABBREVIATIONS

LGED	Local Government Engineering Division
PMB	Polymer Modified Bitumen
PCB	Pyrolysis Carbon Black
PP	Polypropylene
RHD	Roads and Highway Division
ERL	Eastern Refinery Ltd
HMA	Hot Mix Asphalt
HDPP	High-Density Polypropylene
EVA	Ethylene-Vinyl Acetate
APP	Atactic polypropylene
EBA	Ethylene-Butyl-Acrylate
PE	Polyethylene
SBS	Styrene-Butadiene-Styrene
LLDPE	Linear low-density polyethylene
CRT	Crumb Rubber
CA	Coarse Aggregate
FA	Fine Aggregate
MF	Mineral Filler
OPC	Ordinary Portland Cement
ASTM	American Society for Testing and Materials,
BS	British Standard
ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
VMA	Void in the Mineral Aggregate

VFA	Void Filled with Asphalt
ITS	Indirect Tensile Strength
ACV	Aggregate Crushing Value

CHAPTER 1

INTRODUCTION

1.1 Background and Statement of the Problem

Over the last few decades, the pavement has developed rapidly all over the world, especially in developing countries. For the enhancement of a country's economic development, the communication system of that country should be developed. Therefore, the demand for full-fledged roads and highways is increasing day by day. Currently, Bangladesh has 22,324 km of road networks under the Roads and Highways Division of the Ministry of Road Construction and Bridges[1]. There is another 1,92,210 km of 'pakka' roads constructed by the Local Government Engineering Division (LGED) [1]. 95% of the pavements of Bangladesh comprises of bituminous pavement [2]. For fulfilling this huge demand for bitumen, every year the country needs around 4,10,000 tonnes of bitumen. 2,60,000 tonnes of bitumen can be supplied by Eastern Refinery Ltd (ERL) [1]. Previously, Eastern Refinery Ltd was the only state-owned company in our country. But recently in February 2020, with 9 lakh tonnes production capacity, Bashundhara Group has set up the country's biggest bitumen plant in Keraniganj, Bangladesh [3]. Therefore, bitumen may not be imported from outside the country in future.

Apart from the excessive demand for bitumen, another factor that makes flexible pavement inconvenient is the required amount of maintenance work. Fatigue, rutting, high temperature, submergence effect are the reasons behind the premature failure of these types of pavements [4]. Vehicle overloading, tropical monsoon climate and traditional construction practices cause different pavement distresses, including cracking, rutting, potholes in Bangladesh. The amount of rehabilitation work required due to these failures after every monsoon is massive [5]. According to the annual needs report of

RHD, the estimated cost for routine maintenance work of bituminous pavement is 4800 million Taka in 2018-19. In the 2019-20 financial year, it will increase up to 9300 million Taka [6].

To reduce the amount of rehabilitation work, bitumen property has to be improved. Previously several researches were undertaken to enhance the bitumen quality as well as to reduce the bitumen quantity. Polymer Modified Bitumen (PMB) has been found as one of the most efficient replacements of conventional bitumen from several studies [7]. A wide range of additives can be added into bitumen to enhance the quality of bitumen. Unfortunately, the number of researches in this topic is inadequate in our country. Previously few researchers investigated the effect of waste plastic, scrap tyres on bitumen properties [7].

Reduction of permanent deformation at high temperature and thermal and fatigue cracking at low temperature, improvement of thermomechanical resistance, elasticity and adhesivity could be made by the addition of polymers [8]. The mostly used polymers, which can modify bituminous properties, consist of elastomers (rubber or elastics) and plastomers (plastics). Among these polymers, elastomeric rubber is a byproduct of the ground tire [9]. The tire consists of several compounds, including natural and synthetic rubber, carbon black, metal, textile and additives [10]. The utilization of these compounds as modifiers could be a great solution to the premature failure of Hot Mix Asphalt (HMA) pavements. Statistics show that the development of the automobile industry leads to the production of 1,50,000 tons of scrap tires every year in Bangladesh [11]. In a developing country like Bangladesh, the disposal of this huge amount of non-biodegradable waste materials can cause a severe threat to the climate reservation. Among many recycling technologies, pyrolysis is a well-known method for recycling waste tires. Oils, carbon black, gases, and steel cords can be produced through pyrolysis (thermal breakdown in

the absence of oxygen) process. All of these components have the great potentiality of being recycled [12], [13]. Currently, Bangladesh has around 35 recycling plants that are capable of recycling 63,000 tons of scrap tires at least through the pyrolysis process [11]. Therefore, modification of the bituminous mix by using one of the byproducts of this process can be a great contribution to waste management as well as environmental pollution problems [12].

One of the by-products of the waste tire pyrolysis process, Pyrolysis Carbon Black (PCB), was used for modification of bitumen in previous researches [14], [15]. Some of the researchers found improvement in the rheological properties of bitumen by incorporating PCB as a filler material [16], [17]. Wang *et al.* (2019) showed the enhancement of rutting and ageing resistance by using several percentages of PCB with bitumen [18]. This compound was previously used to improve temperature susceptibility as well. Although PCB modified bitumen showed less susceptibility to low temperature for some percentages of PCB, the high-temperature susceptibility of this modified bitumen was found to be improved [19]. However, previous researches were focused on the properties of modified bitumen only. Therefore, this study was focused on the investigation of the properties of the bituminous mix with PCB modified bitumen.

Among plastomers, apart from the mostly used polyethylene, there are some other polyolefins, including polypropylene, ethylene-propylene copolymer and EVA copolymer [9]. The use of plastics, mainly polypropylene and polyethylene, in bituminous mixes enhance the durability and fatigue life of pavement [20]. The properties of the bituminous mix could be improved with the modification of bitumen by virgin polymers. Pavement distresses like rutting and cracking could be minimized by using the plastics as a modifier in the bituminous mix [21]. Therefore, the application of polymers could contribute to the extended life span of pavement [22]. Properties like improved

temperature susceptibility to high temperature and high stiffness, surface hardness and toughness at normal temperature, make the polypropylene a better choice for the modification of bituminous mix among all other plastomers [23]. Otuoze and Shuaibu (2017) showed that the strength and durability requirements of heavy traffic situations could be fulfilled by the intrusion of HDPP (High-Density Polypropylene) [24]. The widespread availability could be another reason due to which, and this could be considered a potential modifier [24]. Processing of this kind of polymer modified bitumen produces no toxic gases [25]. Therefore, the application of this type of plastomers has no adverse effect on the environment. Adequate research has not been done yet on the investigation of the physical properties of polypropylene modified bituminous mix.

Local Government Engineering Department (LGED) of Bangladesh has already constructed pilot trial pavement in three road sections during 2005-06 using crumbed rubber polymers manufactured by KK Plastic Waste Management Pvt. Ltd. Bangalore, India. Post-construction evaluation of one of the trial sections has shown 84%, 57% and 15% fewer Cracks, Depression and Raveling, respectively than the adjoining conventional construction [26]. Currently in some of the significant projects of Bangladesh such as “Approach road of The Kanchpur, Meghna and Gumti 2nd Bridges Construction and Existing Bridges Rehabilitation Project (II)”; “Cox’s Bazar Airport Project”, commercial polymers are being used.

1.2 Objectives of the Study

The specific objectives of the study can be summarized as follows:

- i. To investigate the effect of modifiers on the physical properties of bitumen.
- ii. To observe the effect of modifiers on the mechanical properties of hot mix asphalt

1.3 Scope of the Study

For this study, two polymers (PCB and PP) have been used for the modification of bitumen. The modifiers were blended with the bitumen in a thermostatically and mechanically controlled blending system. Several percentages of the polymers were prepared for the evaluation of the effect of polymer modification. Two combinations consisting of both PCB and PP were also prepared for analyzing the combined effect of polymer modification. A series of experiments including penetration, softening point, ductility, specific gravity was performed on polymer-modified bitumen. To evaluate the mechanical properties like Marshall stability and flow, indirect tensile strength hot mix asphalt was tested. To investigate the moisture resistivity, retained Marshall stability test was performed on the bituminous mix. At the end of the research, the optimum content of a polymer was found based on the obtained result.

1.4 Organization of the Thesis

In this research project work carried out is divided into different topics and presented in five chapters.

Chapter 1 of the thesis describes the background as well as the statement of the problem of the study. It also specifies the objectives of the study.

Chapter 2 of this thesis covers a review of recent and previous studies on polymer modified bitumen conducted at home and abroad. It also provides a detail description of the types of polymer, advantages and disadvantages of the polymer. The process of defining the compatibility of the polymer as a modifier is also discussed in this chapter. This chapter also highlights the detailed procedure for the application of polymer modified bitumen.

Chapter 3 describes the methodology of investigating the polymer-modified bitumen as well as HMA. In this chapter specifications of all tests are provided. It also

describes the materials used for the study. The detail specification of the mechanical stirrer is provided in this chapter.

Chapter 4 enumerates the result of the physical properties of both modified and unmodified bitumen. It also includes the mechanical properties result of HMA.

Chapter 5 provides the conclusion of the study. It also provides some recommendations for future studies on this topic.

At the end of chapter 5, all the references are provided. After that in the Appendix section, the raw data of the test results are provided.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the types of polymer and different blending mechanism will be discussed. Information related to the application of PMB in several countries is provided. The history of polymer modification, its benefits and drawbacks are also highlighted in this chapter. The polymer is not a new addition in the flexible pavement. For constructing and maintaining roads, PMB could be a great replacement for conventional bitumen. Many scientific researchers have already been performed on this topic. This chapter includes a review of the studies of several previous researches. At the end of the chapter, a summary will be provided to give an overview of this chapter.

2.2 Polymer Modified Bitumen (PMB)

Modified bitumen was introduced for commercial uses many years back. Incorporation of polymers in bitumen by mechanical mixing or chemical reaction is the polymer modification of bitumen [27]. The number of articles, published on polymer modification of bitumen, had been increased rapidly over the last 40 years, as researchers started to concentrate on this topic [28]. In previous researches, investigation on polymers included plastomers (e.g. polyethylene (PE), polypropylene (PP), ethylene-vinyl acetate (EVA), ethylene-butyl acrylate (EBA)) and thermoplastic elastomers (e.g. styrene-butadiene-styrene (SBS), styrene-isoprene-styrene (SIS), and styrene-ethylene/butylene-styrene (SEBS)) had been observed frequently [29]–[34]. However, none of these polymers was introduced initially for bitumen modification [28]. But over a few decades using of the polymer as a modifier of bitumen had been established as a trend in the pavement industry. It had been observed previously that some specific polymers have some similarity in behaviour to some constituents of bitumen. Due to similar characteristics,

some polymer, as well as copolymer had been used as a modifier for the improvement of the pavement quality [5]. In various researches, it was found that incorporation of these polymers in bitumen had been proven as an influencing factor for the improved properties of bitumen such as higher stiffness at high temperatures, higher cracking resistance at low temperatures, better moisture resistance or longer fatigue life [35]–[40]. Several researchers also observed minimization of the thickness of the pavement layer, e.g., surface, base with the incorporation of PMB [41], [42]. Because of these positive effects of polymer modification, many developed and developing countries are using PMB mixture extensively nowadays [43].

2.3 Polymer as a Modifier

Polymer can be defined as a synthetic or natural compound of normally high molecular strength made up of repeated, linked molecules [44]. Increasing resistance to permanent deformation at relatively high temperatures, without adversely affecting the properties of the bitumen at low temperatures is one of the key roles of bitumen modifier. Since polymers are viscoelastic material, this can be attained either by increasing the elastic component of the bitumen, thus improving its flexibility, or by stiffening the bitumen, and so reducing the total viscoelastic response. Instead, it is possible to achieve the same structural strength with a thinner layer of modified bitumen. Besides this, modification of bitumen can also improve two other characteristics of bitumen such as ageing and adhesivity [45], [46].

2.3.1 Types of polymer

Atactic polypropylene (APP), a waste by-product of polypropylene production, was one of the first used polymeric materials [47]. But later due to the introduction of new, high-yield units for propylene polymerization, this material was not produced anymore. A wide range of modifying polymeric materials have been investigated to use with bitumen used

in road construction over the last twenty years [48]. The mostly used polymers, which can modify bituminous properties, consist of elastomers (rubber or elastics) and plastomers (plastics). These two types of polymers are going to be discussed in the following section.

Plastomer is one of the most common types of polymers that have been used for pavement construction. Plastomers are slightly branched or linear. At the melting temperature, they deform in plastic or viscous manner and become hard and stiff at low temperatures [5]. Another important feature of these polymers is that they are recyclable. Plastomers cover a wide range of modifiers like polyethylene (PE), polypropylene (PP), ethylene-vinyl-acetate (EVA) and ethylene-butyl-acrylate (EBA) [9], [49], [50]. The structure of polypropylene is given in Figure 2.1. Presence of modifiers like plastomers could improve the rutting resistance at elevated temperature of conventional bituminous pavement. Plastomers could provide qualities of both elastomers and plastics.

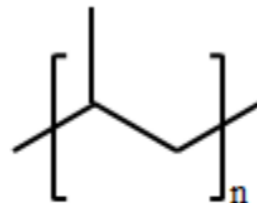


Figure 2.1 Structure of polypropylene

A polymer that has a flexible 'rubber' backbone and large side-chains in its structure is an elastomer. In case of this type of polymer, the molecular structure usually linear. However, the copolymers of this group have a radial form of the molecular chain. These polymers are usually more efficient than plastomers for bitumen modification. Elastomers like Styrene-Butadiene-Styrene (SBS), Styrene-butadiene- rubber are the most frequently used ones [9]. SBS has been observed as one of the most versatile modifiers for modifying bitumen [51], [52]. In previous researches, it has been proved

that the improvement of thermal cracking and fatigue resistance could be achieved by using SBS modified bitumen [9]. Crumb Rubber (CR) modified bitumen was observed to have improved resistance to permanent deformation and fatigue cracking at both low and high temperature [53], [54]. One of the by-products of the waste tire pyrolysis process, Pyrolysis Carbon Black (PCB), was used for modification of bitumen in previous researches [14], [15].

2.3.2 Advantages of PMB

To minimize road maintenance cost, pavements should be constructed with more durability. Polymer modified bitumen could provide greater stiffness as well as stability. PMB is not only advantageous in term of quality improvement of pavement but also cost-effectiveness. Moreover, the use of waste polymer is a great contribution to the waste management problem [7].

Different characteristics of bitumen can be improved by polymer modification. The viscosity of bitumen can be enhanced by polymer, which leads to greater film thickness in paving mixes without excessive drain down or bleeding. The modifiers can decrease distresses of pavement like cracking and dynamic deformation in the internal layers of pavements. Some of the polymers can also improve the mechanical property by increasing fatigue resistance. The physical property of bitumen like softening point becomes higher with the addition of polymer, which helps to reduce the bleeding at high temperature. Moreover, elasticity and resilience of bitumen can be enhanced at high temperature by polymer modification [7].

Due to the improvement of binder properties, some properties of flexible pavement get improved. Fatigue resistance, stripping potentiality get better due to polymer-modified bitumen. Therefore, polymer-modified bitumen can provide more durable pavement than conventional bitumen. Moreover, using waste polymer could

provide a great contribution to the recycling of waste material. This could lessen the dumping of the waste material in the landfill, water clogging in drain etc. Overall bitumen modification by waste polymer could be a great solution to the restoration of the environment.

2.3.3 Limitations of PMB

For all pavement problem, polymer modified binder is not the only solution. There are some other reasons as well behind the pavement failure. For a tropical country like ours, poor drainage condition is one of the main problems behind the huge road maintenance cost. Therefore, to achieve an optimum percentage of polymer for the improvement of pavement performance, it must be properly selected, designed, produced, and constructed. Besides huge advantages, PMB has some disadvantages as well. Many researchers found challenges like high cost, high-temperature sensitivity, low ageing resistance, poor storage stability and the limited improvement in elasticity while working with PMB. Limitations of PMB are discussed below.

PMB needs special equipment for the blending of polymer and bitumen. Transportation cost for carrying this equipment can be offset by increased service life, lower maintenance costs in case of a large project. But in the case of small projects, the same cost might result in an increment of the unit price of the project because of less demand for the material.

Because of specific mixing temperature requirement, sometimes construction of polymer modified bituminous road become more challenging. In the case of some polymer, air pollution due to melting could be a major issue. Because of high stiffness and coarser mixture gradation, polymer modified binders are often difficult to work with.

Storage stability is one of the major influencing factors of polymer modified bitumen. Sometimes in case of remote locations, it might get difficult to keep the material container properly sealed due to insufficient supply of equipment at the project location.

2.4 Compatibility of PMB

Homogenization of the polymer in bitumen and stability of the modified products are the major problems during the preparation and use of PMB. Hence, compatibility between polymer and bitumen must be maintained during storage and use. Since two components of PMB have different chemical structure and molecular masses, viscosities and densities, ensuring of compatibility is quite difficult [28]. The compatibility of polymer with bitumen depends on several factors. Besides the type of polymer used, it can also be affected by the polymer's structure, molecular weight and chemical composition. Characteristics, grade, source, constituents of base bitumen are another influencing factor of the compatibility of polymer with bitumen [5]. The incompatible polymer cannot be used for bitumen modification. Therefore, important criteria of compatibility need to be analyzed before the implication of PMB. Some of the criteria are going to be discussed in the following section.

