A STUDY ON THE PROSPECTS OF USING POLYMERS IN BITUMINOUS BINDER AND MIXES

BY

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The project titled "**A Study on the Prospects of Using Polymers in Bituminous Binder and Mixes**", submitted by **Md. Shafikul Islam,** Roll No: 100004410F, Session: October 2000, has been accepted as satisfactory, in partial fulfillment of the requirements for the degree of **Master of Engineering in Civil Engineering (Transportation).**

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ABSTRACT

In this investigation an attempt is made to study the possibility of blending some selected polymers with bitumen using low cost manual cooking device and thereby exploiting the potential of polymer modified binder in pavement construction in Bangladesh. Other objectives of the research were to study the properties of modified binder and mixes through laboratory experimentations. The qualitative improvement of polymer modified binder and mixes are studied by comparing their characteristic properties with that of unmodified bitumen and bituminous mixes.

In this study low density poly ethylene (LDPE), poly propylene (PP), ethylene vinyl acetate (EVA) and polyvinyl chloride (PVC) are tested to check their mixing compatibility with bitumen. In order to perform the necessary blending operation, a manually operated simple milling device is fabricated. For laboratory investigation of polymer modified binder and mixes, LDPE is selected as a modifier of bitumen and a total of four modified binders and mixes are prepared with 2.5%, 5%, 7.5% and 10% LDPE contents. The rheological properties of unmodified binder and LDPE modified binder are evaluated by comparing parameters like specific gravity, penetration, ductility, softening point, loss on heating and viscosity. The stripping and coating test is also performed to examine the effect of water and temperature on the coated aggregates. In addition, a non-conventional "film thickness" test is carried out to compare the binder film thickness on aggregate coated with unmodified and modified bitumen. The performance of modified bituminous mixes is evaluated by determining stability, flow, density and void in the mixes.

The study results reveal that properties like penetration, ductility and specific gravity of the LDPE modified binder decrease while the softening point and viscosity increase with the increase in concentration of the LDPE in the bitumen. Experimental results indicate that the LDPE polymer reduces the binder's temperature susceptibility and improves consistency by significant amounts. The film thickness experiment conducted with solid steel spheres shows that the binder coating thickness increases significantly with the increase of the LDPE content in the bitumen. With 10% LDPE content, the increase of film thickness was about 150% as compared to that of the unmodified binder. The coating and stripping tests show that the coating of the LDPE modified bitumen on aggregate is stronger than that of unmodified bitumen on aggregate. From this test it is also observed that better adhesive property of the modified binder makes the bituminous mixes more impermeable to water and delays the stripping process.

The Marshall stability results shows that LDPE increases the stability values of the compacted mixes significantly with increasing LDPE content in the bitumen. It is indicated further that the addition of 10% polymer in the binder increases the resulting mixture stability by about 34%. The flow values as obtained in the Marshall tests show slightly increasing pattern with the LDPE content, whereas unlike stability, the density of the compacted mixes slightly decreases with the increase of LDPE content in the bitumen. The effect of LDPE on air void (Va), void in mineral aggregate (VMA) and void filled with asphalt (VFA) is found insignificant.

The study also reveals that the blending of pure forms of polymer with bitumen can be done by using manual cooking device, but there is a need for fabricating a thermostatically and mechanically controlled blending system to blend waste polymers and to facilitate large-scale production of polymer modified binder.

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LIST OF ABBREVIATIONS

AASHTO	=	Association of American State Highway and Transportation Officials
ABS	=	Acronitrile Butadiene Styrene
AC	=	Asphalt Concrete
Acrilic	=	Polymethyl Methacrylate
ADOT	=	Arizona Department of Transportation
ASTM	=	American Society for Testing and Materials
BS	=	British Standard
BS	=	Butadiene-Styrene
CalTrans	=	California Department of Transportation
CR	=	Crumb Rubber
CRT	=	Crumb Rubber from Tyre
EVA	=	Ethylene Vinyl Acetate
GDOT	=	Georgia Department of Transportation
HDPE	=	High Density Polyethylene
HEATEC	=	Chemical Company
KRATON	=	Branded Polymer (a product of Shell Company)
LDPE	=	Low Density Polyethylene
LLDPE	=	Linear Low Density Polyethylene
POLYBILT	=	Branded Polymer
PE	=	Poly Ethylene
PET	=	Polyethylene Terepthalate
PMB	=	Polymer Modified Bitumen
PP	=	Poly Propylene
PVC	=	Polyvinyl Chloride
RAC	=	Rubberized Asphalt Concrete
RMB	=	Rubber Modified Bitumen
RPE	=	Recycled Polyethylene
SAM	=	Stress Absorbing Membrane
SAMI	=	Stress Absorbing Membrane Interlayer
SBS	=	Styrene-Butadiene-Styrene
SE	=	Styrene-Ethylene
SIS	=	Styrene-Isoprene-Styrene
TPE	=	Thermoplastic Elastomer
VSS	=	Valley Slurry Seal
UB	=	Unmodified Bitumen

CHAPTER 1

INTRODUCTION

1.1 Background

Conventional bituminous binder is susceptible to temperature. Its behavior is greatly influenced by temperature and other environmental factors like air, solar radiation and water. These detrimental environmental agents associated with high traffic loading causes deterioration (cracking, stripping, bleeding, deformation, rutting, fatigue, pot-holes and age hardening) in bituminous pavement. The properties of traditional bitumen, in particular temperature susceptibility, can be improved by adding polymer to it. It has been found that the use of polymer modified binder (PMB) in pavements can lengthen the pavement life span and reduce the frequency of maintenance [I.A. Al-Dubabe et al, 1998, G. R. Ambwani et al, 1993, C. L. Beatty et al, 1995, R. E. Baker 1998, C.T. Chari et al.]. As such, the use of polymer as an admixture is gaining popularity around the world, particularly in developed countries [A. K. Gupta et al, 1997, M. Hossain et al, 1999].

The concept of modification of the quality of bituminous binder is not new. In the mid 1960s, Charles McDonald, a materials engineer, modified bitumen with rubber and studied the performances of rubberized pavement. The study results showed that rubberized bituminous pavement provides greater resistance to bleeding in hot weather and reflective cracking in cold weather. CalTrans (California Department of Transportation) started experiment with rubberized bitumen in 1980 [www.rubberpavement.org]. Better performance of rubber modified bitumen encouraged researchers. Many researchers in different countries, recently have studied the effect of different types of polymers such as Styrene-Butadiene-Styrene (SBS), KRATON [Shell Chemicals], POLYBILT [Exxon], Polyethylene [M. Panda et al, 1997], and Crumb rubber [M. Hussain et al, 1999] on the behavior of bituminous binder and the findings of their research works are very positive. These research findings revealed that the mechanical and rheological properties of bituminous binder are improved when special additive like crumb rubber [M. Hussain et al, 1999] and polymer [I.A. Al-Dubabe et al, 1998] are added.

Polymer, which refers to a very large molecule made of long chains, causes significant change in the stress-strain behavior, the creep response and the non-Newtonian flow patterns in bituminous binder. Improved visco-elastic performance makes the modified binder less susceptible to temperature and causes significant improvement in quality such as resistance to rutting, thermal cracking, stripping, fatigue damage and bleeding. In consideration of improved stability, durability and elasticity, modified binders are being replacing the place of conventional bituminous binder. In many countries, modified binders are being used in all paving and maintenance applications including hot mix, warm mix-cold lay, cold mix, chip seals, hot and cold crack filling, patching and slurry seals [M. Panda et al, 1997]. They are being used extensively wherever extra performance and durability are desired.