2.4.1 Selection of potential modifier

The first stage of ensuring compatibility is the identification of the polymer as an effective modifier. In previous research, it was mentioned that the preparation and testing of several trial PMB is the key to ensure compatibility. In previous research by Al-Dubabe *et al.* (1998), several tests were performed on some specific polymers [55]. To blend the PMB, The researchers used a special blender, consisting of the shear blade, a heating oil bath and a DC motor capable of producing rotation up to 3000 rpm. To maintain the accuracy level, the manufacturer's recommended polymer concentration, blending time, blending temperature were used.

For the preparation of each PMB, 500 gm of base bitumen was used. Visual inspection using an optical microscope and softening point test was done to ensure the homogeneity of blending. After blending, storage stability test, shear modulus test, phase angle test, and softening point test were performed on the prepared blend. Besides, an economic analysis was also done on the blend. After obtaining the result from these tests, the appropriate polymers suggested by the researchers were PP (Polypropylene), LLDPE (Linear low-density polyethylene), SBS (Styrene-butadiene-styrene), CRT (Crumb Rubber). For these selected polymers, recommended temperatures by that study are given in Table 2.1 [55].

Table 2.1 Recommended blending temperature [55]

Polymer Type	Recommended blending temperature (°C)	Maximum blending temperature (°C)
LLDPE	160-170	200
PP	170-180	200
SBS	160-170	200
CRT	170-180	200

2.4.2 Factors affecting compatibility

The compatibility of polymer with bitumen may be affected by different parameters. The structural arrangement of the polymer particles, chains or groups within the asphalt matrix is one of the important factors for selecting compatible polymer. The storage stability is another important criterion. For having a compatible PMB, blending mechanism has a great influence. Summarization of the factors that can affect the compatibility of PMB is discussed below.

2.4.2.1 Blending of PMB

The blending of polymer modified bitumen is one of the most significant factors for selecting a compatible polymer. Some important factors of blending are blending process, blending temperature, blending time.

Two basic processes are generally used for modification of bitumen with polymer: Wet Process and Dry Process [56], [57].

Unlike the other process, the dry process won't require any special equipment for the blending of PMB. This process is generally used for bitumen modified with crumb rubber. In this process, recycled tyre rubber, consisting surface area of 1/2-1/8 inches and cubical, uniformly shaped cut is normally used. This material is blended dry into the asphalt mix. Gap graded aggregate should be used to allow for space for the 3% of rubber that is added. By limiting mixing time, the time at "reaction" temperature is limited. Therefore, in this way, the rubber can retain its integrity. Durable bond is created because of the interaction between asphalt and polymer [5].

For blending of polymer modified bitumen, wet process is the most common method. It is also named as the McDonald process. In this process, the polymer is directly added to bitumen using a low or high shear mixer. The shear mixer consists of a container, a mechanical stirrer with a shear blade and controlled heating facilities. Bitumen is then heated, and the polymer is added to it in some particular form. The stirring of this mixture should be continued for a homogenous blending. Blending temperature and time of the PMB depend upon the polymer used for modification [5].

Homogenous blending must be ensured while blending, as PMB is a complex two-phase system. Therefore, for uniform mixing, the high shear force is required. This shear force is determined by the configuration of the shear blade of the stirrer of the blender and the speed of the stirrer. However, some polymer might not require this kind of high shear force such as EVA and LLDPE [5].

A specific blending temperature is a prerequisite for uniform blending of PMB. The blending temperature is mainly decided based on the molecular weight of the polymer. High molecular weighed polymer needs higher blending temperature [58].

However, the temperature must be above the melting temperature. Basing on several researches, it has been observed that a temperature of 160-190 °C is adequate for blending of PMB.

Blending time is another important factor. It is dependent on the blending temperature, applied shear rate and the complexity of the polymer system. The blending temperature should be kept as minimum as possible. Rheological properties of bitumen could be changed due to the blending of PMB for excessive time.

2.4.2.2 Storage stability of PMB

Storage stability of PMB is another prime factor of compatibility. Storage stability of a polymer-modified bitumen can ensure the use of that PMB in future without changing its physical and chemical property. From previous researchers, it was observed that storing of PMB in high temperature had an adverse effect on the stability of blend, whereas storing in room temperature had a moderate effect. However, it was found that the cooling of PMB within minimum time could ensure the highest storage stability of PMB [7].

In previous research by Feng *et al.* (2016), the storage stability test was performed on PMB [19]. For this at first, PMB was poured in an aluminium foil tube of 32 mm diameter and 160 mm height. Then the tube was stored vertically at 163°C for 48 h. After that, the sample was left for cooling to ambient temperature. When the sample was completely cooled, the top and bottom portion of the tube was tested for determination of softening point test. The difference between the softening point of these two-location worked as an indicator of storage stability [19].

2.5 Previous Research Results of PMB

A huge number of researches have already been conducted on different types of polymers. However, in our country, only a few studies have been performed previously. Here in this section, some results of previous results are going to be discussed.

In Table 2.2, the effect of two types of PCB on the physical properties of modified bitumen is shown. Through the research, it was found that with the increase in PCB content, penetration, as well as ductility value, decreased. On the other hand, with the increased PCB content, the softening point increased. Therefore, the modified bituminous mix would be able to show better temperature susceptibility at high temperature than that of base bitumen [19].

Table 2.2 Physical properties of PCB modified bitumen [19]

Properties	SK#70	PCB-1 modified SK#70			PCB-2 modified SK#70		
	bitumen	bitumen			bitumen		
Content of PCB (%)	0	5	10	15	5	10	15
Penetration (25 °C, 0.1 mm)	62	60	59	53	56	52	46
Softening Point, °C	50.5	51.2	52.7	53.9	51.5	53.5	54.3
Ductility, (cm)	88.9	67.6	52.2	42.1	59.9	44.8	32.3
Viscosity (60 °C, Pa-s)	114.9	115.5	117.5	118.9	116.9	119.1	121.0

Table 2.3 shows that up to 6% addition of carbon black, the stability of hot mix asphalt increases with the increased pyrolyzed carbon black content. Increased stability could increase the adhesive properties of HMA due to modification of bitumen. Unacceptable distortion and displacement could be minimized because of this property. The same trend was observed in case of flow value and density as well [59].

Table 2.4 and 2.5 showed the effect polypropylene on the physical properties of modified bitumen. The results indicate that with the increment of polypropylene content, the penetration and ductility value is decreasing, whereas the softening value is increasing. Table 2.6 showed the increment of stability and density with increased polypropylene content [60].

Table 2.3 Modified Hot Mix Asphalt Marshall result [59]

Carbon Black (%)	Stability (N)	Flow (mm)	Density (kg/m ³)	% Air Voids
0	8000	3400	2350	2.75
2	8020	3455	2387	2.8
4	8120	3380	2408	2.65
6	8240	3360	2467	2.5
8	8205	3360	2509	2.20
10	8100	3315	2427	1.95

Table 2.4 Physical properties of Polypropylene modified bitumen [24]

Test Conducted	ASTM Code	Code Used	Test Result for *HDPP (%)						
			0	0.5	1.0	1.5	2.0	2.5	3.0
Penetration (25 °C, 0.1 mm)	ASTM D5	60-70	67.7	62.9	53.8	45.2	38.5	30.9	22.5
Softening Point, °C	ASTM D36	46-56	50.5	53.6	55.3	58.7	66.0	71.3	77.8
Ductility, (cm)	ASTM D113	Min 50	122.4	107.2	88.6	72.4	54.3	42.8	22.6
Specific Gravity at 25 °C (g/cc)	ASTM D70	0.97-1.02	1.022	1.015	1.011	1.008	1.005	1.003	1.001

*HDPP = High-Density Polypropylene

Table 2.5 Modified binder test result as per IS-1203 [61]

Polypropylene (%)	Penetration (25 °C, 0.1 mm)	Ductility, (cm)	Softening Point, °C
0	50	69	51
1	45	69	52
2	31	60	58
3	24	52	65

Table 2.6 Engineering properties of PP modified bituminous mix [60]

Description	Stability (kN)	Flow (mm)	Density (kg/cm ³)
Control Mix	12.64	2.3	2.38
1 % PP wet mix	15.38	3.01	2.35
2 % PP wet mix	17.03	3.2	2.26
3 % PP wet mix	18.82	2.86	2.39

2.6 Mix Design of PMB

Aggregate gradation, the maximum size of aggregate, wheel load and its frequencies and rheology of the binder are the factors on which mix design of HMA depends upon. Because of the change in viscosity, there might be a difference in mixing and compaction temperature of the modified and unmodified bituminous mix. Marshall mix design method for the polymer-modified bituminous mix is described shortly in the following section.

Similar aggregate gradation should be used for both modified and unmodified mix [7]. Based on the viscosity, each polymer has different mixing temperature. The mixing temperature should be maintained while mixing PMB and aggregate to preserve the rheological property of PMB. While heating the PMB, the binder should be stirred continuously to avoid any local over-heating. Mechanical mixing or vigorous manual mixing should be performed to ensure uniform mixing. The mixing of PMB and aggregate should be done within least possible time to ensure proper coating of aggregate with PMB. If the mixing couldn't be completed within the designated time, some adjustment like increment of binder content or increasing of mixing temperature should be made.

For a PMB mix, recommended compaction temperature is 135°C-150°C. While compacting, this temperature should be maintained strictly. After compaction, the specimen should be left for cooling to ambient temperature before extracting from the mold. The Marshall specimen should be experimented for the evaluation of its mechanical properties like Marshall stability, flow, air void, indirect tensile strength etc.

2.7 Construction Practice

PMB can be incorporated in new pavement construction as well as rehabilitation and maintenance of old pavement. PMB can be used as the replacement of conventional

bitumen. The construction practices that can be done with PMB are Hot mix pavement, Surface treatment, Crack and joint sealant [7].

2.7.1 Hot mix pavement

PMB is mainly used in hot mix pavement. Mc. Donald and Plus Ride technology are two widely used technologies for hot mix. These two methods are known as wet process and dry process respectively [7]. The technologies are described below.

Mc. Donald Technology was introduced by Charles Mc. Donald (1964), a material engineer of Arizona. This method consists of blending crumb rubber with bitumen and provides a modified mix design technique. This method is applicable to dense graded, open graded and gap graded aggregate mixtures. Aggregate gradation, rubber content in the binder and its rheological properties, i.e. viscosity, elasticity and softening point are the factors on which the binder content depends on. Higher polymer content creates thicker binder film around the aggregate.

Plus Ride Technology does not follow the conventional Marshall and Hveem method of mix design. In this process, the crumb rubber is directly added to a gap-graded aggregate before mixing with the bitumen. In the gap graded aggregate mix, coarse rubber particles act as elastic aggregate. It produces a more flexible and ice-debonding pavement surface. The process recommends a binder content of 7.5 % to 9 %. It also recommends that the maximum size of rubber should be less than ¼ inch.

2.7.2 Surface treatment

Road maintenance is another important sector, where PMB can be used. The surface treatment is one of the most significant parts of road maintenance. Pavement surface failure like cracking, bleeding, stripping can be lessened by using PMB [59], [61]. Through modification of bitumen with polymer, impermeability of surface course can be improved. This could ensure the minimization of water intrusion, which is the major

reason for pothole failure [5]. Therefore, PMB can not only reduce the maintenance cost but also increase pavement life.

2.7.3 Crack and joint sealant

To minimize the intrusion of water into the pavement, Crack Sealing is used. It is the placement of a mixture of a neat or modified binder, mixed with polymers, into existing cracks in the pavement. Since the water intrusion is impeded through crack sealing, there will be less erosion of the mix. Moreover, the development of crack will be slowed down. In the case of rehabilitation work, bitumen modified with rubber is widely used as a crack and joint sealant. For an effective crack sealing, the PMB must have the property of less temperature susceptibility and high elasticity to resist cracks that induced in the pavement at low temperature. In cold weather, the PMB should be flexible enough to keep pavement flexible. Modified bitumen consisting of high penetration grade as well as high polymer content, can satisfy both the requirement [7]. The factors on which the choice of sealant depends upon are the type of pavement, type of crack and joint, shape and size of the crack or joint and degree of pavement distress [59].

2.8 Application of PMB in Different Countries

Polymer modified bitumen had already been used in many countries due to its rheological and mechanical property. Many countries achieved longevity in their pavement by using PMB. Our neighbouring country India has around 33,796 kilometres plastic roads. Over the years, these roads have proven to be surprisingly durable and have yet to develop any potholes, rutting, ravelling or edge flaw. Some of the examples are given in Table 2.7. From this table, it has been observed that the road constructed with PMB showed really good performance after a certain period of time.

Table 2.7 Investigations on the actual long-term performance of field test sections with PMB [28].

Year investigated	Location of sites	Number of sites	Polymer information	In-service time before investigated	Conclusions	Reference No.
1990	USA, Canada and Austria	More than 30	Various polymers including PE, EVA, SBR and SBS	Less than five years	<ul style="list-style-type: none"> No significant difference was observed in performance between most test sections and the control ones. 	[62]
1993	USA	6	Various polymers including EVA, SBR and SBS	Various, no longer than 73 months	<ul style="list-style-type: none"> No distinctive pattern was found between the performance of modified and unmodified bitumen, nor among the performance of the same modified bitumen types when compared between different sections. 	[63]
1995	USA and Canada	20	Various polymers including LDPE, some unspecified polyolefin, EVA, SBR and SBS	Various, no longer than nine years	<ul style="list-style-type: none"> The lack of related information made it different to draw more than a couple of specific observations: EVA modification has a tendency for brittle behaviour as seen by the reports of premature cracking; and There were no consistent trends in rutting resistance for any of the reported modifiers. 	[64]
2001	India	1	Plastic waste bag	12 years	<ul style="list-style-type: none"> After twelve years, the road surface showed smoothness and uniformity in comparison with an unmodified road. Less rutting was observed as well. 	[65]

Table 2.7 Investigations on the actual long-term performance of field test sections with PMB [28].

Year investigated	Location of sites	Number of sites	Polymer information	In-service time before investigated	Conclusions	Reference No.
2002	USA	1	Various polymers including LDPE, SBR and some styrene-butadiene block copolymers	11 years	<ul style="list-style-type: none"> • For most test sections, the use of PMB did improve the field cracking resistance over the unmodified bitumen. However, LDPE increased the brittleness of the bitumen and mixture, leading to extensive cracking. • Bitumen modification is not necessary to control rutting. Properly designed and constructed mixture can perform under heavy traffic without rutting. 	[66]
2007	Switzerland	16	Various polymers including PE, EVA, SBS and EPDM	19 years	<ul style="list-style-type: none"> • After 14 years, PMBs showed some improved performance. Especially, one section with SBS modified bitumen showed great cracking resistance. However, one section with base bitumen performed as well as some PMBs. • After 19 years, the crosslinked polymer modified bitumen showed very good durability. 	[67], [68]
2011	Canada	7	Various polymers including SBS, SB and RET	8 years	<ul style="list-style-type: none"> • Bitumen modified with RET and PPA performed as desired, without virtual crack after eight years of service. • One of the two SBS modified bitumen sections cracked at a moderate amount, 	[69], [70]

Table 2.7 Investigations on the actual long-term performance of field test sections with PMB [28].

Year investigated	Location of sites	Number of sites	Polymer information	In-service time before investigated	Conclusions	Reference No.
					<p>with intermittent full-width transverse cracks of moderate severity.</p> <ul style="list-style-type: none"> • The remaining sections all experienced severe and excessive distress, with numerous longitudinal and transverse cracks. 	

2.9 Possibility of PMB in Bangladesh

The maximum number of pavements in our country are flexible pavement. This kind of pavements faced different kind of distresses every year because of the moisture effect, poor drainage condition, poor workmanship, material quality etc. A single type of failure could lead to the deterioration of roads. The identified deteriorations for flexible pavements are pothole, ravelling, alligator cracking, polished aggregate, bleeding, upheaval, depression, transverse cracking, longitudinal cracking, edge cracking [71]. Since properties of polymer modified bitumen could increase rutting resistance, fatigue resistance, impermeability, etc., these distresses could be minimized to a certain extent through bitumen modification [72]. Therefore, the use of PMB could be proved beneficial in case of our country.

2.10 Summary

The literature review provided a brief description of polymer modified bitumen. In this chapter, it has been observed that the improved physical, rheological and mechanical properties of PMB could minimize different types of failure. Application of PMB in different countries has also been discussed in this chapter. However, few studies have been observed on the potentiality of reducing drainage induced pavement failure. Based on the previous study, a guideline has been given for using PMB in the bituminous road in this chapter. Different important factors of the blending of PMB has also been discussed here.