Another important reason for using modified binders, particularly in the developed countries, is environmental considerations. The modifiers that are normally used in the modification of raw bitumen viz. scrap tires, polyethylene shopping bags and rubber products are dangerous for environment. As polymer products take a very long time (i.e. say 800 years) to decompose, the dumping of these materials poses a great threat to the environment and make waste management very expensive. To some extent, the alternative use of these environmentally hazardous materials in pavement construction gave a way of reducing waste disposal problem. Although, in Bangladesh the use of thin polythene shopping bag has recently been prohibited, polymer is being extensively used as covers or as containers of different commodities. Moreover, the quantity of scrap tires is increasing rapidly as vehicle ownership is increasing. It is anticipated that their increased volume will pose a great problem in the management of these environmentally hazardous wastes. If these waste materials are useable in pavements, it will minimize the cost of management of these disposed wastes and will be environmental friendly.

In view of these, the proposed study will be important and useful in the context of Bangladesh. It is expected that the proposed study will help to explore the potential of polymer modified binder and thereby would encourage the use of polymer/rubber wastes in pavement construction in Bangladesh.

1.2 Statement of the Problem

Due to poor quality of resurfacing work and lack of proper drainage facilities, the pavements of Bangladesh, particularly in the urban areas, deteriorate quickly after construction. From the field observation it is found that even a good quality pavement losses its serviceability due to inadequate drainage system coupled with movements of heavy traffic under submerged condition (Photo 1.1). Stripping of aggregates is one of the main causes of pavement failure in Bangladesh and this stripping occurs due to the combined effect of wheel load and rain or floodwater. Frequent heavy rain during the monsoon, inundates the roadway pavement in cities and towns. A large portion of roadways pavement undergoes water due to recurrent high flood. The voids in bituminous pavement are filled with water under submerged condition. At this condition, pore pressure is developed by the action of wheel load. This pore pressure creates a tremendous uplift force that eventually breaks the bond between aggregate and binder. Thus aggregate is loosened and lifted by the action of wheel. As a result, stripping of aggregate initiated and "pot hole" like deterioration occurs in the pavement. Thereby, the frequent and prolonged submergence of road causes maximum damage to the pavement. Polymer modified bituminous binder is more viscous than conventional bitumen. As, higher viscosity of polymer modified bitumen (PMB) increases the thickness of aggregate coating, it has the potential to make aggregates more water-resistant and to make the bond between binder and aggregate stronger.

Photo 1.1 Vehicular Movements on Pavement under Submerged Condition

In Bangladesh, the reason for premature failure of pavement is not only the lack of proper drainage facilities but also high temperature in summer period. In summer the weather becomes very hot and the ambient temperature of the pavement reaches near to the softening point of the binder. As a result, during this time the traditional binder become soft and flow condition arises in the pavement. At this flow condition, bleeding of bitumen, heaping and rutting of pavement induced by the movements of overloaded vehicles causes serious riding problems. Photo 1.2 and 1.3 demonstrates such a typical condition of pavement. In Bangladesh this is one of the common mode of temperature induced pavement distresses.

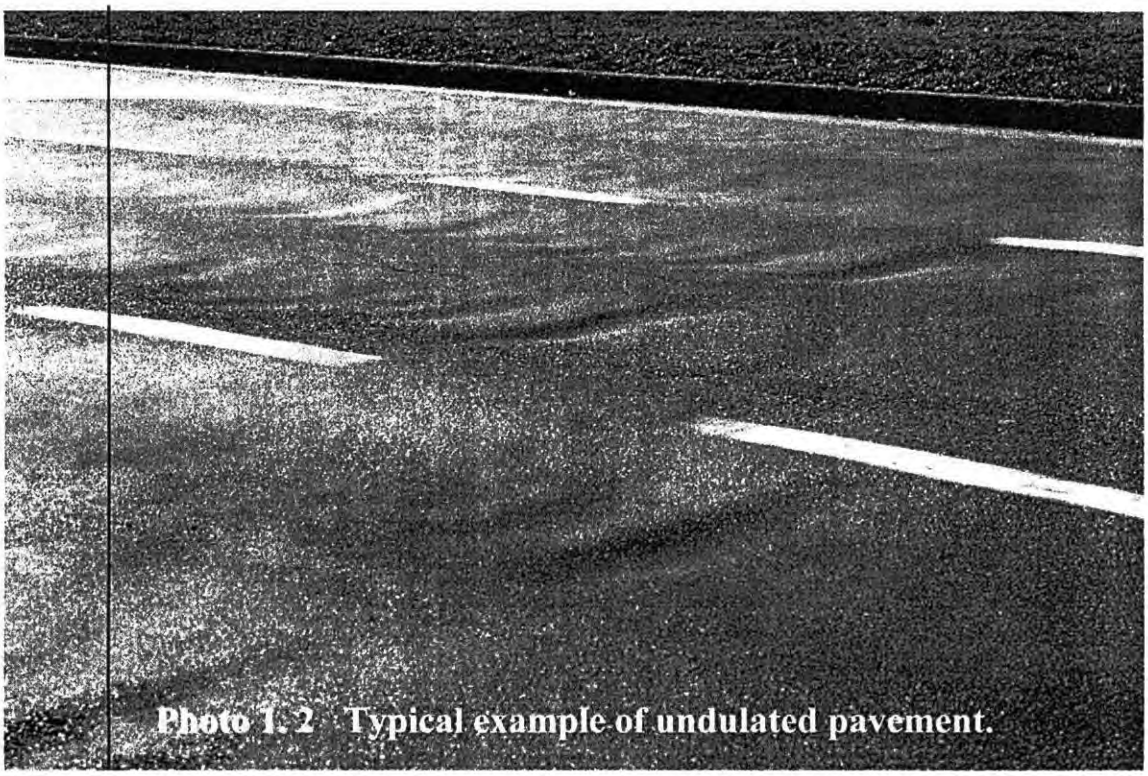


Photo 1. 2 Typical example of undulated pavement.

Photo 1.3 Typical Example of Pavement Rutting.

Further it is to be noted that, during pavement construction, the improper way of heating and lack of temperature control, accelerates the binder aging process and make it more susceptible to low temperature. In consequence, the pavement become brittle and develops cracks even with our moderately cold temperature in the winter season.

Because of these inherent weaknesses in construction practice and severe weather condition of Bangladesh, every year almost all of the major roads in urban area need a massive rehabilitation work particularly immediately after the monsoon period. Frequent maintenance work not only involves large amount of money but also interrupt normal traffic flow and resulting road users' discomfort and delay.

In this regard the use of polymer-modified bitumen (PMB) in pavement construction and as well as rehabilitation work could minimize the frequency of maintenance work and thereby provide an economical solution. PMB, due to its improved visco-elastic properties, has the potential to alleviate some common problems like bleeding, heaping, rutting etc of binder during peak summer temperature and stripping of aggregates in moisture prone areas. As such there is a scope to minimize maintenance frequency by using PMB.