CHAPTER 3

METHODOLOGY

3.1 Introduction

For the improvement of pavement quality, many countries are using modified bitumen for a very long time. But in our country, this material has not been used by road agencies yet. To make the use of the modified bitumen, extensive research has to be done in this field. In our study, two polymers have been used for the modification of bitumen. To evaluate the compatibility of these materials with a bituminous mix, physical as well as mechanical properties of this material should be assessed. In this chapter, materials, material collection, the experimental setup of these modified bitumen is discussed. Moreover, the description of the test method of bitumen and the bituminous mix is described briefly. Figure 3.1 indicates the chronological development of the methodology.

3.2 Collection of Material

Properties of bitumen play an essential role as a binder in the performance of the flexible pavement. Moreover, a good source of aggregate could ensure an effective interlocking between bitumen and aggregate. Therefore, the source of bitumen and aggregate is significant to ensure the longevity of the pavement. Two types of polymers have been used as modifiers in this study. A short description of the properties of these mentioned materials will be discussed in the following section.

3.2.1 Bitumen

Bitumen is an amorphous, solid, semi-solid or viscous, cementations substances, natural or manufactured, generally composed without limitation of high molecular weight hydrocarbons, as naturally found in asphalts, tars, and pitches. Bituminous materials are a by-product of petroleum or crude oil. Whether the composition is made of coal, coal tar

pitched, crude oils, and natural asphalts depends upon the geological origin and/or geographical source. Therefore, the physical characteristics of natural and manufactured bituminous material differ significantly from one another. Because of the diversity in the characteristics of bituminous material, it is considered as one of the most widely used pavement materials in the case of road construction [5].

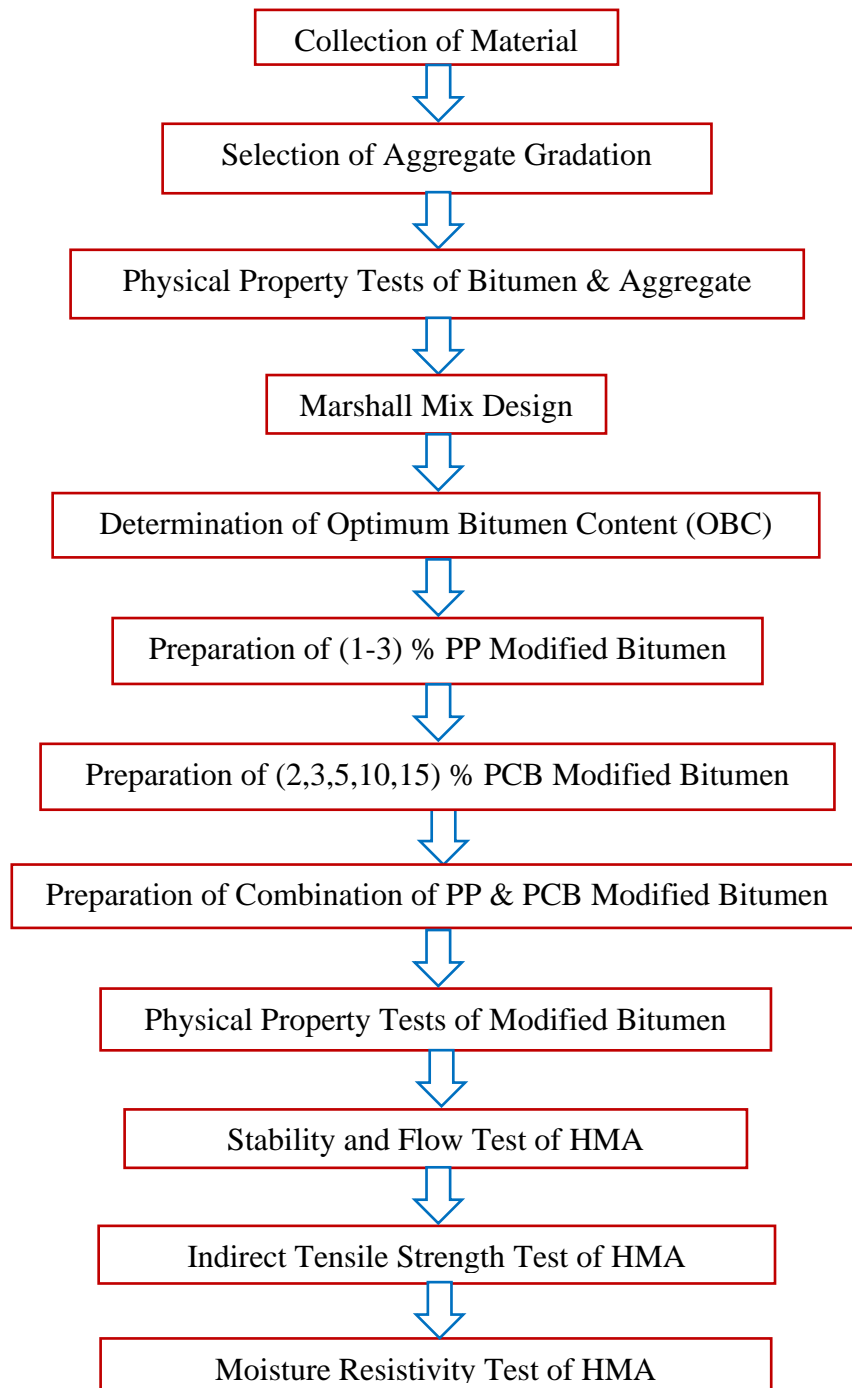


Figure 3.1 Flow chart of the methodology



Figure 3.2 60/70 grade bitumen

Bitumen is used as a binder with aggregate in the case of Hot Mix Asphalt (HMA). Crude source, refining process, and chemical composition are some important information on which the quality of bitumen depends on. The compatibility of bitumen with the polymer can be affected by the chemical composition of bitumen. Although the grade is not an indicator of the quality of bitumen, it is designated generally by "grade." Usually, 60/70 and 80/100 grade bitumen is widely used in the pavements of Bangladesh. For this study, the 60/70 grade bitumen (Figure 3.2) was used. Eastern Refinery, Chittagong supplied it. Several physical property tests were performed on neat bitumen like penetration, softening point, ductility, and specific gravity.

3.2.2 Aggregate

One of the prime ingredients of pavements construction is aggregate. In the case of flexible pavement, aggregates are used as granular base course, sub-base course, and surface course in bituminous concrete. Properties of asphalt mix can be significantly influenced by the physical properties (i.e., gradation) as well as mechanical properties (i.e., hardness, toughness, durability) of aggregate.

The amount of aggregate required for preparing a compacted specimen of 63.5 ± 1.27 mm height is sufficient for one sample. Usually, 1200 g of aggregate is used for one compacted sample. A trial sample should be prepared by compacting 1200g aggregate with optimum bitumen content to ensure the height requirement. Aggregate gradation is

an essential factor for the Marshall mix design. In this research, the same gradation of aggregate was used for both neat bitumen and Polymer Modified Bitumen (PMB) to make a significant comparative study. The physical properties of Coarse Aggregate (CA), Fine Aggregate (FA), and mineral filler are presented below.

Coarse aggregate consists of crushed stone, crushed gravel, or crushed boulder. It is the aggregate, which is 25mm passing as well as 2.36 mm (#8) sieve retained. It occupies a significant portion of the total volume of the Marshall mix. Gradation and quality of coarse aggregate can affect the behavior of bituminous mixtures. Therefore, the selection of an appropriate coarse aggregate of the desired gradation is imperative.

Moreover, the aggregate should be clean, tough, durable material as well as free from any objectionable matter [73]. Maddhapara stone chips (Figure 3.3) were used as coarse aggregate in this study. The aggregates were produced from mechanically crushed boulders. The maximum size of aggregate that was used for the mix was 19 mm.



Figure 3.3 Coarse aggregate

Fine aggregate consists of aggregates passing #8 and retained #200. The fine aggregate occupies the interspaces of coarse aggregate. Natural sand, stone screenings, or a combination of both can be used as fine aggregate. The aggregates should be clean, hard, durable particles, rough-surfaced and angular, free from vegetable matter, soft

particles, clay balls, or other objectionable matter [5]. For this study, Sylhet sand, as well as stone screenings, were used as fine aggregate for the mix (Figure 3.4).



Figure 3.4 Fine aggregate

Besides binder and aggregate, filler material has a significant influence on the properties of bituminous materials. Mineral filler comprises of limestone dust or similar rock dust, Portland cement, hydrated lime, silica cement, and other mineral matter. This material should be free from foreign and other objectionable material. The voids in aggregates are filled by mineral, which in turn increases the density of the compacted mixes. Therefore, the void percentage in the mineral aggregate can be controlled by the use of mineral fillers in the proper amount [5]. In this study, Ordinary Portland Cement (OPC) was used as a mineral filler.

For the preparation of the Marshall mix, the gradation of the aggregate is an essential factor. Workability and density can be significantly influenced by gradation. Nowadays, densely graded mixes are recommended by various engineering departments and other large engineering organizations. Well, graded aggregates yield the densest mix and, therefore, can ensure the most stable and durable mixes requiring the minimum bitumen content for satisfactory results [5]. The aggregate gradation, which was used in this research, is shown in Table 3.1. For both modified and unmodified bituminous mix, the same graded aggregate was used.

Table 3.1 Gradation of aggregate

Sieve Fraction (mm)	% Finer	% Retained	Type of Aggregate (%)
12.5	94.00	6.00	Coarse Aggregate 60%, Fine Aggregate 36% & Mineral Filler 4%
9.5	79.40	20.60	
#4	50.70	49.30	
#8	40.10	59.90	
#16	32.70	67.30	
#30	26.50	73.50	
#50	20.90	79.10	
#100	11.50	88.50	
#200	4.30	95.70	
Pan		100	

3.2.3 Polymer

Polymers can be categorized into two main classes elastomer and plastomers. Among these polymers, many have already been used in several researches. For this study, one elastomer and one plastomers have been used. Polypropylene is a type of plastomers, which has been frequently used in previous researches but fiber form. But for this study, the granular form of polypropylene has been used. Crumb rubber, an elastomer, is one of the most widely used modifiers of a bituminous mix. Pyrolysis Carbon Black is one of the by-products of rubber. In this investigation, both of the polymers have been examined to assess the compatibility of them for using as a modifier in a bituminous mix.

Polypropylene, used for this research, is an ethylene-propylene copolymer, as shown in Figure 3.5. The manufacturer of this product is IRPC Public Company Limited, Thailand. Bashundhara Group, Dhaka, Bangladesh, supplied the sample. According to the company specification, the Melting point of this modifier is 130-170°C. Some of the fundamental physical properties of this modifier, provided by the company, are shown in Table 3.2. One of the main reasons behind using this modifier is that there will be no hazardous polymerization.



Figure 3.5 Polypropylene

Table 3.2 Physical properties of polypropylene

	Method	Unit	Value
Melt Flow Index (2.16 kg/230 °C)	ASTM D1238	G/10 min	35
Tensile Strength at Yield	ASTM D638	N/mm ²	30
Elongation at Yield	ASTM D638	%	23
Flexural Modulus (1% Secant Modulus)	ASTM D790	MPa	1200
Heat Distortion Temperature	ASTM D648	°C	100

Pyrolysis Carbon Black (PCB) is a by-product of the scrap tire pyrolysis process. Pyrolysis is a process of chemically decomposing organic materials at elevated temperatures in the absence of oxygen. PCB was collected from Bengal Shipyard Limited, Dhaka, Bangladesh, for this research. It was in slightly granular form. So, it was used after passing through #200 sieve, as shown in Figure 3.6. The processing temperature of PCB is 350°C. The market price of PCB in Bangladesh is 10 to 15 BDT per kg.



Figure 3.6 Pyrolysis Carbon Black (PCB)

3.3 Preparation of Modified Bitumen

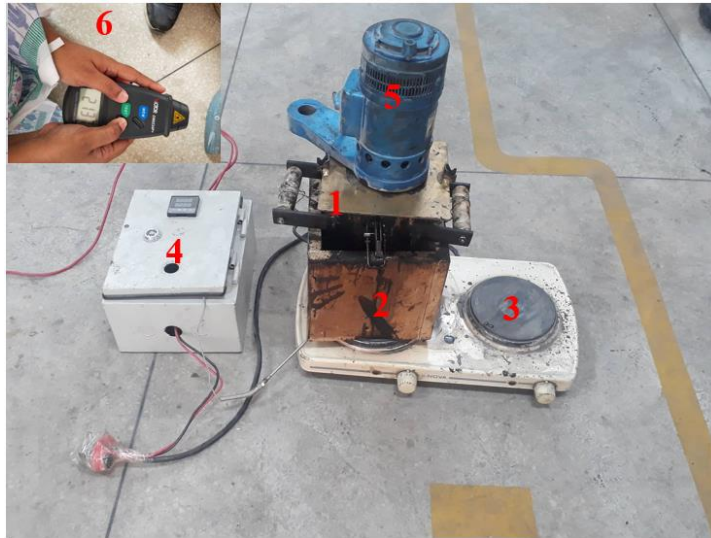
To preserve the properties of Polymer Modified Bitumen (PMB), the homogeneous mixing of bitumen and polymer should be ensured. For homogeneous blending of PMB, a mechanically controlled blender or high shear mixer has already been proven very effective in several researches [5], [7], [74]. Basing one result of previous researchers, two modifiers have been selected for the modification of bitumen. Initially, the modifiers were blended individually with bitumen. Later based on the obtained results, two combinations have been prepared to consist of both polypropylene and PCB. Three factors are significant for the homogeneous blending of PMB. The factors are blending temperature, blending time, and shear force (rotation speed). For different types of polymer, the value of these factors frequently changes [7]. For this study, PCB modified bitumen needs more blending time and rotation speed than those of polypropylene. However, to preserve the rheological properties of PMB, the blending time shouldn't exceed the limit [7]. The blending method of PMB, detailing of the blender, blending temperature of PMB are discussed in the following section.

3.3.1 Mechanically controlled blending device

A previous researcher prepared a mechanically and Thermo statistically controlled bending device to blend waste plastic with bitumen [7]. Basing on the concept of this device, an experimental setup has been prepared for this research to ensure the homogeneous mixing of PMB, as shown in Figure 3.7.

The device consists of the following parts. A high shear mixer has been used, which has a maximum capacity of rotating at 4000 rpm. The mixer had the benefit of adjusting the rotational speed as per requirement. Since brass can preserve the temperature of the material. So, the cylindrical container used for blending was made of brass. Besides, a copper lid, with a hole at its center, was placed on the top of the

container. Through the hole, the stirrer of the mixer was inserted to blend the material. This lid prevented any loss on heating as well as ensured proper safety while blending.



- | | | |
|---|---------------------|--------------------|
| 1. Brass cylindrical
Container with a lid on | 2. Wooden cover | 3. Electric heater |
| 4. Thermocouple | 5. High shear mixer | 6. RPM meter |

Figure 3.7 Mechanically controlled blending device

Moreover, the container was placed in a wooden cover, so that heat could not transfer to any other parts of the setup except the container. For heating the material, an electric heater of high capacity was used. Since blending temperature is one of the most critical factors for the efficient blending of PMB, a thermocouple was attached with the heater to maintain a specific temperature while blending. In this thermocouple, a particular temperature could be fixed as per requirement. Another significant factor for blending is the rotational speed of the stirrer. For blending the PMB at specified shear force, an RPM meter was used. This meter was used to fix the rotational speed before starting the blending. The complete setup of the device is shown in Figure 3.7.

3.3.2 Factors of blending

Three factors have a significant influence on the proper blending on polymer-modified bitumen. The first factor is the blending temperature. In previous researches, it has been observed that for polypropylene modified bitumen blending temperature of 170°C could

ensure the proper mixing of the material [21], [75]. While basing on the previous study, in the case of PCB modified bitumen, it was 160°C [76], [77].

The next important factor is the rotational speed. Since the granular polypropylene was already heated for melting before blending. The rotational speed used for PCB modified bitumen was higher than that of polypropylene modified bitumen. Based on the previous study, the rotational speed used for polypropylene and PCB was 120 rpm and 4000 rpm, respectively [60], [75]–[77].

The third factor for homogeneous blending is blending time. For blending polypropylene and bitumen, the blending time used was half an hour. But for PCB modified bitumen, the material was blended for one hour basing on a previous study [76], [77]. Since there was no previous study on the combined modified bitumen, the materials were blended at 170°C and 4000 rpm for one hour.

3.3.3 Method of blending

For all types of polymer modified bitumen, the wet process is an effective one for ensuring the homogeneous mixing of material. Therefore, in this study, the materials were blended through the wet process. Since pyrolysis carbon black was a waste material, the modifier was used after passing through #200 sieve to avoid the presence of any objectionable material. On the other hand, the polypropylene was in granular form. So, this was melted before blending. In both cases, at first, the bitumen was melted separately. Since PCB was in powder form, it was directly added into liquid bitumen. The electric heater and thermocouple should be started a little earlier before blending so that specific temperature could be attained, as shown in Figure 3.8. When the temperature reached the specified value, the bitumen was poured in the container. Then the polymers were added to the bitumen by a certain percentage. After that, the rotational speed should be fixed based on the polymer used. At this point, the shear mixer was turned on, and the blending

had been started. Once the blending time is over, the mixture was poured into another container, as shown in Figure 3.9.