Use of modified bituminous binder has generated considerable interest in the developed countries because of an awareness of the need to conserve fund, energy and natural resources. This need for conservation should be more evident in Bangladesh because of the limited financial resources that can be used for other development programs.

Therefore, there is need for comprehensive study on this topic. Review of literature reveals that no extensive study has so far been undertaken in Bangladesh.

1.3 Objective of the Research

The project is aimed at exploring the possibility of using polymer modified binder (PMB) in bituminous pavement construction with locally available technology and resources. The specific objectives of the proposed project are:

- to device a low cost milling and blending process for production of PMB
- to verify the compatibility of polymer products and thereby select a suitable modifier for use in bituminous pavements
- to determine the engineering and rheological properties of selected polymer modified binders
- to evaluate the performance of polymer modified bituminous mixes

1.4 Scope of the Study

Though there are many types of pure and reclaimed forms of polymer, all of them would not be compatible with bitumen and could not be used as a modifier if the proper blending technique is not followed. Since, all the reclaimed forms of polymer such as rubber, tyre, polythene and plastic products required mechanical means to process, this research work is concerned only with the pure form of polymer, which can be blended manually. Moreover, as the selection of compatible polymer, production of blend and process of evaluation requires huge laboratory work, this investigation will be performed on a single polymer type. Besides, for the selection of a suitable polymer a total of four locally available sources of pure polymer viz. polyvinyl chloride (PVC), ethyl vinyl acetate (EVA), polypropylene (PP) and low-density polyethylene (LDPE) will be studied.

1.5 The Research Program

Considering the fact that two previous research attempts taken at BUET had ended without producing any results due to the lack of proper knowledge on blending technique, in this study especial emphasis will be given to acquire the technical know how of blending process and in particular the fabrication of a low cost blending device. To fulfill this objective of this research work and as well as to obtain adequate information and knowledge on polymer modification, first a comprehensive literature review on PMB will be carried out. After making a blending device with locally available resources, trial will be given with four different types of raw polymer to select a compatible one to work with.

To see the effect of polymer on raw binder, several conventional tests would be carried out both on original bitumen and modified binder. Marshall mix design method will be followed for the evaluation of the properties of the mixes prepared with original and modified bitumen.

The details of the research program are schematically shown in the Figure 1.1.

1.6 Organization of Thesis

In this study the research work carried out is divided into different topics and presented in six chapters.

A brief introduction of statement of the problem is presented in the first chapter with special emphasis on the objectives of the proposed study.

Chapter 2 of this thesis covers a review of recent studies on polymer-modified bitumen conducted home and abroad. It includes, a detail description of polymer including its type, sources, blending, mixing process and as well as mechanics of polymer modified binder (PMB). The benefits of modification of bitumen and application of PMB are also highlighted in this chapter. Finally, a summary of the whole literature review is added at the end of the chapter.

Chapter 3 describes the methodology and investigation techniques employed in this research. The properties of raw materials, which are used in this study, are also briefly presented in this chapter.

The laboratory works are described in Chapter 4. It contains the description of compatibility test of polymer, production of blend, process of blending, blending device, preparation of samples and tests on binder and mixes.

Chapter 5 enumerated the analysis of test results on binder and mixes. It also included the finding on evaluation of PMB as compared to that of traditional binder and mixes.

The conclusions of the entire study and some recommendations for future research are presented in Chapter 6. In order to fabricate a large mechanical blending device with locally available resources and for the production of PMB in large quantity, a schematic diagram of blending device is provided at the end of this chapter.

An appendix is attached at the end of this report, which contains all raw data and graphs.

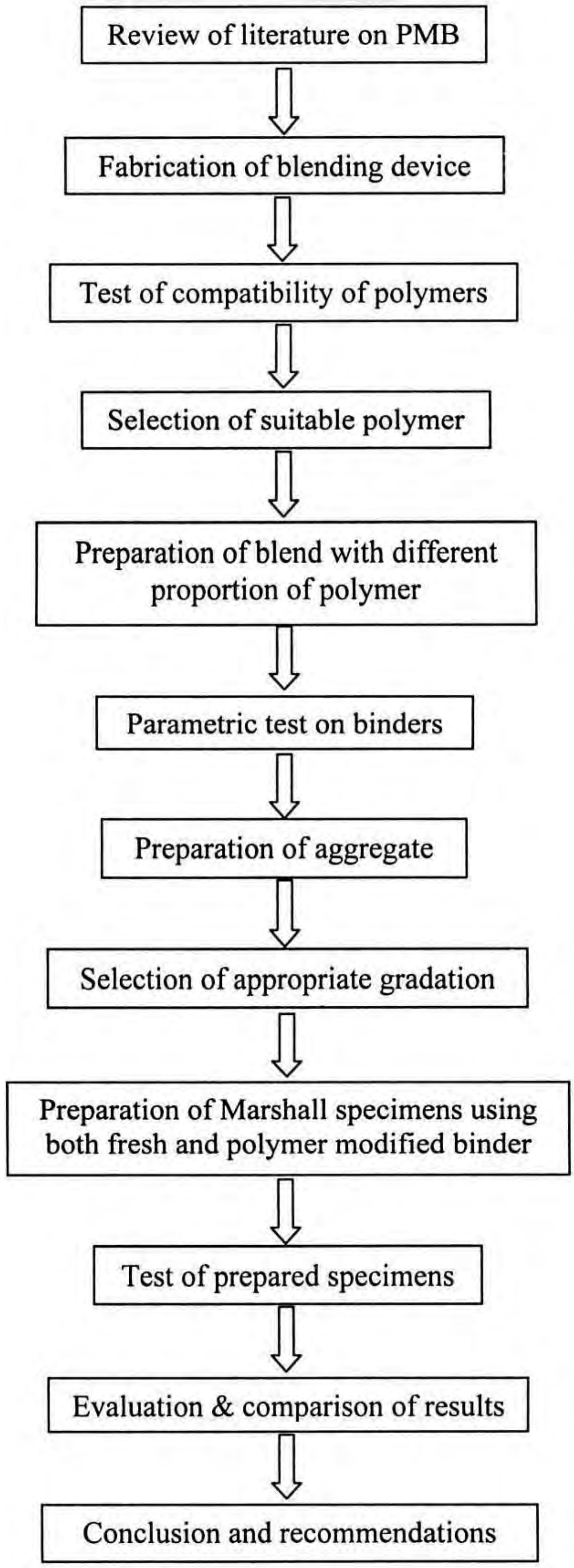


Figure 1.1 Flow Chart Showing Detail of the Study Work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter deals with the general understanding of the polymer, blending mechanism, common sources of polymers and its application around the world. The history of polymer modification, its benefits and field performance evaluation are also highlighted in this chapter. The use of polymer as a modifier of bitumen is not very new. Many countries have been using polymer with bitumen from the last few decades. Scientific research is going on the modification of bitumen with different types of polymer and purposefully new types of polymers are being invented. Besides, some countries are trying to use scrap tyre, polythene bags and plastic bottles from the economic and environmental considerations. This chapter includes a brief discussion on these study reports. It also contains, a comprehensive review of literatures which were collected from different international journals and as well as down loaded from the web site of different pavement construction and chemical companies. Finally, a summary of the literature review is presented at the end of this chapter.

2.2 Modifier

A huge quantity of bituminous binder is required every year for pavement construction. This massive quantity of bitumen comes from the petroleum products and from the natural sources. The sources of bitumen are not unlimited. Hence researchers are thinking of quality improvement of bitumen and trying to extend pavement life. To improve the rheological and mechanical properties of bituminous binder different types of additives are added to it in different forms and in different ways. The recent trend of pavement industry is to use polymer as a modifier of bitumen as polymer is to some extent similar in nature to some constituents of bitumen. Bitumen itself is a complex mix of different compound. The major constituents of bitumen are asphaltenes and malthenes. Aromatic malthenes and asphaltenes content [R.E. Baker, 1998] play a major role in the suitability of bitumen modification. Due to the similar in nature polymer and copolymer of different category and grade are being used as the modifier of bitumen for its overall quality improvement. Polymer increases the viscosity [M. Murphy et al, 2001; A.A. Yousefi et al, 2000] of bitumen and increases the thickness of coated film around the aggregates. Thus the adhesive and cohesive properties of bitumen are improved. Natural rubber (in powder or latex form) [M.M. Kumar et al, 2001] or recycled rubber dust [M. Hussain et al, 1999] are another potential modifier of bitumen. The scrap polyethylene [M. Panda et al, 1997] is also possible to use in modification of binder.

2.3 Rubber

Rubber is produced from the juice of a tropical plant or manufactured artificially. Natural rubber collected from the rubber trees is a thick, white liquid. This raw rubber is called latex. Latex contains about 30 percent dry rubber content. Latex is centrifuged to increase the percentage of rubber content in it. Natural rubber is vulcanized with sulphur and other materials to make it less susceptible to temperature. The tyres of vehicles and automobiles are made of vulcanized rubber. Rubber is more elastic than polymer. Both natural rubber and the crumb rubber from the used tyres of vehicles can be used for the modification of bituminous binder. Scrap rubber may be used in aggregate during pavement construction to improve riding quality [Infratech Polymers Inc.; Rubberized Asphalt Concrete Technology Centre, 2000] and reduce noise of vehicular movement [Web Article, Public Works Department, The City of Thousand Oaks, USA].

2.4 Polymer

Polymer modified bitumen is an important material for constructing and maintaining pavements. But what are polymers? The term "polymer" simply refers to a very large molecule made by chemically reacting many (poly) smaller molecules (monomers) to one another in long chain or clusters. The physical properties of a specific polymer are determined by the sequence and chemical structure of the monomers from which it is made. When polymers are added to bitumen, the properties of the modified bitumen depend on the polymer systems used [A. Peterson, 1998]. The molecules of polymers are very much larger than that of bitumen. So, when combined with bitumen, polymer creates drastic changes in the physical properties of the final binder.

Polymers are visco-elastic material. Polymer will recover its original shape from deformation after the removal of stress. Again it will reach the flowing condition when heated to temperature near the melting point. The response of polymer can be classified into three types – elastic response, elastomeric response (time dependent elasticity) and viscous (plastic) response. The response of any polymer will depend upon the structure and the conditions of loading in terms of time and temperature. When mixes with bitumen the polymer will impart its elasticity and flow resistance to the bitumen if the polymer and the bitumen are compatible.

Different kinds of polymers and copolymers are available in the market. Each kind of polymer may have different grade. All types of polymer available in the market cannot be used for modification of binder; some polymers are thermoplastic in nature where as some are elastomeric. Elastomeric and thermoplastic polymers play an important role in the modification of bitumen. Bitumen modified with elastomer behaves very differently from conventional bitumen. It becomes more elastic throughout the temperature experienced on the road. At low temperature, it is less stiff and its ductility and Fraass breaking points [Shell Chemicals] are improved.

2.4.1 Types of Polymers

Polymer is a chemical compound. It is manufactured artificially in chemical industry to use in various purposes. There are different groups of polymer. Each group of polymer has its own characteristics. Within each group there are many option regarding molecular weight, structural form, composition of their monomers and physical state. The subject of polymers is thus very complex. Polymers can be classified according to their nature, molecular weight and density. A simple classification [R. E. Baker, 1998] of polymer can be as follows.

Thermoplastic Polymer (plastic like): These types of polymer are linear or slightly branched. These polymers can be melted and reshaped. They are recyclable. Thermoplastic polymers are used for pavement application. Examples of this type polymer are polyvinyl chloride (PVC), poly ethylene (PE), ethylene vinyl acetate (EVA), poly propylene (PP), polyethylene terepthalate (PET), linear low density polyethylene (LLDPE), high density polyethylene (HDPE), acronitrile butadiene styrene (ABS), polymethyl methacrylate (Acrilic).

Elastomer (rubber like): The molecular structure of this type polymer is usually linear. The copolymers of this group have radial form of molecular chain. The most potential modifiers are available in this family. Examples of these types of polymers are styrene butadiene styrene (SBS), synthetic rubber, neoprene latex, natural latex etc.

Thermo-harden polymers: Thermo-harden or thermosetting polymers are not recyclable. They cannot be remolded or reshaped if once manufactured to final product. The most common thermo-harden polymers are celluloid, bakelite, epoxy resins, poly eurothanes etc.

Classification of Polymers

a) Based on structure

Linear: The molecular chain of this type polymer is unbranched. It has low melting point and high flow index compared to others. Such as linear low-density polyethylene (LLDPE), linear high-density polyethylene (LHDPE) and linear polypropylene (LPP).

Nonlinear: The chain of this polymer is branched. This type of polymer has high melting point. Example of nonlinear polymer is radial SBS.

b) Based on density

Low Density Polymer: The molecular weight of this polymer is less compared to other. Example of low-density polymer is LLDPE.

High Density Polymer: The molecular weight of this type polymer is high compared to other polymers. Example of high-density polymer is HDPE (high-density polyethylene).

c) Based on physical form

Pellet: Most of the polymers available in the market are in pellet form.

Powder: Polymer also available in powder or latex form.

Latex: Natural rubber collected from the trees is in latex form.

Recycled: Recycled rubber or polymer is at present being used in binder modification.

2.4.2 Potential Polymer for Bitumen Modification

It is stated earlier that all available polymer will not improve the performance of bitumen. The polymers that are compatible with bitumen can improve its property. The compatibility of polymer with bitumen depends on not only the type of polymer but also on its structure, molecular weight and chemical composition. Compatibility also depends on the characteristics of base bitumen. The source of base bitumen, its constituent compound and its grade are the key factors [R. E. Baker, 1998] that determine weather the polymer will improve its quality or not. Hence the identification of potential compatible polymer is the first stage of modification of bitumen. Incompatible polymer cannot be blended with bitumen. The better way is to find compatible polymer is the preparation of several trial blends with the candidate polymer and testing its properties. I. A. Al-Dubabe et al [1998] at the King Fahad University has performed test on some selected polymers. To blend the polymer they assembled a special blender. The blender comprised of a shear blade, a heating oil bath and a DC motor capable of producing rotation up to 3000 rpm. They followed the recommendations of the manufacturer of the polymers to approximate the tentative polymer concentrations, blending time and blending temperature for each of the collected polymers. They have used 500 gm of base bitumen for each type of polymer to prepare blend. The homogeneity of blending was ensured by visual inspection using an optical microscope. They performed shear modulus test, phase angle test, and softening point test on the prepared blend. They also performed economic analysis on the blend. Based on the technical and economic analysis they suggested PP, LLDPE, SBS, CRT as appropriate polymers. Their recommended blending temperature for some selected polymers and some properties of modified binders are presented in Table 2.1

Table 2.1: Properties of Some Selected Polymer Modified Binders and Their Blending Temperatures.