Figure 3.8 Controlling temperature through a thermocouple



Figure 3.9 PMB stored in a container

Since storage stability is an essential factor for ensuring the properties of polymer modified bitumen in the long run, therefore, based on the previous research, to preserve the property of the blending, the containers were sealed with aluminum foil [19], [60]. These PMB were then stored for further experiments. It was previously observed that the properties of these mixes wouldn't be affected if they were prepared by following the mentioned procedure [5], [19]

3.3.4 Combinations of polymer modified bitumen prepared for testing

Using two modifiers, ten combinations of polymer modified bitumen were prepared. In each of the cases, all the mentioned criteria have been followed strictly. In this research, 1%, 2%, and 3% polypropylene by the weight of bitumen were used to modify bitumen content. In the case of PCB, 5%, 10%, and 15% are the most frequently used percentages for the modification of bitumen [19], [78]. However, for this research, 2 % and 3%, PCB by weight of bitumen content, was also tested for better comparative study. Basing on the obtained results from the above combinations, two combinations consisting of both PP and PCB were prepared as well. Some notations have been used in each case, for making the explanation more straightforward, as shown in Table 3.3. In this table, B5 is indicating the 5 % optimum bitumen content, which will be discussed later.

Table 3.3 Composition of polymer modified bitumen

Sample ID	Composition	Sample ID	Composition	Sample ID	Composition
B5	Bitumen	B5	Bitumen	B5	Bitumen
B5PP1	Bitumen+ 1% Polypropylene	B5PCB2	Bitumen+ 2% PCB	COMB1	Bitumen+ 3% PCB+1% Polypropylene
B5PP2	Bitumen+ 2% Polypropylene	B5PCB3	Bitumen+ 3% PCB	COMB2	Bitumen+ 3% PCB+2% Polypropylene
B5PP3	Bitumen+ 3% Polypropylene	B5PCB5	Bitumen+ 5% PCB		
		B5PCB10	Bitumen+ 10% PCB		
		B5PCB15	Bitumen+ 15% PCB		

3.4 Physical Property Tests of Bitumen

Both unmodified and modified bitumen specimens were experimented to assess the physical properties. Penetration, softening point, ductility, and specific gravity tests were performed. The result of these tests for unmodified bitumen is given in Table 3.4. A brief description of these test methods and their significance are discussed below.

3.4.1 Penetration test

The penetration of bituminous material is its consistency expressed as the distance in tenths of a millimeter that a standard needle penetrates vertically into a specimen of the material under specified conditions of temperature, load, and duration of loading. Two penetration values designate grades of straight-run bitumen, for example, 40/50, 60/80, 80/100, etc.; the penetration of an actual sample of the bitumen in any grade should fall between the lower and upper value given.

This test was done following the ASTM D5 code. The sample was heated and stirred well and left to cool for 45 minutes. After cooling, it was kept in a water bath for 1.5 hours at 25 °C. A penetrometer was used to undergo this test. The sample was penetrated on three different points with a minimum of 10 mm distance from each other.

3.4.2 Softening point test

For measuring the consistency of the binder, the softening point test was also performed. The temperature at which the binder changes from its semi solid-state to a liquid state is its softening point. Through the softening point test, the temperature susceptibility of the binder could be evaluated. Binders with the same penetration value might have different softening points, which could lead to different susceptibility to temperature.

The test was performed following ASTM D36. The Ring and Ball apparatus was used for this test. According to this method, asphalt samples were placed in a brass ring with a steel ball on it. Then the arrangements were placed in a beaker filled with water.

The sample was then heated at a rate of 5°C/min. With the increment of temperature, the asphalt became softer. Then, when the asphalt touched the plate, the temperature was recorded as the softening point of that specific bitumen.

Table 3.4 Physical property of unmodified bitumen

Name of the Test	Values	
	Laboratory Tests	*RHD Standard
Penetration (mm) at 25°C, 100 gm, 5 sec	69	60-70
Softening Point, °C	48	48-56
Ductility, cm	100 ⁺	Min 100
Specific Gravity	1.03	1.01-1.05

[*RHD= Roads and Highways Department]

3.4.3 Ductility test

Ductility is a measure of elasticity of bitumen. The distance up to which the sample elongates in cm before it ruptures when kept at standard conditions in standard briquettes is the ductility of that sample. This test was done following the ASTM D113 code. After heating the bitumen sample at 25 ± 0.5 °C, it was kept to cool for 90 minutes. The briquette was then removed from the plate, and the side pieces were detached. Then the rings were attached at each end of the clips to the pin in the testing machine. The two clips apart were pulled at a uniform speed of 5 cm/min \pm 5.0 % until the briquette ruptures. Then the distance through which the clips had been pulled to produce rupture was recorded as the final length or ductility value of that specimen.

3.4.4 Specific gravity test

The specific gravity of the bituminous binder is the ratio of the mass of a given volume of the material at 25°C to that of an equal volume of water at the same temperature. The specific gravity of the binder could influence the absorption capacity of aggregate and

Marshall mix design criteria. ASTM D70 code was followed for this test. This test was used to classify binders.

3.5 Physical Property Tests of Aggregate

3.5.1 Elongation and flakiness test

The flakiness index of an aggregate sample was found by separating the flaky particles and expressing their mass as a percentage of the mass of the sample tested. The elongation index of an aggregate sample was found by separating the elongated particles and expressing their mass as a percentage of the mass of the sample tested. Both of the tests were performed following BS 812 code.

3.5.2 Aggregate Crushing Value (ACV) test

Aggregate Crushing Value could provide a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. For aggregate passing a 14.0 mm test sieve and retained on a 10.0 mm sieve, this test could be performed. The test was done using code BS 812.

3.5.3 Aggregate Impact Value (AIV) test

Aggregate Impact Value could provide a relative measure of the resistance of an aggregate to “sudden shock or impact,” which in some aggregates differs from its resistance to a slowly applied compressive load. For aggregate larger than 14 mm, this test was not applicable. The test was done using code BS 812.

3.5.4 Los Angeles abrasion test

The test was performed following the ASTM C131 code. For aggregates of different sources with similar mineral compositions, this test had been widely used as an indicator of the relative quality.

3.5.5 Specific gravity test

ASTM C127 and ASTM C128 codes were followed for performing the specific gravity test of coarse aggregate and fine aggregate, respectively. According to these methods, firstly, the samples were immersed in water for 24±4 h so that the pores could be filled with water. After the specified time, the aggregates were removed from the water, and the mass was recorded after drying the aggregates. Finally, another mass of the aggregates was recorded after oven drying the sample. Using these masses, the specific gravity of coarse and fine aggregate was then calculated.

3.5.6 Fractured face test

To maximize shear strength by increasing inter-particle friction in either bound or unbound aggregate mixtures, this test was performed. Providing stability for surface treatment aggregates and increased friction and texture for aggregates used in pavement surface courses are other reasons behind this test. The test was performed following the ASTM D5821 code.

3.6 Marshall Mix Design

At first, Bruce Marshall, a former bituminous engineer of the Mississippi State Highway Department, formulated the concept of the Marshall method of designing paving mixtures. Later, the American Society for Testing and Materials (ASTM) had standardized the Marshall test procedure. For Hot Asphalt Mix (HMA) containing aggregates of the maximum size of 25 mm or less, the original Marshall method was applicable. However, later this method was replaced by a modified Marshall method, which could be used for aggregates with maximum sizes up to 38 mm [79].

In this method, basing on a selected particle size distribution, firstly, aggregates were prepared and blended to make samples. For mix design purposes, different asphalt contents were used to make samples. After that, those samples were compacted with a

certain number of blows depending on the expected traffic. The properties of the compacted samples like bulk density, air voids, and stability and flow, were then determined. The mix was reformulated, and the tests were repeated until the Marshall mix design criteria were achieved, as shown in Table 3.5 [79].

Table 3.5 Marshall mix design criteria [79]

Description	Light Traffic		Medium Traffic		Heavy Traffic	
	Surface & Base		Surface & Base		Surface & Base	
	min	max	min	max	min	max
Number of blows	35		50		75	
Stability, N	3336	-	5338	-	8006	-
Flow (0.25 mm)	8	18	8	16	8	14
Percent Air Voids, V_a	3	5	3	5	3	5
Percent Voids filled with Asphalt, VFA	70	80	65	78	65	75

Standard test specimens of 64 mm (2.5") height and 102 mm (4") diameter were used for the Marshall method. All these specimens were prepared following the specified procedure of heating, mixing, and compacting the asphalt-aggregate mixtures. There are two principal features of the Marshall method of mix design. One is density-voids analysis, and another one is the stability-flow test of the compacted specimens [79].

3.6.1 Preparation of test specimens

For determining an Optimum Bitumen Content (OBC), a series of test specimens were prepared as per ASTM D6926-16 for a different range of asphalt contents by the Marshall method. At first, an expected design asphalt content was decided. Then a total of five asphalt contents were used, two above the expected asphalt content, and two below the content with a 0.5 percent increment [79].

The "expected design" binder content was determined using dust-to-asphalt ratio guidelines. Then the content, in percent by total weight of mix, was estimated to be

approximately equivalent to the percentage of aggregate in the final gradation passing the 75 μm (No.200) sieve. The computational formula (3.1) used For estimating the expected design asphalt content is given below [79] :

$$P = 0.035a + 0.045b + Kc + F \quad (3.1)$$

Where, P = approximate asphalt content of the mix, percent by weight of the mix, a = percent of mineral aggregate retained on 2.36 mm (No. 8) sieve, b= percent of mineral aggregate passing the No. 8 sieve and retained on the No.200 sieve, c = percent of mineral aggregate passing No. 200 sieve, K= (0.15 for 11-15 percent passing No. 200 sieve; 0.18 for 6-10 percent passing No.200 sieve ; 0.20 for 5 percent or less passing No.200 sieve), F = 0 to 2.0 percent, based on the absorption of light or heavy aggregate. In the absence of other data, a value of 0.7 is suggested.

The gradation of combined aggregates indicates, a = 59.9%, b=40.1%, c = 4.3%. Using K = 0.2 and F = 0.7, the calculated expected design asphalt content was 5.461 %. Therefore, the Marshall specimens were prepared using 4.5%, 5.0%, 5.5%, 6.0% and 6.5% of binder. Around 1148.4 gm of aggregate was required for preparing one specimen. The weights of the aggregates were determined based on the gradation. After that, they were oven-dried at 110°C before mix design. Then the aggregates were separated by dry sieving into desired fractions [79].

For accuracy of the test results, according to the Marshall method, at least three specimens should be prepared for one asphalt content [79]. So, for obtaining OBC, thirty specimens were prepared. To get representative results, during sample preparation and testing, the specifications of the mix design method were strictly followed. Although mixing and compaction temperature depends on the viscosity of the binder but based on the previous study, the temperature was decided. For the Marshall mix design of

unmodified bituminous mix, 152°C-158.8°C and $145^{\circ}\text{C} \pm 3^{\circ}\text{C}$ were used as mixing and compaction temperature, respectively.

For preparing the mold and hammer at first, the assembly and the face of the compaction hammer were cleaned carefully. After that, they were heated in an oven to a temperature between 95°C and 150°C to preserve the mixing temperature of the specimen while mixing. Before placing the mixture in the mold, a filter paper was placed in the bottom of the mold [79]. After the preparation of the mold assembly, the specified aggregate contents were heated in a pan at the mixing temperature. Care was taken to keep the mixing temperature within 28°C of the specified value. The aggregates were then poured in a mixing bowl and mixed thoroughly. Then asphalt content was added to the mixture by forming a crater in aggregate based on the calculated batch weights. While mixing the specimen using a spoon, the mixing temperature was maintained strictly. The mixing was done within the minimum possible time [79]. After mixing the material, it was poured in the mold and spaded vigorously 15 times around the perimeter and ten times over the interior using a heated spatula. The surface of the mixture in the mold was then smoothed to a slightly rounded shape. It was made sure that the mixing temperature remains within the limit of compaction temperature ($145^{\circ}\text{C} \pm 3^{\circ}\text{C}$) before starting the compaction [79].

After completion of the mixing, another filter paper was placed on the top of the mixture. Then the mold, base plate, and filling collar along with the specimen were placed in the Automatic Marshall compaction apparatus. The sample was compacted by 75 blows with a compaction hammer because of heavy traffic consideration, as shown in Figure 3.10. After compacting one side, the mold assembly was then dismantled for reversing the mold, and the same number of blows were given on the reverse side of the sample. Then the mold assembly was placed in a suitable location to remove the base

plate and collar, as shown in Figure 3.11. To avoid any deformation while extracting the sample from the mold, the specimen was then allowed to cool down in the air overnight. After cooling, the specimen was extracted from the mold using an extrusion jack. Then the samples were used for further testing.



Figure 3.10 Compaction of Marshall specimen using Automatic Compactor



Figure 3.11 Compacted Marshall specimen

3.6.2 Volumetric analysis for mix design

A density and void analysis were done for each series of test specimens. The detailed calculation of this section is given in appendix A-2.

After extracting the specimen form mold, the freshly compacted specimens were then tested for the determination of bulk specific gravity as per ASTM D2726-19.

According to ASTM D2726, the mass of the specimens was determined at first in the air. Then the specimens were submerged in the clean water of 25°C temperature. After submerging the specimen in water for 3 to 5 minutes, the mass was determined in water. Finally, after removing the sample from water, the mass of the saturated surface dry specimen was recorded in the air within 15s of removal from water. The bulk specific gravity was then calculated using the equation mentioned in code.

At first, the average bulk specific gravity (G_{mb}) of all specimens was determined. Then the unit weight for each asphalt content was calculated by multiplying the bulk specific gravity with a unit weight of water (1000 kg/m³).

After the determination of unit weight, the theoretical maximum specific gravity (G_{mm}) was determined for 5% asphalt content as per ASTM D2041. The theoretical maximum specific gravity is a fundamental property whose value is influenced by the composition of the mixture in terms of types and amounts of aggregates and bituminous materials.

For the determination of G_{mm} , the mass of loose samples was recorded in the air at first. Then the loose paving mixture was placed in a tared vacuum vessel. The sample was then submerged with water of 25°C temperature. A residual pressure of 4 kpa was then applied in a vacuum vessel for around 15 minutes. After that, the vacuum was gradually released. At this stage, the mass was recorded with sample, cover plate, and flask. The mass of the flask filled with water, including the cover plate, was also recorded for calculation. Then, the theoretical maximum specific gravity was calculated using the given equation in the code.

Effective Specific Gravity of the aggregate (G_{se}) includes all void spaces within the aggregate particles, except those that absorb bitumen. Using theoretical maximum

specific gravity (G_{mm}) of a bituminous mixture, G_{se} was determined following the equation provided in the code.

Since the total aggregate consisted of several fractions of aggregates like coarse aggregate, fine aggregate, mineral filler, and all were having different specific gravities. Therefore, the Bulk Specific Gravity (G_{sb}) of total aggregate was calculated following the equation provided in the code.

Although the theoretical maximum specific gravity was determined as per ASTM D2041, to maintain the precision, the maximum specific gravity was calculated for asphalt content close to the design bitumen content. Using the effective specific gravity of the aggregate (G_{se}), the maximum specific gravity (G_{mm}) was calculated following the equation provided in the code.

Air void is defined as the air spaces bitumen, the coated aggregate of paving mixture. In the case of pavement performance, it is an influencing factor. Too much air voids in the paving mixture might cause stripping allowing water to stay in it. Air void of compacted mixes was determined using the equation provided in the code.

The void in the mineral aggregate (VMA) is defined by the intermolecular spaces between the aggregate particles in compacted paving mixtures that include the air voids and the effective asphalt content [12]. VMA is calculated based on the bulk specific gravity of the aggregate and is expressed as a percentage of the bulk volume of the compacted paving mixture. VMA should be sufficient to adhere bitumen to aggregate properly. VMA was measured using the equation provided in the code.

The void filled with asphalt (VFA) is defined as the percentage of the intermolecular void spaces between the aggregate particles that are filled with asphalt [79]. It was calculated using the equation provided in the code.

3.6.3 Marshall stability and flow test

The pavement is desired to have higher stability and lower flow value, but not too much rigidity. Too much rigidity may be the cause of cracks in the pavement. The pavement should have reasonable flexibility that also depends on the quality of the binder.

After the evaluation of bulk specific gravity, the specimen was tested for Marshall stability and flow value as per ASTM D6927-15. For the next 30 minutes, the samples were immersed in a water bath at $60^{\circ}\text{C}\pm 1^{\circ}\text{C}$. For the Marshall stability and flow test, digital equipment was used, as shown in Figure 3.12a. Between two consecutive tests, the testing head was always cleaned with lubricant. In all cases, the temperature of the testing head was kept between 21.1°C and 37.8°C . After preparing the apparatus, the specimen was removed from the water bath and experimented for stability and flow value within 30s period, as shown in Figure 3.12a. While testing, the deformation rate was kept at a constant value of 51 mm/min until failure occurred.



a) Digital Marshall stability and flow apparatus



b) Stability and flow value

Figure 3.12 Marshall Stability and Flow value test

The point of failure was recorded as the maximum load. The total force at which the specimen failure occurred was recorded as Stability (kN). Since this test was performed in digital equipment, the values of stability and flow value were automatically

flashed on the screen, as shown in Figure 3.12b. For the sample without standard height (63.5 mm), stability was corrected using the correction factor using the chart provided in ASTM D6927. The Marshall stability and flow value of the unmodified bituminous mix are provided in appendix A-1.