Concentration of polymer in bitumen	Grade of polymers	Complex shear modulus at 70°C	Phase angle at 70°C degrees	Softening point (°C)	Recommended blending temperature (°C)	Maximum blending temperature (°C)
Pure Bitumen	------	737.0	88.2	49	------	------
LLDPE6%	M	3463.5	84.4	60.8	160-170	200
HDPE 6%	M	2885.9	84.7	62.2	------	-------
PP 3%	500U	2556.7	81.2	61.8	170-180	200
SBS 6%	------	6428.1	57.1	89.2	160-170	200
CRT 10%	------	2695.1	73.6	58.2	170-180	200

2.4.3 Polymer that can be used as Modifier

Polymers can be classified into two major class based on their responsive nature to heat: thermoplastic and thermoharden. The product of thermoharden polymer cannot be remolded. So this type of polymer cannot be used as modifier of bitumen. Thermoplastic polymers are recyclable. Polymers that will be used as modifier of bitumen must be recyclable. In fact any thermoplastic polymer can be used as modifier of bitumen if it is compatible to bitumen. Thus selection of polymer to be used in bitumen primarily depends on compatibility.

Again the purpose of polymer modification of bitumen is to construct durable pavement with greater stiffness and stability in order to minimize maintenance cost. So economy is the major considerable factor. Frequent maintenance of road pavement not only involves much money but also interrupt normal traffic movements. Economic benefits may be attained in two ways. One way is building of high performance road of longer life span. Here the initial cost of pavement construction with PMB may be a little higher than that of pavement constructed with conventional binder. But maintenance cost is saved in this case. The other way is use of such (reclaimed) polymers [M. Panda, 1997] with binder that pollute the environment. Use of these polymer (scrap/reclaimed) will reduce the requirement of binder of certain percentage and will keep the environment safe.

Any thermoplastic elastomer (TPE) [Shell Chemicals] can be used as modifier based on economic and technical analysis. Investigations were made on low density polyethylene (LDPE), poly propylene (PP) [I. A. Al-Dubabe et al, 1998], ethylene vinyl acetate (EVA) [M. Panda Et al, 1999], crumb rubber (CR) [M. Hussein et al, 1999], and recycled polyethylene (RPE) [M. Murphy et al, 2001] by many investigators. EVA, CR and RPE have potential to be used in bitumen modification. Shell and Exxon chemicals introduce styrene butadiene styrene (SBS) and POLYBILT polymers respectively. These two polymers are specially manufactured to use as bitumen modifier. Shell chemicals supply SBS in powder or latex form. POLYBILT is available in pellet form. HEATEC (a chemical company) supplies polymer-bitumen blending system. Valley Slurry Seal (VSS), Colas, Vogele and Akzo Nobel are working with PMB. Rubberized roads are being built in USA, UK, Portugal, Egypt and Middle East [World Highways, September 1998]. India is using waste polythene in pavement.

2.4.4 Properties of SBS / KRATON Polymer

Styrene-Butadiene-Styrene (SBS) co-polymers were invented by the Shell Chemical Company in 1960. It belongs to thermoplastic elastomer (TPE) or Styrene block co-polymers. There are three main groups of Styrene block co-polymers. These three groups are SBS, SIS (Styrene-isoprene-Styrene) and Styrene-ethylene (SE)/Butadiene-Styrene (BS). SBS and SIS are composed of two very different polymers. The elementary polymers are chemically united strongly in the chain. The chain is formed by two hard thermoplastic Poly-Styrene end blocks & a highly elastic rubber in the mid block.

Styrene-Butadiene-Styrene (SBS) can be linear or radial in structure (Fig.2.1). Linear SBS is normally used in road bitumen and radial SBS is used in roofing. SBS is used mainly for bituminous joint sealants and to improve the adhesive quality of surface dressing binders [Shell Chemicals]. Styrene-ethylene/Butadiene-Styrene (SE/BS) is used for road and roofing application where high resistance to oxidative and thermal attack is required.

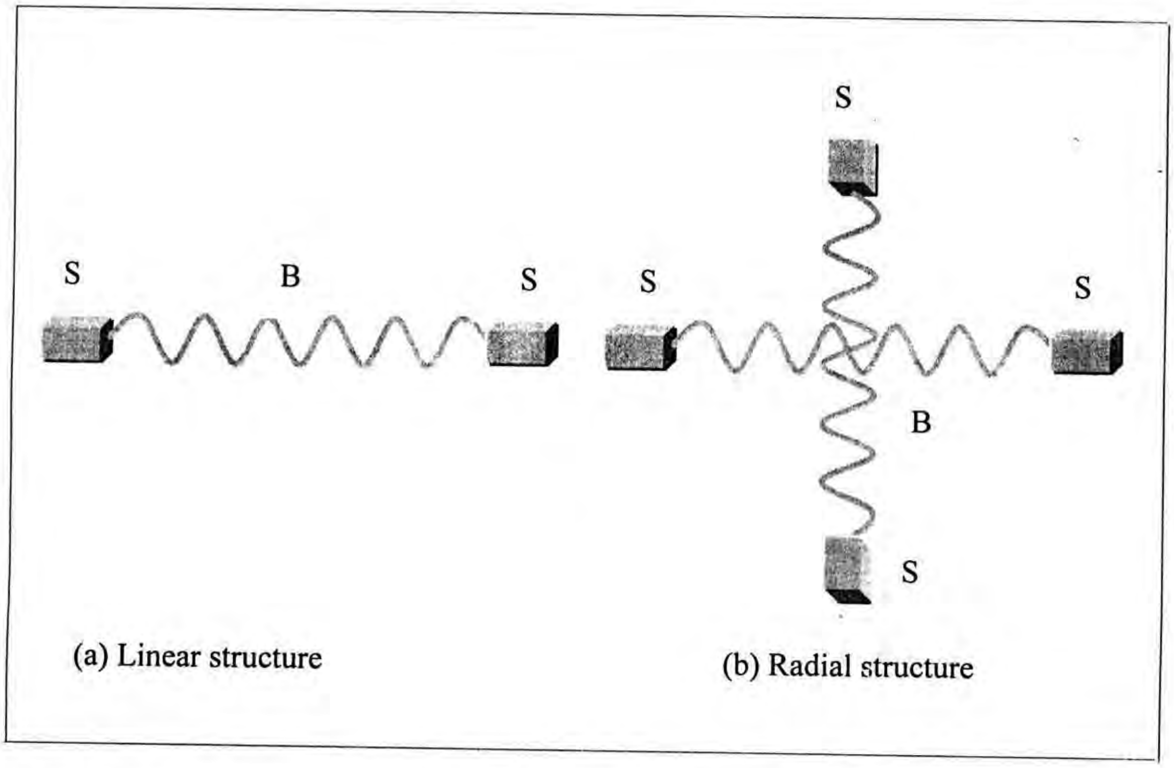


Figure: 2.1 Molecular Structure of SBS Polymer. [Source: Shell Chemical]

Recently Shell Chemical Company has upgraded SBS to a new grade polymer branded as KRATON. KRATON polymers are compatible to bitumen. It has improved processing quality and durability. KRATON-D is most well known grade of KRATON polymers that improves the rheiological properties of bitumen. When KRATON-D is added to hot bitumen the polymer absorbs malthenes from the bitumen and swells by up to nine times its initial volume [Shell Chemicals]. As the temperature of bitumen decreases, the polystyrene end blocks form domain below 100°C. The polystyrene end block gives strength to the structure and the poly-butadiene mid block gives the material exceptional elasticity. When the bitumen heated again above 100°C the polystyrene end block softens and the material flows again.

2.4.5 Benefits of Polymer Modification of Bitumen

The purpose of polymer modification is to improve the quality of binder. Use of polymer some time may increase cost of construction. In this case the benefit is evaluated by quality improvement of pavement. The use of RPE (recycled polyethylene) and CR (crumb rubber) give benefits in quality improvement and cost effectiveness. The benefits of PMB are assessed in three ways.

Quality improvement of binder: Polymers in bitumen improve the following quality of bitumen.

- ◊ Polymer increases the elasticity of bitumen [Shell Chemicals].
- ◊ It raises the softening point of binder that helps in reducing bleeding.
- ◊ It reduces the Fraass breaking point temperature [Shell Chemicals].
- ◊ It increases the cohesion of binder.
- ◊ It provides improved aging quality.
- ◊ It reduces thermal susceptibility.

A significant improvement in pavement is possible as-

- ◊ It increases flexibility of pavement.
- ◊ It reduces deformation in pavement.
- ◊ It provides greater fatigue resistance [Shell Chemicals].
- ◊ It provides greater resistance to stripping.
- ◊ It provides improved self-healing properties.
- ◊ It provides greater durability.
- ◊ It provides longer life span [Arizona Department of Transportation, (ADOT)].

In surface treatment, the achievable performance benefits are

- ◊ Reduced fretting, cracking and rutting [Shell Chemicals].
- ◊ Less bleeding
- ◊ Very skid resistant [ADOT].
- ◊ Long lasting color contrast.
- ◊ Noise reduction [ADOT].
- ◊ Stress absorbent.
- ◊ Impermeability

Environmental improvement: Waste polymers and rubbers are hazardous for environment. They take at least 800 years to decompose [E. Hoque, 1996]. The use of waste polymers and tyres in pavement may be a good solution of managing these environmentally hazard materials. Disposal of waste polymers is a matter of great concern and there is no suitable method to exploit it. Moreover the quantity of used tyre is increasing as the vehicle ownership is increasing every year. A lot of scrap polymers are being produced every day. The effective use of these materials as modifier of bitumen will save the environment.

2.5 Process of Blending

2.5.1 General

The major task of polymer modification of bitumen is the blending of polymer with bitumen. Blending depends on the compatibility [R. E. Baker, 1998] of polymer and bitumen to each other. Incompatible polymer cannot be blended with bitumen. Compatibility is the main considerable factor for the preparation of blend. There are two processes of blending. The processes are described in article 2.5.4 and 2.5.5

2.5.2 Compatibility

A polymer can be considered compatible with particular bitumen when the visible changes in the colloidal mixer of the bitumen do not arise. A manifestation of incompatibility can be noted by precipitation of asphaltenes and oil exudation by blend. The compatibility of polymer with bitumen depends upon the type and grade of polymer system, its structure (linear and radial), molecular weight and density. Linear and low-density polymer is more compatible with bitumen. The lesser the molecular weight the higher the compatibility [R. E. Baker, 1998]. But polymers having too low molecular weight impart very low cohesion to the bitumen.

The composition of base bitumen has a tremendous effect on compatibility. Bitumen is a complex mix of different chemical compound with different molecular weight. The constituent of bitumen can be classified as asphaltenes (compound containing heavy carbon particles) and malthenes (paraffin, aromatic compound and resin). Asphaltenes and malthenes play an important role in polymer modification of bitumen. But high asphaltene content is not desirable because bitumen containing high amount of asphaaltene compound will loss compatibility specially when high percentage of polymers are desired to be added. Again too low content of asphaltenes will prevent proper compatibility. The aromatic content of malthenes also influences the homogeneous mixing of polymer and bitumen. In short, the success of blending of a polymer with particular bitumen will depend on the following three important factors.

1. Chemical composition of bitumen.
2. Composition, type or grade of polymer.
3. Blending process

2.5.3 Dry Process

Dry process is suitable for crumb rubber. Crumb rubber is used as aggregate instead of modifier of binder. The dry process blends the crumb rubber with aggregate and bitumen without using any special equipment required by other processes. Recycled rubber tyre is sized in a particular form. This particular size of rubber aggregate is used in gap-graded aggregate to fill up the gap. The dry process has been used extensively in Southern California in USA [www.rubberpavement.org]. Shock absorbing pavement for children play ground is being built with rubber aggregate.

2.5.4 Wet process

In wet process polymer/rubber is mixed with bitumen to produce a composite material of bitumen and polymer. The resulting material is then used as binder in pavement construction. Wet process is the most common method of polymer modification of bitumen. This process requires special equipment to blend polymer. There are two wet process. They are 1) Chemical reaction process and 3) Blending process.

Chemical Reaction Process: Polymer chemically reacts with bitumen and produces blend. The process is performed at the refinery. Obtained blend from this method has higher storage stability.

Blending Process: This process may be called cooking process and suitable for scrap polymer and rubber. Polymer/rubber is cooked in the bitumen in this process. This method requires a blending/cooking system. Major parts of the blending equipment are a container, a mechanical stirrer with shear blade and controlled heating facilities. Bitumen is heated in the container to make it liquid. Then the polymer in particular form (powder, pellet, latex) is added to the bitumen and stirring is continued up to completion of blending. Required blending time and temperature and speed of stirrer depend on the type of polymer used.

2.5.5 Factors Influencing Blending

The process of blending of compatible polymer with bitumen is affected by the following factors.

Blending Mechanism: Blending of bituminous binder with polymer is not an easy task, because two complex materials are forced together to form a two-phase system. The polymer must disperse uniformly into bitumen. Hence it is required to provide high shear force during blending. The configuration of shear blade of the stirrer of blender and the speed of the stirrer determine the shear rate. The speed of the stirrer should not be less than 2500 rpm [I. A. Al-Dubabe et al, 1998]. However some polymer do not require high shear force such as EVA and LLDPE.

Blending Time: The duration of blending time depends on the blending temperature and applied shear rate and on the complexity of polymer system. Blending time should be kept minimum by adjusting blending temperature and applied shear rate. Too long blending time may cause the change of rheological properties of PMB.

Blending Temperature: Blending of polymer should be performed within a specified temperature range. It is an important factor. Without controlling the temperature it is not possible to prepare blend properly. The blending temperature mainly depends on the molecular weight of the polymer. Polymer of higher molecular weight requires higher blending temperature [I. A. Al-Dubabe et al, 1998; R. E. Baker 1998]. Blending temperature of particular polymer is above its melting point.

2.5.6 Storage Stability of Blend

Storage stability can be defined as the quality of blend for which it can be preserved for future use without physical and chemical change. It is an important factor to be considered to store prepared blend. Storage stability indicates successful blending and better compatibility of polymer with bitumen. In fact storage stability is a measure of compatibility.