3.6.4 Determination of design bitumen content

Basing on the result obtained from all the calculations, some property curves were plotted to determine the design asphalt content, as shown in Figure 3.13. It is mentioned in MS2 that the asphalt content obtained at 4 % air void can be considered as initial design bitumen content. Therefore, from the percent air void vs. asphalt content graph, it has been observed that for 4% air void content, the asphalt content is 5%. This initial design bitumen content was later checked against the Marshall mix design criteria (Table 3.5). After comparing the obtained result with the design criteria, it has been observed that 5% asphalt could be used as design bitumen content for further testing.

3.7 Preparation of Modified Marshall Test Specimen

Basing on the optimum bitumen content, the other Marshall specimens were prepared following the procedure mentioned in section 3.6, as shown in Figure 3.14. For polypropylene modified bitumen, using BPP1, BPP2, and BPP3, nine specimens were prepared.

In the case of PCB modified bitumen, fifteen specimens were prepared using BPCB2, BPCB3, BPCB5, BPCB10, BPCB15. Apart from that, COMB1 and COMB2, six Marshall specimens were prepared. The mixing and compaction temperatures, used while making samples in all cases, are given in Table 3.6.

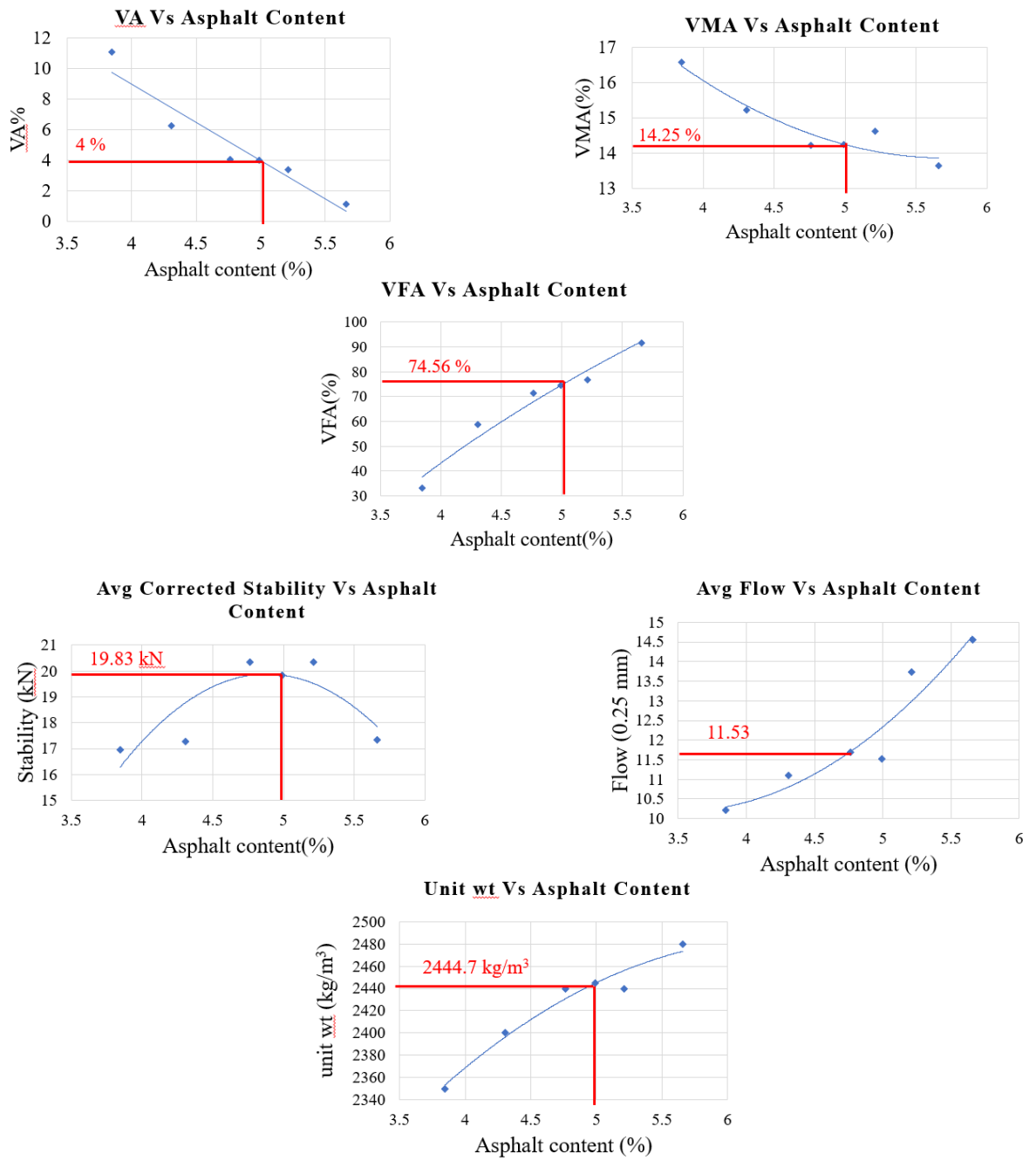


Figure 3.13 Test property curves of mix design data by the Marshall method



Figure 3.14 Marshall test specimen

Table 3.6 Mixing and compaction temperature of polymer modified bituminous mix

Type of Asphalt Mix	Mixing temperature	Compaction temperature
PP	170 ⁰ C [21]	145 ⁰ C [21]
PCB	160 ⁰ C [76]	145 ⁰ C [76]
COMB1 & COMB2	170 ⁰ C	145 ⁰ C

3.8 Mechanical Property Tests of Marshall Specimen

Marshall specimens, prepared earlier, were tested for the evaluation of the mechanical properties of the Hot Mix Asphalt (HMA). The experiments are discussed below:

3.8.1 Determination of bulk specific gravity of the compacted mixture

The Marshall specimens prepared in section 3.7 were tested for the determination of bulk specific gravity. For testing, the procedure mentioned in section 3.6.2 was followed. These values were later compared with the bulk specific gravity value of neat bituminous mix.

3.8.2 Marshall stability and flow test

After obtaining the results of bulk specific gravity, the Marshall specimens were then subjected to the Marshall stability and flow test. For testing, the procedure mentioned in section 3.6.3 was followed. These values were later compared with the stability and flow value of the neat bituminous mix.

3.8.3 Marshall Quotient test

The Marshall quotient value calculated as the ratio of stability to flow is used as a measure of the materials' resistance to permanent deformation, shear stress, and rutting in the road service [80].

3.8.4 Indirect Tensile Strength (ITS) test

To assess the quality of asphalt paving mixture, an indirect tensile strength test was performed on some specified specimen. The ITS strength of asphalt mixtures was

determined by loading the cylindrical specimen across its vertical diametral plane at a deformation rate of 50 mm/min. The peak load at failure was recorded and used to calculate the IDT strength of the specimen following equation 3.2.

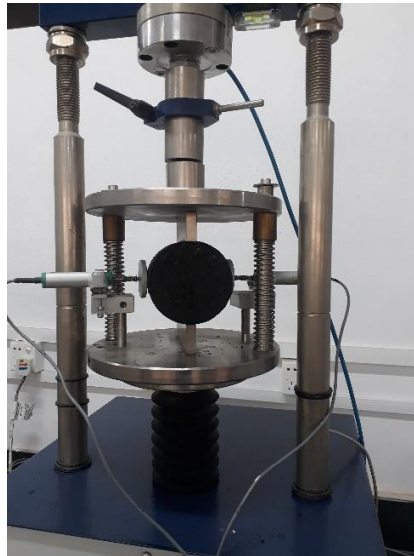


Figure 3.15 Indirect Tensile Strength (ITS) test

$$S_t = \frac{2000 * P}{\pi * t * D} \quad 3.2$$

Where, S_t = IDT strength (kPa), P = maximum load (N), t = specimen height immediately before test (mm) , and D = specimen diameter (mm).

Basing on the Marshall stability and flow result, BPCB3, COMB1, COMB2, and neat bitumen were subjected to this test. The specimens were prepared following the procedure mentioned in section 3.6. After cooling down the sample in air, the sample was kept in a 25°C water bath for 30 minutes. After that, the sample was placed in the apparatus for the test, as shown in Figure 3.15. Each test was completed within 2 minutes. The failure plane of the specimens after the ITS test should be along the diametrical plane, as shown in Figure 3.16.



Figure 3.16 Failure of the specimen after ITS test

3.9 Moisture Resistivity Test

Stripping potentiality is a function of the affinity between the aggregate and bitumen and its consequent capacity to resist the displacing effect of water [20]. Materials with high void content lead to the risk of stripping. Therefore, it could result in a loss of internal cohesion and possibly disintegration of the surfacing. By determining the retained stability of the Marshall specimen, the moisture susceptibility of bituminous pavement can be evaluated.



Figure 3.17 Conditioning of Marshall sample in a 60°C water bath

In this study, some specimens were tested for evaluating this property. The retained stability test was performed on BPCB3, COMB1, COMB2, and neat bituminous mix. The Marshall samples were placed in a 60°C water bath for 24 hours, as shown in Figure 3.17 [72]. The ratio of Marshall stability of the conditioned and unconditioned specimen was recorded as retained stability. The retained stability was presented in percentage.

3.10 Summary

In this chapter, the blending method of the polymer-modified bitumen has been discussed. Besides detailed procedures for determining the design, asphalt content has also been discussed. For evaluation of the physical properties of asphalt and aggregate, the required experiments have been illustrated. In this chapter, the necessary tests for evaluating the mechanical properties of the Marshall mix have been discussed as well. In the next chapter, all the results obtained from these tests will be compiled. Moreover, there will be a comparative study between the results obtained from modified and unmodified bitumen in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The main objectives of this research were to investigate the effect of modifiers on the physical properties of asphalt and observe the effect of modifiers on the mechanical properties of Hot Mix Asphalt (HMA). As modifiers, Polypropylene (PP) and Pyrolysis Carbon Black (PCB) were used. Penetration, Ductility, Softening point, and Specific gravity tests were performed for the assessment of the physical properties of modified and unmodified bitumen. Several tests were performed on HMA to evaluate the mechanical properties like Marshall stability, Flow, Indirect Tensile Strength value, Retained stability. This chapter contains all the results of these tests in tabular & graphical forms, analysis, comparison, and discussion on results.

4.2 Physical Properties of Bitumen

Experiments like penetration, softening point, ductility, and specific gravity were conducted to evaluate properties like consistency, adhesiveness, high-temperature susceptibility. Both unmodified and modified bitumen were tested to assess the effect of the modification.

4.2.1 Penetration test result

All possible combinations were tested for the determination of penetration value. The results are shown in Table 4.1. A graphical representation of penetration value vs. polymer content (%) is also shown in Figure 4.1. The penetration value for unmodified bitumen was 68 mm. From Figure 5.1, it is found that the penetration value of unmodified bitumen lies between lower and higher threshold value, specified by RHD. The penetration value of polypropylene modified bitumen decreases by 19% from that of unmodified bitumen, and the value gradually decreases with increasing polypropylene

concentrations, as shown in Figure 4.1. The presence of PCB content in bitumen decreased the penetration grade of bitumen from 60/70 to 30/40, which are shown in Figure 4.1. In the case of both combinations, the same decreasing trend was observed as well (Table 4.1). This kind of decreasing trend of penetration was found in some previous research as well [17].

Table 4.1 Penetration value of modified and unmodified bitumen

Sample ID	Penetration (1/10 mm)	Sample ID	Penetration (1/10 mm)	Sample ID	Penetration (1/10 mm)
B5	68	B5	68	B5	68
B5PP1	56	B5PCB3	42	COMB1	41
B5PP2	54	B5PCB5	41	COMB2	40
B5PP3	53	B5PCB10	40		
		B5PCB15	35		

This decreasing trend of penetration indicates the increase in hardness of polymer modified bitumen, and it is beneficial because it increases the stiffness of the material and also load spreading capabilities of the structure [60]. This lower penetration grade is preferable at high temperatures, as it will be convenient and more comfortable to handle during the construction process. For tropical countries, higher values of penetration are preferable since they prevent bleeding in new pavement. In the case of aged pavement, due to oxidation, penetration value decreases with time. Therefore, it initiates cracking in the aged pavement. Polymer modified bitumen could be a solution to this problem. Since the polymer is a non-biodegradable substance, initially, its presence in the binder decreases the penetration of modified bitumen. Still, it has the potential to retard the time-dependent hardening process. Thus, it enhances the performance of the pavement [5].

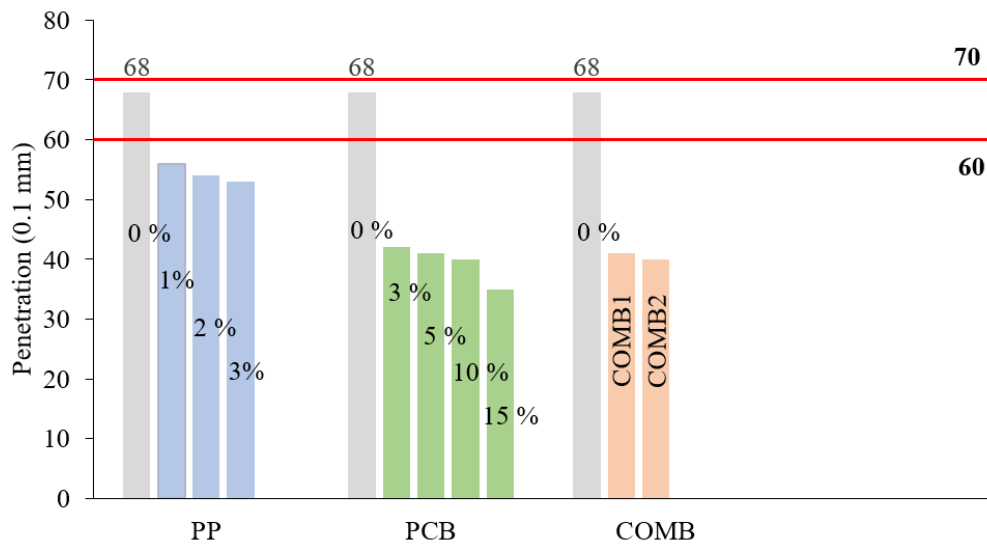


Figure 4.1 Penetration value vs. polymer content (%)

4.2.2 Softening point test results

The softening point test results are presented in Table 4.2 and Figure 4.2. The softening point for unmodified bitumen was 48 °C. From Figure 4.2, it has been found that the softening point of unmodified bitumen lies between lower and higher threshold value, specified by RHD. The results obtained from the softening point test indicate the gradually increasing (of about 3%) of softening point value with increasing polypropylene concentration (Figure 4.2). For the addition of 5 % polypropylene content, the softening point value increased by about 2 %. Likewise, with increasing PCB content, the softening point value has been increased. The highest value has been observed for the addition of 15 % PCB content. A similar increasing trend in the case of PCB has been observed in previous researches as well [19], [59]. In the case of both combinations, the same increasing trend was observed as well (Table 4.2).

The softening point of bitumen indicates the temperature at which the bitumen will attain a certain degree of softening. Higher the softening point of bitumen, the lesser the temperature susceptibility of bitumen. The higher softening point is preferable for a hot climate. PMBs with increasing softening points have been found to show increment in pavement performance characteristics in terms of rutting and fatigue [75]. Polymer

modified bitumen would be useful in terms of storage stability and would give better rutting resistance in high temperatures [60].

Table 4.2 Softening point of modified and unmodified bitumen

Sample ID	Softening Point (⁰ C)	Sample ID	Softening Point (⁰ C)	Sample ID	Softening Point (⁰ C)
B5	48	B5	48	B5	48
B5PP1	49	B5PCB3	48	COMB1	48
B5PP2	51	B5PCB5	49	COMB2	49
B5PP3	52	B5PCB10	50		
		B5PCB15	50		

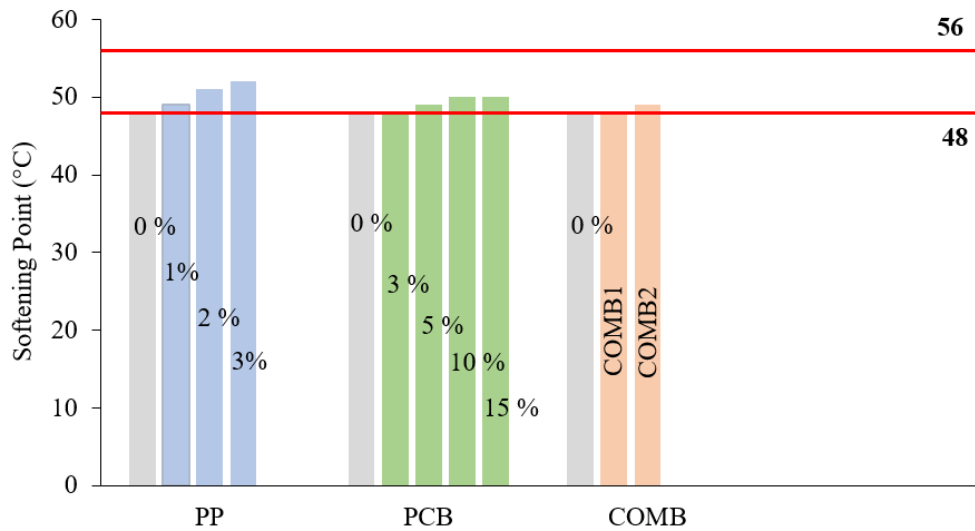


Figure 4.2 Softening point vs. polymer content (%)

4.2.3 Ductility test result

With the increasing polypropylene content, the ductility value decreased. The ductility value decreased by 55 % for a 3 % addition of polypropylene (Figure 4.3 and Table 4.3). However, a similar trend was found in other researches as well[72]. Similarly, the ductility value decreased with increasing PCB content. A similar trend was found in other researches as well [17], [19]. The ductility of neat bitumen is determined 141 cm at 25°C.