The polymer modified bituminous binders are generally two phase system in which the polymer is dispersed in to the bitumen. The storage stability of PMB is necessary to store it for future use. Study on storage stability of PMB expresses that quick cooling of blend has least effect on storage stability, storage at room temperature has moderate effect and hot storage has adverse effect [Xiaohu et al, 1999; I. A. Al-Dubabe et al, 1998] on stability of blend. Xiaohu et al[1999] studied phase separation of SBS polymer modified bitumen. They prepared SBS modified binders and tested its storage stability. They concluded as "the introduction of SBS polymer disturbs the dynamic equilibrium and reduces the homogeneity of the bitumen system. Under the influence of gravitational fields a phase separation can occur in which the associated asphaltenes (asphaltene rich phase) settle to the bottom, while the swollen SBS polymers (polymer rich phase) move to the top of modified binders. The two phases differ considerably in rheological behavior and their effects on binder properties are dependent."

It has been shown that the "phase separation of SBS modified binder is influenced by the nature of the base bitumen and the characteristics and content of polymers. At a given SBS content, the modified binders produced from the bitumen with higher content of aromatics exhibit a lower phase separation. An increase in asphaltenes may increase the phase separation, which in turn increases with the SBS content. Compared with the modified binders containing the branched SBS, the linear SBS modified binders display a lower phase separation during hot storage."

2.6 Evaluation of Modified Binder

The conventional tests (Penetration, Softening Point etc.) that are generally performed to evaluate the quality of bitumen cannot measure adequately the significance improvement of modified binder. Polymer improves elastic properties of bitumen and that can be measured by elastic recovery test of binder.

The elastic properties of binder can be evaluated by the elastic recovery test. It is a very simple test. In this test, a test specimen (3 cm long) made of binder is elongated to 20 cm to 50 cm at specified temperature (13°C) and cut into two halves. After one hour elastic recovery is measured as a percentage of the applied strain. Following figure (Figure No. 2.2) represents typical results of the elastic recovery test of SBS modified bitumen. The results are collected from the report published by the Shell Chemicals. The results show that polymer improves elastic recovery of bitumen very noticeably.

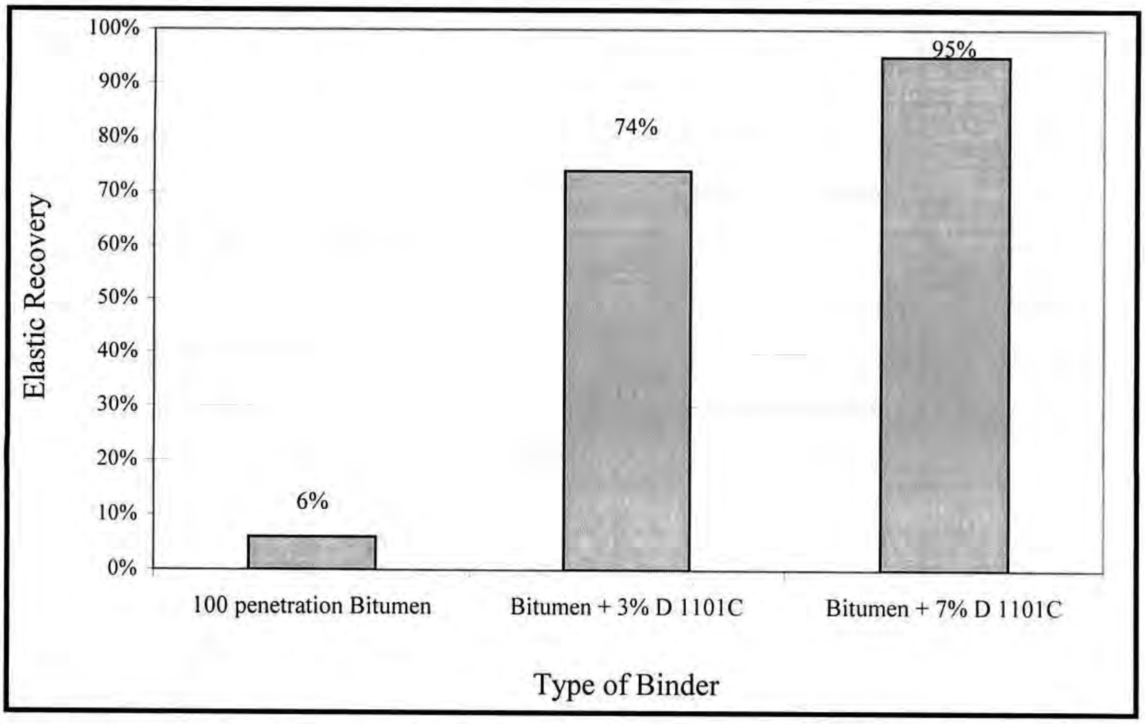


Figure 2.2: Elastic Recovery Test Results of Unmodified and SBS Modified Bitumen [Source: Shell Chemical]

2.7 Some Study Results

Although the application of polymer modified bitumen (PMB) in pavement construction can reduce the frequency of maintenance, no study on PMB is performed yet in Bangladesh. A few students tried to study the properties of recycled rubber modified bitumen and RPE modified bitumen. But their research work was abandoned at the preliminary stage for want of proper procedure and information. But it is necessary to study the performances of PMB from the consideration of economy and environment. Many countries are researching on PMB to study its behavior. The preparation of modified binders with Ethylene Vinyl Acetate (EVA), Crumb Rubber (CR) and Recycled Polyethylene (RPE) and some of the study results [M. Panda et al, 1999, M. M. Kumar et al, 2001] are presented in the following articles.

2.7.1 EVA Modified Binder

M. Panda et al [1999] studied the engineering properties of Ethylene Vinyl Acetate (EVA) modified bituminous binder for paving mixes. Their process of binder preparation is described here shortly. Some properties of EVA modified binder is shown in Table 2.2 and in Table 2.3

Table 2.2: Physical Properties of Binder at Different EVA Concentrations

EVA Concentration	Grade of EVA	Penetration at 25°C (1/10th mm)	Softening Point (°C)	Ductility, 27°C (cm)	Specific Gravity
0	Bitumen	88	44	100+	1.032
2.5	1802	55	59	72	1.027
	2806	65	54	102	1.030
5	1802	45	68	43	1.022
	2806	51	61.5	75	1.020
7.5	1802	39	72	27	1.020
	2806	42	64	50	1.023
10	1802	35	74	18	1.015
	2806	39	66	35	1.016

Preparation of Binder: The production of EVA modified binder was described by M. Panda et al as "400gm of bitumen was heated on an electric hot plate with manual stirring to avoid local overheating. As the bitumen attained a temperature of 165°C, 5% by weight of 2806 EVA was added and mixed manually for about 5 min. With the cover properly fitted to the container, the mixture was then vigorously agitated for about 20 min by a 186.5 W (1/4 hp) mechanical stirrer rotating at 3000 rpm. Care was taken to maintain the temperature between 160°C and 170°C. The uniformity of dispersion of EVA in the binder was confirmed by passing the binder at 165°C through an ASTM 100 sieve."