Gradually this value is reduced to 42 cm (at 25°C) for 15% PCB content. For COMB2, the lowest ductility value has been observed.

Table 4.3 Ductility value of modified and unmodified bitumen

Sample ID	Ductility (cm)	Sample ID	Ductility (cm)	Sample ID	Ductility (cm)
B5	141	B5	141	B5	141
B5PP1	84	B5PCB3	70	COMB1	37
B5PP2	77	B5PCB5	75	COMB2	24
B5PP3	63	B5PCB10	55		
		B5PCB15	42		

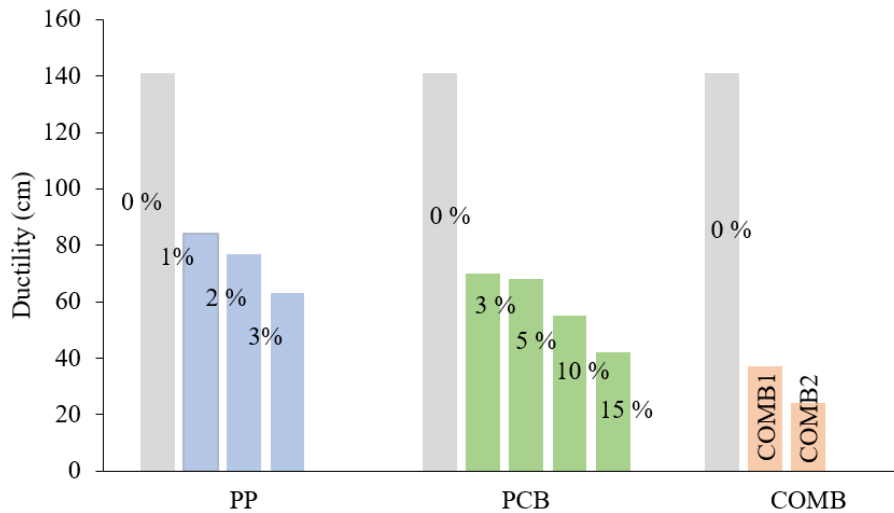


Figure 4.3 Ductility value vs. polymer content (%)

Ductility is the measure of internal cohesion of bitumen, which imparts cementing property in a bituminous mix. Although bitumen with high ductility shows the better binding property, initially, only ductility value cannot ensure the longer service life of asphalt pavement. For all types of bitumen, ductility value decreases with time generally. From previous researches, it has been observed that polymer-modified bitumen could lessen the decreasing rate of ductility with time. The optimum polymer content should be selected as a modifier, as excessive reduction of ductility might cause the bitumen incompetent as a pavement material. Besides decreasing ductility value, polymer

modification helped to increase the elasticity (flow value) of the bitumen. Therefore, modified bitumen with lower ductility value could be used safely in the asphalt mixes [5].

4.2.4 Specific gravity test result

The specific gravity for unmodified bitumen is 1.035. The results obtained from the specific gravity test of unmodified and modified bitumen are shown in Table 4.4 and Figure 4.4. In the case of polypropylene content, at 1 % PP, the specific gravity decreased. However, with increasing polymer content, it has been increased. A similar trend has been observed in the case of PCB and COMB as well. The highest and lowest specific gravity value has been observed for 15 % PCB and 1 % PP consecutively.

Table 4.4 Specific Gravity of modified and unmodified bitumen

Sample ID	Specific Gravity	Sample ID	Specific Gravity	Sample ID	Specific Gravity
B5	1.035	B5	1.035	B5	1.035
B5PP1	1.011	B5PCB3	1.029	COMB1	1.029
B5PP2	1.015	B5PCB5	1.036	COMB2	1.032
B5PP3	1.023	B5PCB10	1.057		
		B5PCB15	1.081		

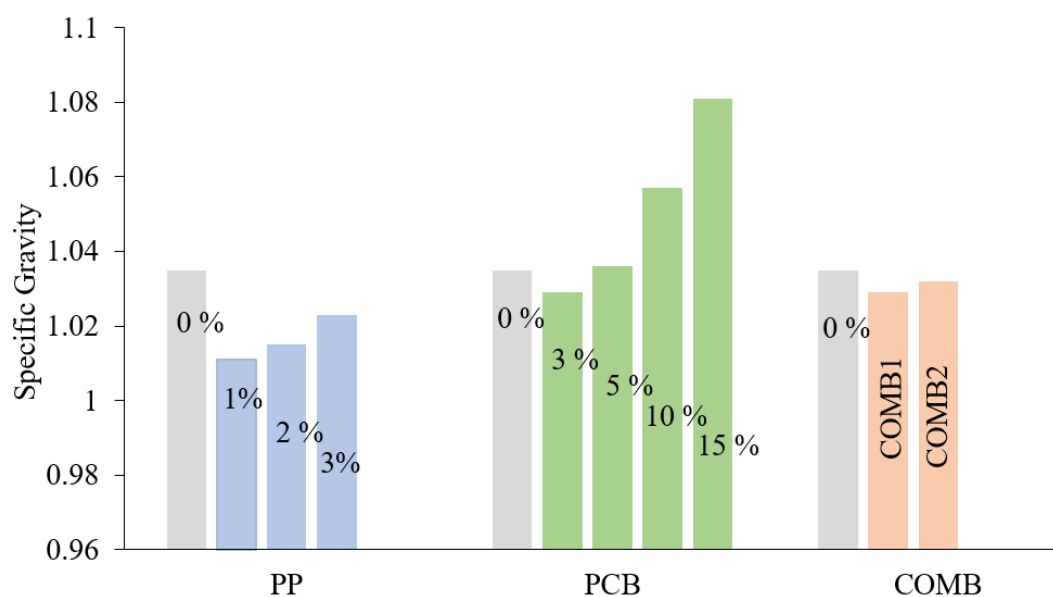


Figure 4.4 Specific gravity vs. polymer content (%)

4.3 Physical Properties of Aggregate

For determining the gradation of aggregate, sieve analysis was done. Later this gradation has been used for Marshall mix design. The gradation of aggregates is shown in Figure 4.5. The gradation fulfilled the RHD standard for gradation.

Experiments like Elongation index, Flakiness index, aggregate crushing value, specific gravity, etc. were performed to examine the physical properties of coarse and fine aggregates, as shown in Table 4.5. It has been observed that the flakiness index of coarse aggregate was within the limit. The abrasion value of the used aggregate was found within the permissible limit. The ACV value of the aggregate used for the test was 24 %, which is less than the maximum ACV value. Besides these, some other parameters were also evaluated like apparent specific gravity of coarse and fine aggregate, fractured particles in coarse aggregate.

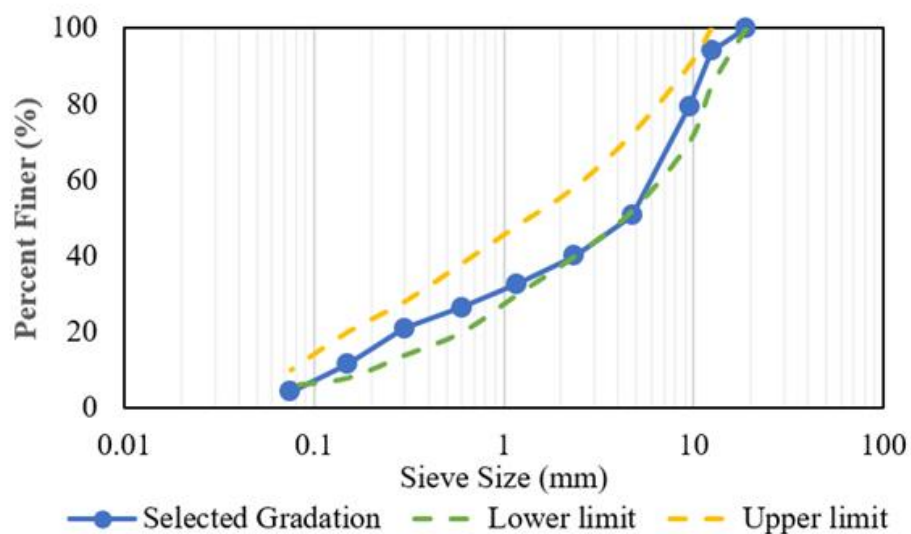


Figure 4.5 Gradation of aggregate

Table 4.5 Physical properties of aggregate

Name of the Test	Values	
	Test Value	RHD Standard
CA Flakiness Index (%)	27	Not more than 30%
CA Elongation Index (%)	30	-
CA Los Angeles Abrasion (%)	28	Less than 30%
CA Crushing value (%)	24	Less than 25%
CA Apparent Specific Gravity	2.780	-
FA Apparent Specific Gravity	2.610	-
Fractured Particles in CA (%)	100	100

4.4 Mechanical Properties of HMA

To assess the performance of the modified and unmodified bituminous mixture, several tests were performed. Different tests were conducted on the Marshall specimen to evaluate Marshall stability, flow value, indirect tensile strength, and retained Marshall stability value.

4.4.1 Marshall stability test result

The stability test of Marshall helps to identify the maximum load the specimen can take before deformation. The stability of design bitumen content was 19.84 kN. With the employment of PCB content, the stability value decreased, as shown in Figure 4.6 and Table 4.6. Although the highest stability was obtained at 3% PCB content, for 2 % PCB content, it decreased by about 32 %. With the increment of PCB content (5% -15%), stability values showed a decreasing trend. Even at its lowest value, the stability of the PCB modified bituminous mix did not fall from the design value. In previous research, it has been found that, above 6% of PCB modification, the stability values generally start to decrease [59]. In the case of polypropylene, the stability value is gradually increasing with increasing percentages.

Nevertheless, for 3% polypropylene, it is approximately 22% higher than that of the unmodified Marshall mix. A similar trend was observed in earlier research work [81]. For

both combinations, the stability values were almost similar. In both cases, the value was around 29 % higher than that of unmodified bitumen.

Table 4.6 Stability of modified and unmodified bitumen

Sample ID	Stability (kN)	Sample ID	Stability (kN)	Sample ID	Stability (kN)
B5	19.84	B5	19.84	B5	19.84
B5PP1	20.108	B5PCB2	20.461	COMB1	25.583
B5PP2	21.471	B5PCB3	29.875	COMB2	25.198
B5PP3	24.277	B5PCB5	26.812		
		B5PCB10	24.02		
		B5PCB15	22.378		

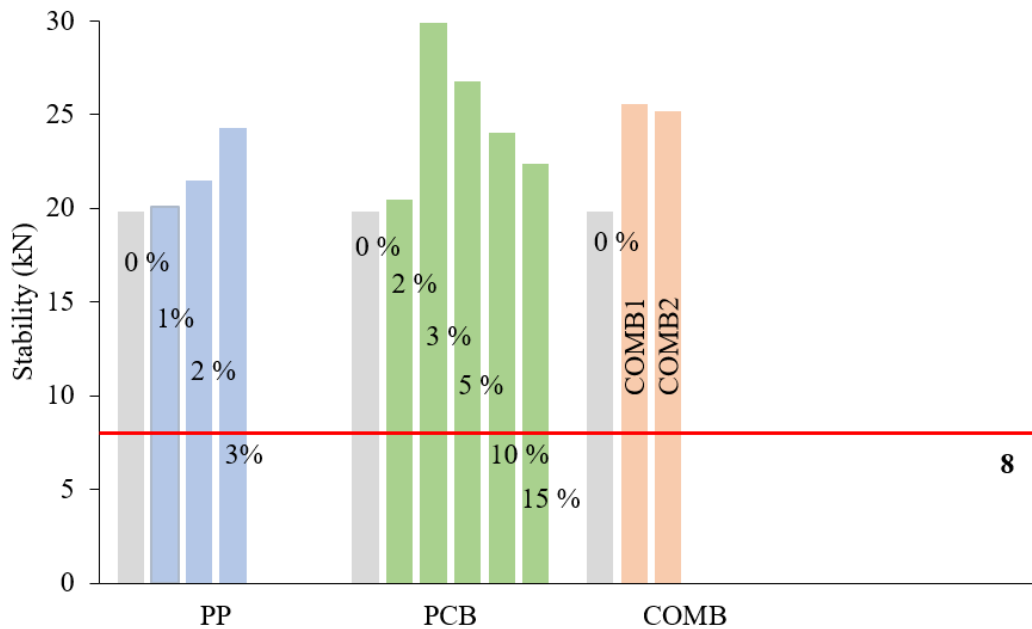


Figure 4.6 Marshall stability vs. polymer content (%)

The stability values of unmodified and modified mix samples meet the requirements of RHD specifications greater than 8.0. The results represent that modified bitumen can take more load than neat bitumen, although it may increase the rigidity. Low Marshall stability values indicate reduced stability of the bituminous concrete mixes, which may lead to raveling of the road surfaces [72]. The higher stability made it difficult for water to penetrate aggregates. This characteristic of the modified mix increases its resistance to distortion, displacement, rutting, and shearing stresses.

4.4.2 Flow value test result

Flow values for both modified and unmodified mix almost remain the same as shown in Figure 4.7 and Table 4.7. In the case of modification of bitumen with PCB, the lowest flow value was observed for 3% PCB content. However, with the increasing content of the polymer, the flow value started to increase.

Table 4.7 Flow value of modified and unmodified bitumen

Sample ID	Flow (0.25 mm)	Sample ID	Flow (0.25 mm)	Sample ID	Flow (0.25 mm)
B5	12.108	B5	12.108	B5	12.108
B5PP1	11.428	B5PCB2	12.101	COMB1	11.728
B5PP2	11.332	B5PCB3	11.18	COMB2	11.892
B5PP3	10.732	B5PCB5	11.764		
		B5PCB10	11.882		
		B5PCB15	11.984		

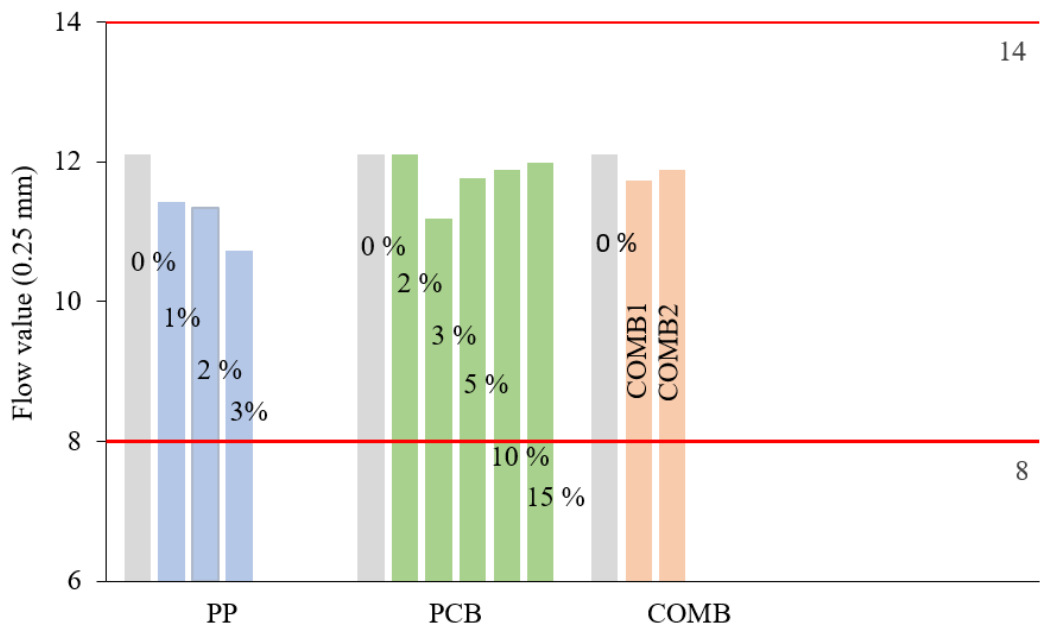


Figure 4.7 Flow value vs. polymer content (%)

In the case of polypropylene, the flow value showed an opposite trend than that of PCB. With increasing polypropylene content, the flow value started to decrease. A

similar trend was found in previous research work related to polypropylene modified mix [44]. For both combinations, the observed flow values were almost similar to that of neat bitumen. The flow values of unmodified and modified mix samples satisfy the requirements of RHD standards of flow value ranges from 8 to 14 [73]. As the values were within the limit, it will have less effect on permanent deformation.

4.4.3 Marshall Quotient test result

The Marshall Quotient values obtained from all specimens are presented in Table 4.8. In the case of PCB, these values showed a similar trend to stability values. For 3% PCB content, the Marshall Quotient value was 1.63 times higher than that of unmodified bitumen. However, after a 3% PCB, the quotient value started to decrease. While in the case of polypropylene, it was 1.38 times higher for 3% polymer in comparison with that of an unmodified bituminous mix. For both combinations, it was approximately 1.25 higher than that of conventional HMA. Therefore, PCB3 and COMB2 have shown significant resistance to permanent deformation, shear stress, and rutting in the road service.

Table 4.8 Marshall Quotient of modified and unmodified bitumen

Sample ID	Marshall Quotient (kN/mm)	Sample ID	Marshall Quotient (kN/mm)	Sample ID	Marshall Quotient (kN/mm)
B5	6.553	B5	6.553	B5	6.553
B5PP1	7.038	B5PCB2	6.764	COMB1	8.726
B5PP2	7.579	B5PCB3	10.689	COMB2	8.476
B5PP3	9.048	B5PCB5	9.117		
		B5PCB10	8.806		
		B5PCB15	7.469		

4.4.4 Bulk density test result

The bulk density values of modified and unmodified mixes are presented in Table 4.9. The bulk density of neat bitumen was 2.44. All mixes showed almost similar bulk density as that of neat bitumen. The maximum difference between modified and unmodified mixes.

Table 4.9 Bulk Density of modified and unmodified bitumen

Sample ID	Bulk Density	Sample ID	Bulk Density	Sample ID	Bulk Density
B5	2.44	B5	2.44	B5	2.44
B5PP1	2.35	B5PCB2	2.47	COMB1	2.45
B5PP2	2.43	B5PCB3	2.45	COMB2	2.44
B5PP3	2.44	B5PCB5	2.47		
		B5PCB10	2.45		
		B5PCB15	2.45		

4.4.5 Indirect Tensile Strength (ITS) test result

Basing on the previous result, only B5PCB3, COMB1, and COMB2 were tested for the determination of the ITS test. Unmodified bitumen was tested to provide a reference as well. The results obtained from the test are provided in Table 4.10 and Figure 4.8. The detailed result of the ITS test is provided in Appendix A-3. The ITS value for COMB2 was around 28.7% higher than that of the unmodified bituminous mix, while in the case of PCB, it was around 9.7% higher for 3% PCB content. Therefore, a bituminous mix prepared with 3% PCB and 2% PP could be capable of withstanding much larger tensile strains before cracking.

Table 4.10 Indirect Tensile Strength (ITS) of modified and unmodified bitumen

Sample ID	B5	B5PCB3	COMB1	COMB2
ITS (Mpa)	1.019	1.118	1.040	1.311

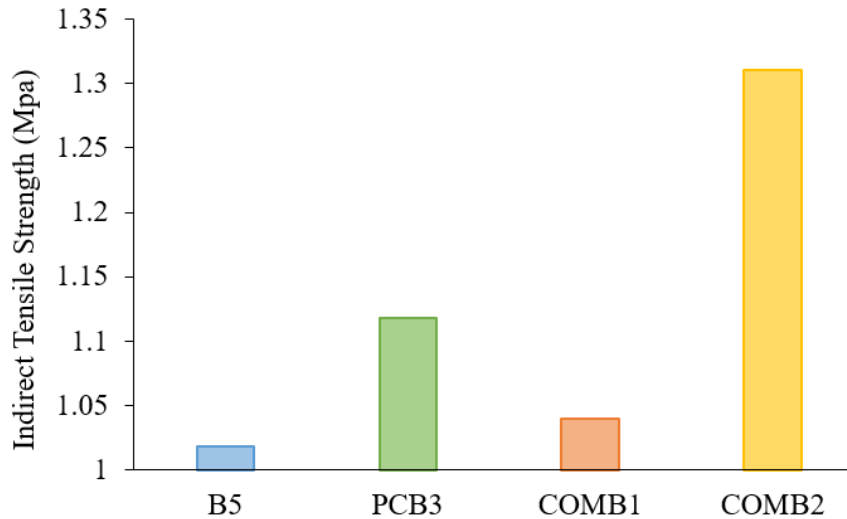


Figure 4.8 Indirect Tensile Strength for unmodified bituminous mix, PCB3, COMB1 and COMB2

However, an Indirect tensile strength test is an indirect measure of resistance to damage of flexible pavement due to rutting and lower temperature cracking [82]. Therefore, the higher ITS value of a modified bituminous mix could ensure more resistivity to failure like rutting and cracking.

4.5 Resistance to Moisture Damage

Previously it was observed that the polymer-modified mix showed better performance than the conventional mix in terms of its resistance to moisture susceptibility [72], [82]. Basing on Marshall stability value, B5PCB3 (Bitumen with 3% PCB), both the combinations and neat bitumen were experimented to evaluate the retained stability value. The retained stability values are presented in Table 4.11. The retained stability (Figure 4.9) indicates that the PCB modified bituminous mix containing 3% PCB retained 85% of its unconditioned stability. For COMB2, the mix retained around 90% of its pre-conditioned stability. These tests further ensured that COMB2 could be considered as the optimum polymer content. Higher retained stability value of modified bitumen indicates more resistant to loss of stability of road due to waterlogging of flexible pavements than neat bitumen [82].

Table 4.11 Retained Marshall stability of modified and unmodified bitumen

Sample ID	Marshall stability (Unconditioned) (kN)	Marshall stability (Conditioned) (kN)	Retained stability (%)
B5	19.84	14.84	74.80
B5PCB3	29.875	25.307	84.71
COMB1	25.583	21.082	82.41
COMB2	25.198	22.752	90.29

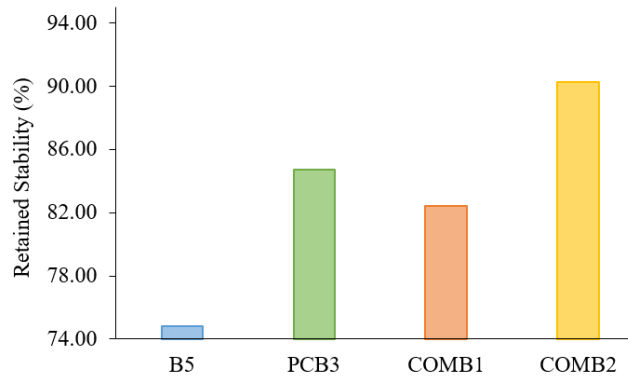


Figure 4.9 Retained stability vs. polymer content (%)

4.6 Summary

This chapter has presented an analysis of all experimental results. Conventional tests were performed for evaluation of the physical properties of modified and unmodified bitumen. From the mechanical properties of the Marshall specimen, it has been observed that polymer-modified bitumen could improve the properties of conventional bitumen. Incorporation of optimum polymer content in traditional bitumen would be able to improve properties like consistency, temperature susceptibility, stiffness, moisture susceptibility, etc. Since our country has to bear a tremendous amount of road maintenance costs every year. Therefore, these findings could be significant to incorporate modified bitumen in the traditional flexible pavement to reduce the cost. In the next chapter, a summary of the findings of this study is provided.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Introduction

There were two significant objectives for this research. The first objective was to evaluate the physical properties of modified and unmodified bitumen. Another objective of the research was to determine the mechanical properties of the modified and unmodified Hot Mix Asphalt Mix (HMA). Overall, at the end of the study, it was expected to achieve an optimum content of a specific modifier. An extensive laboratory investigation was carried out to determine the results. The conclusion based on obtained results is presented in the following section.

5.2 Conclusion

Several tests were performed to evaluate the physical properties (Penetration, Softening Point, Ductility, Specific Gravity) on both neat and modified bitumen. The following conclusions can be drawn from the analysis of these test result:

- In the case of bitumen modified with polypropylene (PP), the penetration value decreased by about 18 % from that of neat bitumen for the addition of 1% polypropylene. On the other hand, the value decreased by about 48.5 % in the case of PCB modified bitumen with the increase of polymer. For COMB1 and COMB2, a decrease of 41.2% was observed. The lowest penetration value was observed in 15 % PCB content.
- In the case of ductility value, a similar decreasing trend was observed. A decrease of 55 % and 70 % in ductility value was observed in the case of PP and PCB modified bitumen, respectively. For combination, the decreasing percentage was 83 %.

- From the softening point result, it was observed that with the increment of polymer content in both cases, the softening point increased. In the case of PP modified bitumen, the value was increased by 8 %. For PCB modified bitumen, it was 4 %. The softening point for each combination was similar to that of neat bitumen (48°C).
- In the case of specific gravity test, the highest value was observed for 15% PCB content. The specific gravity of neat bitumen was 1.035. For all samples, the specific gravity was almost similar to that of neat bitumen content.

Marshall stability and flow test, Indirect Tensile Strength (ITS) tests were performed to evaluate the mechanical properties of modified and unmodified bitumen. To investigate the moisture resistivity of the bituminous mix Retained Marshall Stability test was performed. The conclusion that can be drawn from these tests are given below:

- From the Marshall stability test, an increasing trend was found in the case of all polymers. In the case of PP modified bitumen, the stability increased by 22 % at 3 % PP content. For PCB modified bituminous mix, the highest stability was found at 3 % PCB content. With the increment of PCB content, the stability was decreasing. However, at 2 % PCB content, the stability was decreased by 32 % from that of 3% PCB content. For both combinations, the stability was increased by 29 %.
- In the case of PP modified bituminous mix, the flow value decreased by about 11.3 %. For 3 % PCB, the flow value was decreased by 7.6 %. A reduction of around 2% in flow value was observed in the case of COMB2.
- An increment of 63% in the Marshall Quotient value was observed for 3% PCB content. After that, the value started to decrease with increasing PCB content. In

the case of PP modified bitumen, the value was increased by 38%. For COMB2, a 33% increment was observed in the case of the Marshall Quotient value.

- The bulk density value of the neat bituminous mix was 2.44. For each modified bituminous mix, the value was almost similar to that of unmodified bitumen.
- Basing on stability and flow value, the retained Marshall stability test was performed on the only B5, BPCB3, COMB1, and COMB2 samples. The retained stability was 74.80 % for neat bitumen. For PCB3, it was 84.71%. The highest percentage was observed for COMB2.
- The Indirect Tensile Strength value for neat bitumen was 1.019 Mpa. An increment of 28.7 % in ITS value was observed in the case of COMB2.

5.3 Recommendations for Future Study

Viscosity tests for all samples should be performed for accurate mixing and compaction temperature. To analysis the rheological properties more accurately, some other tests like Film Thickness, Elastic Recovery, Dynamic Shear Rheometer, and Bending Beam Rheometer could be performed. Due to time constraints, the storage stability test could not be performed. Because of the unavailability of the specification of polymer modified bitumen in our country, the obtained result of modified bitumen couldn't be compared with any specification. To evaluate the fatigue life of pavement constructed with the modified bituminous mix, fatigue analysis based on repeated wheel load should be done in the future.

- [1] Mahmud, F. (2019), “*Bitumen demand far outstrips supply*”. The Independent, Dhaka, Bangladesh.
- [2] RHD (2006), Pavement design guide 2006. Ministry of Communication, Roads and Railways Division, Dhaka, Bangladesh.
- [3] “*Bashundhara builds Bangladesh’s biggest bitumen plant*”, The Daily Star, Dhaka, Bangladesh 2020.
- [4] Bhuyan, M. A. (2009) “Evaluation of flexible and rigid pavements construction in Bangladesh”, *M. Sc. Engg. Thesis*, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.
- [5] Kashem, M. A. (2012), “Use of Waste Plastic Blended Bitumen for Road Construction and Maintenance”, *M. Sc. Engg. Thesis*, Department of Civil Engineering, BUET, Bangladesh.
- [6] RHD (2018). Maintenance and rehabilitation needs report of 2018 - 2019 for RHD paved roads 2018, Ministry of Road Transport and Bridges, Bangladesh.
- [7] Hossain, M. A. (2006), “A Study on The Rheological Properties of Polymer Modified Bituminous Binder and Mixes”, *M. Sc. Engg. Thesis*, Department of Civil Engineering, BUET, Bangladesh.
- [8] González, V., Martínez-Boza, F. J., Gallegos, C., Pérez-Lepe, A. and Paez, A. (2012) “A study into the processing of bitumen modified with tire crumb rubber and polymeric additives”, *Fuel Processing Technology*, vol. 95, pp 137-143.
- [9] Daly, W. H. (2017) “Relationship between chemical makeup of binders and engineering performance”, *National Cooperative Highway Research Program, NCHRP Synthesis 511*, Transportation Research Board.
- [10] Loderer, C., Partl, M. N. and Poulidakos, L. D. (2018), “Effect of crumb rubber production technology on performance of modified bitumen” *Construction and Building Materials*, vol. 191, pp 1159-1171.
- [11] Chowdhury, A. T. A. (2017). Turning waste tires into energy 2017, The Financial Express.
- [12] Roy, C., Chaala, A., and Darmstadt, H. (1999), "The vacuum pyrolysis of used tires End-uses for oil and carbon black products" *Journal of Analytical and Applied Pyrolysis*, vol. 51, pp 201-221.
- [13] Islam, M. R., Islam, M. N., Mustafi, N. N., Rahim, M. A, and Haniu, H. (2013), "Thermal recycling of solid tire wastes for alternative liquid fuel: the first commercial step in Bangladesh", *Procedia Engineering*, vol. 56, pp 573-582.
- [14] Nabil, H., Ismail, H., and Azura, A. R. (2013), "Comparison of thermo-oxidative ageing and thermal analysis of carbon black-filled NR/Virgin EPDM and NR/Recycled EPDM blends", *Polymer Test.*, vol. 32, no. 4, pp 631–639.

- [15] Wang, J., Dongshan, N. Y. G., Chunhua, L., Zhanggang, F., Zhongzi, X. (2014), "A new method of fabrication of TiC by employing pyrolytic carbon black and titanium" *International Journal of Refractory Metals and Hard Materials*, vol. 45, pp 137-140.
- [16] Chaala, A., Roy, C., and Ait-Kadi, A. (1996), "Rheological properties of bitumen modified with pyrolytic carbon black" *Fuel*, vol. 75, no. 13, pp 1575-1583.
- [17] Darmstadt, H., Chaala, A., Roy, C., and Kaliaguine, S. (1996), "SIMS and ESCA characterization of bitumen reinforced with pyrolytic carbon black", *Fuel*, vol. 75, no. 2, pp 125-132.
- [18] Wang, H., Lu, G., Feng, S., Wen, X., and Yang, J. (2019), "Characterization of bitumen modified with pyrolytic carbon black from scrap tires", *Sustainability*, vol. 11, pp 1631.
- [19] Feng, Z., Rao, W., Chen C., Tian, B., Li, X., Li, P. and Guo, Q. (2016), "Performance evaluation of bitumen modified with pyrolysis carbon black made from waste tires", *Construction and Building Materials*, vol. 111, pp 495-501.
- [20] Zorrob, S. E. and Suparama, L. B. (2000), "Laboratory design and investigation of the properties of continuously graded asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt)", *Cement & Concrete Composites*, vol. 22, no. 4, pp 233-242.
- [21] Moubark, S., Khodary, F., and Othman, A. (2017), "Evaluation of mechanical properties for polypropylene modified asphalt concrete mixtures", *International Journal of Scientific Research and Management*, vol. 5, no. 12, pp 7797-7801.
- [22] Xu, Q., Chen, H., and Prozzi, J. A. (2010), "Performance of fiber reinforced asphalt concrete under environmental temperature and water effects", *Construction and Building Materials*, vol. 24, pp 2003–2010.
- [23] Sadeque, M. and Patil, K. A. (2013), "Rheological properties of recycled low-density polyethylene and polypropylene modified bitumen", *International Journal of Advanced Technology in Civil Engineering*, vol. 2, no. 2, pp 24-26.
- [24] Otuoze, H. S. and Shuaibu, A. A. (2017), "An experimental study on the use of polypropylene waste in bituminous mix", *Nigerian Journal of Technology*, vol. 36, no. 3, pp 677-685.
- [25] Menaria, Y. and Sankhla R. (2015), "Use of waste plastic in flexible pavements-green roads", *Open Journal of Civil Engineering*, vol. 5, no. 3, pp 299-311.
- [26] Islam, M. A (2008), "Experience on Road Surfacing used by Polymer Modified Binder", Technical Paper Presentation about the LGED Trial Roads using Polymer Modified Bitumen at Asia Pacific University, Dhaka.
- [27] Lu, X. (1997), "Polymer modified road bitumens", *Doctoral dissertation*, KTH Royal Institute of Technology, Stockholm.
- [28] Zhu, J., Birgisson, B. and Kringos, N. (2014), "Polymer Modification of Bitumen: Advances and Challenges", *European Polymer Journal*, vol. 54, pp 18-38.

- [29] Polacco, G., Berlincioni, S., Biondi, D., Stastna, J. and Zanzotto, L. (2005), "Asphalt modification with different polyethylene-based polymers", *European Polymer Journal*, vol. 4, no. 12, pp 2831-2844.
- [30] Giavarini, C., De Filippis, P., Santarelli, M.L. and Scarsella M. (1996), "Production of stable polypropylene-modified bitumens.", *Fuel*, vol. 75, no. 6, pp 681-686.
- [31] Panda, M. and Mazumdar, M. (1999), "Engineering properties of EVA-modified bitumen binder for paving mixes", *Journal of Materials in Civil Engineering*, vol. 11, no. 2, pp 131-137.
- [32] Sengoz, B., Topal, A. and Isikyakar, G. (2009), "Morphology and image analysis of polymer modified bitumens", *Construction and Building Materials*, vol. 23, no. 5, pp 1986-1992.
- [33] Becker, Y., Müller, A. J. and Rodriguez, Y. (2003), "Use of rheological compatibility criteria to study SBS modified asphalts", *Journal of Applied Polymer Science*, vol. 90, no. 7, pp 1772-1782.
- [34] Polacco, G., Muscente, A., Biondi, D. and Santini S. (2006), "Effect of composition on the properties of SEBS modified asphalts", *European Polymer Journal*, vol. 42, no. 5, pp 1113-1121.
- [35] Tayfur, S., Ozen, H. and Aksoy, A. (2007), "Investigation of rutting performance of asphalt mixtures containing polymer modifiers", *Construction and Building Materials*, vol. 21, no. 2, pp 328-337.
- [36] Isacson, U. and Zeng, H., "Low-temperature cracking of polymer-modified asphalt.", *Materials and Structures*, vol. 31, no. 1, pp 58-63.
- [37] Gorkem, C. and Sengoz, B. (2009), "Predicting stripping and moisture induced damage of asphalt concrete prepared with polymer modified bitumen and hydrated lime", *Construction and Building Materials*, vol. 23, no. 6, pp 2227-2236.
- [38] Alataş, T. and Yilmaz, M. (2013), "Effects of different polymers on mechanical properties of bituminous binders and hot mixtures", *Construction and Building Materials*, vol. 42, pp 161-167.
- [39] Ponniah, J. and Kennepohl, G. (1996), "Polymer-modified asphalt pavements in Ontario: Performance and cost-effectiveness", *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1545, pp 151-160.
- [40] von Quintus, H. L., Mallela, J. and Buncher, M. (2007), "Quantification of effect of polymer-modified asphalt on flexible pavement performance", *Transportation Research Record: Journal of the Transportation Research Board*, pp 141-154.
- [41] Ozen, H., Aksoy, A., Tayfur, S. and Celik, F. (2008), "Laboratory performance comparison of the elastomer-modified asphalt mixtures", *Building and Environment*, vol. 43, pp.1270-1277.
- [42] Al-Hadidy, A. and Yi-Qiu (2009), "Effect of polyethylene on life of flexible pavement", *Construction and Building Materials*, vol.23, pp.1456-1464.

- [43] Cassy, McNally, C., Gibney, A. and Gilchrist, M. D. (2008), "Development of a recycled polymer modified binder for use in stone mastic asphalt", *Resources, Conservation and Recycling*, vol.52, issue. 10, pp. 1167-1174.
- [44] Tapkin, S., Cevik, A. and Usar, U. (2009), "Accumulated strain prediction of polypropylene modified marshall specimen in repeated creep test using artificial neural networks", *Expert Systems with Applications*, vol. 36, pp. 11186-11197.
- [45] Whiteoak, D. (1990) "The Shell Bitumen Handbook", *Shell Bitumen UK*, Surrey, pp 149-168.
- [46] Yen, T. E. and Chilingarian, G. V. (1994), Eds., *Asphaltenes ad Asphalls, I. Development in Petroleum Science*, 40, USA.
- [47] Costantinides, G., Lomi, C. and Schromek, N. (1985), "Studio su mescole con APP.", *Riv. Combust. ((Milan)*, vol. 39, no. 1, pp 1-14.
- [48] Boutevin, B., Pietrasanta, Y. and Robin, J. J. (1989), "Bitumen-polymer blends for coatings applied to roads and public constructions" *Progr. Org. Coatings*, vol. 17, pp. 221-249.
- [49] Attaelmanan, M., Feng, C.P. and Al, Al-H. (2011), "Laboratory evaluation of HMA with high density polyethylene as a modifier", *Constr. Build. Mater*, vol. 25, issue 5, pp. 2764-2770.
- [50] Yeh, P. H., Nien, Y. H., Chen, J. H. *et al.* (2005), "Thermal and rheological properties of malleated polypropylene modified asphalt", *Polymer Engineering and Science.*, vol. 45, issue 8, pp. 1152-1158.
- [51] Becker, Y., Méndez, M.P., Rodríguez, Y. (2001), "Polymer Modified Asphalt", *Vision Technological*, vol. 9, pp. 39-50.
- [52] Lesueur, D. (2009), "The colloidal structure of bitumen: Consequences on the rheology and on the mechanisms of bitumen modification", *Advances in Colloid and Interface Science*, vol. 145, issue 1-2, pp. 42-82.
- [53] Nejad, F. M., Aghajani, P., Modarres. A. and Firoozifar, H. (2012), "Investigating the properties of crumb rubber modified bitumen using classic and SHRP testing methods", *Constr. Build. Mater*, vol. 26, issue 1, pp. 481-489.
- [54] Mturi, G. A. J., O'Connell, J., Zoorob, S. E. and Beer, M. D. (2014), "A study of crumb rubber modified bitumen used in South Africa", *Road Materials and Pavement Design*, vol. 15, issue 4, pp. 774-790.
- [55] Al-Dubabe, I.A., Al-Abdul Wahhab, H.I., Asi, I.M. and Ali, M.F. (1998), "Polymer Modification of Arab Asphalt", *Journal of Materials in Civil Engineering*, vol. 10, issue 3, pp. 161-167.
- [56] Nemade, S.N. and Thorat, P.V. (2013), "Utilization of polymer waste for modification of Bitumen in road construction", *Scientific Review and Chemical Communications*, vol. 3, no. 4, pp. 198-213.

- [57] Modarres, A. and Hamed, H. (2014), "Effect of waste plastic bottles on the stiffness and fatigue properties of modified asphalt mixes", *Materials and Design*, vol. 61, pp. 8-15.
- [58] Baker, R.E. (1998), "Polymer Modified Bitumen", *Indian Highways*, January 1998.
- [59] Eme, D.B, Nwaobakata, C. (2018), "Modification of Properties of Hot Mix Asphalt Using Pyrolyzed Carbon Black As Modifier.", *IOSR Journal of Engineering*, vol. 8, no. 10, p 6-12.
- [60] Srikanth, G., Saha, A. and Kumar, R. (2019), "An Experimental Investigation on the Effect of Mixing Procedures on Polypropylene Modified Bituminous Mix." *International Journal of Research Technology and Engineering*, vol. 8. No. 1, ISSN: 2277-3878.
- [61] Habib, Z., Kamaruddin, N. I., Napiah, M. and Tan, I. M. (2011), "Effect of mixing process on polypropylene modified bituminous concrete mix properties", *World Academy of Science, Engineering and Technology, International Journal of Civil and Environmental Engineering* vol. 5, no. 10, pp 477-482.
- [62] Button, J.W. (1992), "Summary of asphalt additive performance at selected sites", *Transportation Research Record: Journal of the Transportation Research Board*, vol. 1342, pp 67-75.
- [63] Elmore, W.E., Kennedy, T.W., Solaimanian, M. and Bolzan, P. (1993), "Long-term performance evaluation of polymer-modified asphalt concrete pavements." Washington, D.C.: Federal Highway Administration.
- [64] Stroup-Gardiner, M. and Newcomb, D.E. (1995). Polymer literature review 1995. St. Paul, Minnesota: Minnesota Department of Transportation.
- [65] Kashiyani, B., Pitroda, J., Umrigar, F.S. (2013), "Plastic Waste : Opportunities for Eco-Friendly", *Proceedings of National Conference CRDCE13*, pp 20-21.
- [66] McDaniel, R. and Shah, A. (2003), Asphalt additives to control rutting and cracking.2003, Washington, D.C.: Federal Highway Administration.
- [67] Dumont, A. G. and Ould-Henia, M. (2004), "Long term effect of modified binder on cracking resistance of pavements.", *Proceedings of the Fifth International RILEM Conference on Reflective Cracking in Pavements*, Limoges, France, pp 5-7.
- [68] Dreessen, S., Planche, J. P., Ponsardin, M., Pittet, M. and A. G. Dumont (2010), "Durability study: field aging of conventional and polymer-modified binders." *Transportation Research Board 89th Annual Meeting Compendium of Papers DVD 10-2127*, Washington, D.C., pp 10-14.
- [69] Hesp, S. A. M., Genin, S. N., Scafe, D., Shurvell, H.F. and Subramani, S. (2009), "Five-year performance review of a northern Ontario pavement trial: Validation of Ontario's double-edge-notched tension (DENT) and extended bending beam rheometer (BBR) test methods." *Proceedings of the Fifty-fourth Annual Conference of the Canadian Technical Asphalt Association*, Moncton, New Brunswick, pp 15-18.

- [70] Erskine, J.A., Hesp, S. A. M. and Kaveh, F. (2012), “Another look at accelerated aging of asphalt cements in the pressure aging vessel.”, *Proceedings of the Fifth Eurasphalt and Eurobitumen Congress*, Istanbul, Turkey, pp 13-15.
- [71] Mahmud, S. M. N., Islam, T. and Rabbi, F. (2015), “Typical Pavement Distresses of Dhaka City Roads.” *International Conference on Recent Innovation in Civil Engineering for Sustainable Development*, Department of Civil Engineering, DUET - Gazipur, Bangladesh.
- [72] Sangita, Khan, T. A., Sabrina, Sharma, D.K. (2011), “Effect of waste polymer modifier on the properties of bituminous concrete mixes”, *Construction and Building Materials*, vol. 25, pp 3841-3848.
- [73] Roads and Highways Department (2011). STANDARD TENDER DOCUMENTS. Government of the People’s Republic of Bangladesh, Ministry of Communications, Dhaka, Bangladesh.
- [74] Fernandes, S., Costa, L., Silva, H. and Oliveira, J. (2017), “Effect of incorporating different waste materials in bitumen”, *Ciência & Tecnologia dos Materiais*, vol. 29, pp 204-209.
- [75] Appiah, J. K., Fernandes, Berko-Boateng, V.N. and Tagbor, T.A. (2017), “Use of waste plastic materials for road construction in Ghana”, *Case Studies in Construction Materials*, vol. 6, pp 6-7.
- [76] Dong, F., Yu, X., Chen, J., Liu, S. and Chen, Q. (2017), “Investigation on Compatibility and Microstructure of PCBs-Modified Asphalt”, *Journal of Applied Polymer Science*, vol. 134, no. 25.
- [77] Li, C., Fan, Z., Wu, S., Li, Y., Gan, Y. and Zhang, A. (2018), “Effect of carbon black nanoparticles from the pyrolysis of discarded tires on the performance of asphalt and its mixtures”, *Applied Science*, vol. 8, no. 4, pp 624.
- [78] Gao, Y., Wu, X., Islam, S. and Hossain, M. (2019). “Evaluation of carbon char in hot-mix asphalt mixture.” *International Airfield and Highway Pavements Conference*, Chicago, Illinois, pp 21-24.
- [79] Asphalt Institute. Mix Design Manual Sixth Edition. Asphalt Institute, Lexington, Kentucky, USA.
- [80] Sinan, H., Emine, A. (2004), “Use of waste high density polyethylene as bitumen modifier in asphalt concrete mix.”, *Mater Lett*, vol. 58, pp 3-4.
- [81] Abdullah, A., Kareem, Y. N. A. (2015), “Fatigue behavior of polypropylene fiber reinforced bituminous concrete mix.”, *International Journal of Engineering Research & Technology*, vol. 4, no. 2, pp 449-453, 2015.
- [82] Khan, A., Imam, M.A. and Roy, A.D. (2018), “Use of crumb rubber in flexible pavements.”, *Proceedings of the 4th International Conference on Civil Engineering for Sustainable Development (ICCESD)*, KUET, Khulna, Bangladesh, pp 9-11.

A-1: Marshall mix design: Stability and Flow value of neat bituminous mixture

Asphalt content (% by Aggregate)	Height (in)	Stability (kN)	correction factor	Corrected Stability (kN)	Flow (mm)	Flow (0.25 mm)
4	2.48	17.311	1.01	17.48411	2.857	11.428
	2.52	18.553	0.986	18.293258	2.606	10.424
	2.51	15.197	0.993	15.090621	2.192	8.768
4.5	2.55	18.022	0.967	17.427274	2.768	11.072
	2.46	16.486	1.027	16.931122	2.697	10.788
	2.5	17.477	1	17.477	2.857	11.428
5	2.53	18.747	0.98	18.37206	2.942	11.768
	2.49	21.691	1.01	21.90791	3.027	12.108
	2.5	20.724	1	20.724	2.792	11.168
5.5	2.48	17.872	1.01	18.05072	2.91	11.64
	2.46	19.02	1.027	19.53354	3.48	13.92
	2.5	23.481	1	23.481	3.902	15.608
6	2.5	16.007	1	16.007	2.11	8.44
	2.49	16.736	1.01	16.90336	4.208	16.832
	2.52	19.423	0.986	19.151078	4.596	18.384

A-2: Density and void analysis of bituminous mixture without polymer

Asphalt content (% by Aggregate)	CA % by wt of aggregate P ₁	FA % by wt of aggregate P ₂	MF % by wt of aggregate P ₃	Sp. Gravity of CA G ₁	Sp. Gravity of FA G ₂	sp. Gravity of filler G ₃	Bulk sp. gravity of aggregate G _{sb}	% by wt of total loose mixture P _{mm}	sp. Gravity of Asphalt G _b	% Asphalt content by wt of total mixture P _b	% aggregate by wt of total mixture P _s	Theoretical maximum specific gravity G _{mm}	Effective sp. Gravity of aggregate G _{se}	Maximum sp. Gravity of paving mixture G _{mm}	Bulk sp. Gravity of compacted mixture G _{mb}
4	49.3	46.4	4.3	2.785	2.6	3.15	2.7091	100	1.035	3.846153846	96.15384615	2.604	2.81756797	2.642522417	2.35
4.5	49.3	46.4	4.3	2.785	2.6	3.15	2.7091	100	1.035	4.306220096	95.6937799	2.543	2.74281924	2.560856285	2.4
5	49.3	46.4	4.3	2.785	2.6	3.15	2.7091	100	1.035	4.761904762	95.23809524	2.543	2.74281924	2.543003705	2.44
5.5	49.3	46.4	4.3	2.785	2.6	3.15	2.7091	100	1.035	5.213270142	94.78672986	2.543	2.74281924	2.525564046	2.44
6	49.3	46.4	4.3	2.785	2.6	3.15	2.7091	100	1.035	5.660377358	94.33962264	2.543	2.74281924	2.508523146	2.48

Asphalt content (% by Aggregate)	Voids in mineral aggregate VMA (%)	Air voids in compacted mixture V _a (%)	Voids filled with asphalt VFA (%)	Avg Corrected Stability (kN)	Unit Wt (kg/m ³)	Avg Flow 0.25 mm
4	16.590	11.070	33.276	16.956	2350	10.207
4.5	15.223	6.281	58.738	17.278	2400	11.096
5	14.221	4.050	71.517	20.335	2440	11.681
5.5	14.627	3.388	76.838	20.355	2440	13.723
6	13.637	1.137	91.662	17.354	2480	14.552

A-3: Indirect Tensile Strength (ITS) result

SL. No.	Specimen	Specimen Height (mm)	Specimen Diameter (mm)	Maximum Load (kN)	Maximum Load (N)	Maximum Strength (N)	Indirect Tensile Strength (kPa)	Indirect Tensile Strength (MPa)	Average IDT (MPa)
1	B5	66.8	98.6	11.868	11868	1.096	1054.96073	1.0550	1.019
2		65.3	97.6	11.886	11886	1.205	1091.905015	1.0919	
3		65.3	97.8	9.917	9917	1.256	909.1601902	0.9092	
1	PCB3	65.95	101.45	13.115	13115	1.373	1147.660878	1.1477	1.118
2		66.35	100.4	11.496	11496	1.204	1010.378855	1.0104	
3		66.43	100.8	12.79	12790	1.339	1118.298889	1.1183	
1	COMB1	67.6	98.55	11.868	11868	1.243	1043.004895	1.0430	1.040
2		67.8	99	11.886	11886	1.245	1036.771311	1.0368	
3		66.8	97.8	9.917	9917	1.038	888.7449165	0.8887	
1	COMB2	67.55	100.75	12.514	12514	1.31	1076.559099	1.0766	1.311
2		65.89	100.96	12.224	12224	1.28	1075.862142	1.0759	
3		65.45	100.89	14.787	14787	1.548	1311.095822	1.3111	