Table 2.3: Marshall Properties at Optimum EVA Modified Binder Content

EVA Content in Binder (%)	Optimum Binder Content in Mix (%)	Marshall Stability (lb)	Flow Value (1/100 inch)	Unit Weight (lb/cft)	Air Voids (%)
0	5.50	2157	12.8	143	3.8
2.5	5.75	2641	13.8	143	4.0
5	6.00	3079	14.2	142	4.0
7.5	6.30	3180	15.0	141	4.0
10	6.60	3304	15.0	141	3.4

2.7.2 Rubber Modified Binder

The characteristics of rubberized bituminous mixes are studied by M. M. Kumar et al [2001]. They have used natural rubber latex, centrifuged latex and tyre dust as modifier. Their results of Marshall test are presented in Table 2.4 and in Table 2.5.

Table 2.4: Marshall Properties of Centrifuged Latex Modified Binder

Centrifuged Latex (%)	Specific Gravity	Unit Weight (lb/cft)	Marshall Stability (lb)	Flow Value (1/100 inch)	Air Voids (%)	VMA (%)	VFB (%)
0	2.33	148	2544	9.1	4.0	16.62	74.94
1	2.337	147	2256	11.0	4.8	10.41	53.89
1.5	2.339	148	2625	10.6	4.7	10.38	54.72
2	2.341	148	2706	9.4	4.6	10.34	55.53
3	2.359	149	2670	10.2	3.8	9.62	60.48
4	2.381	149	2596	11.4	2.6	8.47	69.35

Table 2.5: Marshall Properties of Tyre Dust Modified Binder

Tyre Dust (%)	Specific Gravity	Unit Weight (lb/cft)	Marshall Stability (lb)	Flow Value (1/100 inch)	Air Voids (%)	VMA (%)	VFB (%)
0	2.33	148	2544	9.1	4.0	16.62	74.94
1	2.32	148	1775	6.3	5.58	11.22	50.27
5	2.34	149	3142	8.7	4.2	10.28	59.14
10	2.30	146	2243	7.5	5.08	11.72	56.66
15	2.27	144	1018	6.7	5.65	12.86	56.07

2.7.3 RPE Modified Binder

The performances of RPE modified binder were also studied by M. Panda et al [1997]. They use reclaimed polyethylene (shopping bag) to modify bitumen. Their test results on binder are presented in Table 2.6.

Table 2.6: Physical Properties of RPE Modified Binder.

RPE Content by % Weight of Bitumen	Penetration, 25°C ($1/10^{th}$ mm)	Softening Point, (°C)	Ductility, (cm)	Specific Gravity
0	88	44	100+	1.042
2.5	64	51	73	1.034
5	47	55	60	1.028
7.5	39	61	51	1.021
10	18	81	6	1.012

2.8 History of PMB/RMB

The use of modified binder in road construction has been started in the mid 1960s in the city of Phoenix in USA. Charles McDonald, the material engineer for Phoenix city produce a bitumen blend using approximately 8% crumb rubber from scrap tyres in this year. To evaluate the binder the city built a test road of half mile long with rubberized chip seal. The performance of this test road was so good that the city constructed 3000 lane miles of rubberized asphalt chip seal between 1967 to 1988. In 1980, California Department of Transportation (CalTrans) began experimenting with rubberized asphalt and provided a design procedure that was approved by the Federal Highway

Administration in 1990. The county of Los Angeles used rubber in bitumen first in 1970. In 1985 a street of this county was resurfaced with rubber-modified bitumen and no reflective crack was seen in these days. The use of rubberized asphalt concrete (RAC) greatly increased in Los Angeles from 1992. By using crumb rubber in roadway pavement the county diverts scrap tyres from landfills, which was creating environmental hazard. A local road of the county of Sacramento was resurfaced with 1-1/2 inches rubberized bitumen in 1989. The Department of Public Works of this county constructed 210 lane miles RAC resurfacing using nearly one half millions scrap tyres. A noise study survey was conducted in the city of Thousand Oaks constructing rubberized roads and conventional road. The study result showed that rubberized road reduces noise above five dB (A). [Public Works Department, The City of Thousand Oaks, USA]. Another efficient use of scrap rubber in the form of aggregate has been started in this time in different state of USA and becomes popular to user. The use of rubber aggregate in the playground pavement for the children is most welcomed by the user since it is comfortable and shock absorbing.

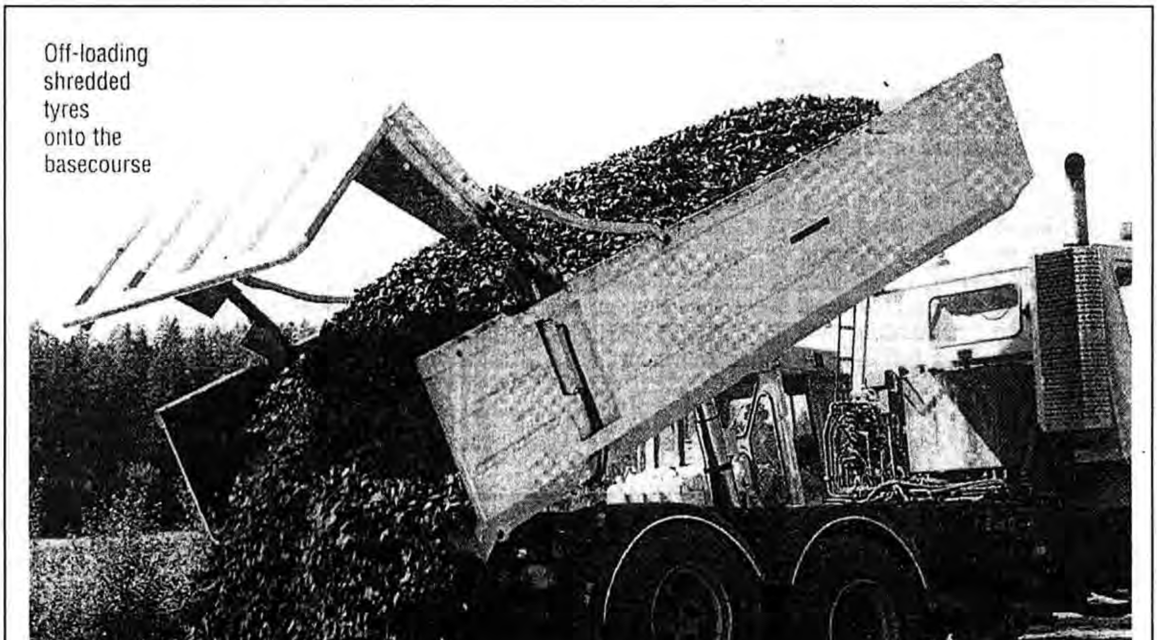


Photo 2.1 Use of Shredded Tyres in Base Course.

Ralumac 2000 is a cold applied, fibre reinforced emulsion based system. It incorporates a polymer modified bitumen emulsion binder and fibres with small, high quality aggregates. It is applied to the road surface as a self-leveling screed and has the ability to fill wheel ruts and deformation in road surface. Ralumac acts as noise absorbers, reducing surface noise generated from vehicle wheels. About 70 % - 90 % noise in motorways is caused by wheel on the road surface. Ralumac can reduce noise levels by up to four decibels. For a trunk road this is equivalent to halving road noise from a loud roar to hum.

Colsoft, the low-noise asphalt from Colas Ltd. has undergone trials at the Transport Research Laboratory (TRL) in the UK. The test followed construction of a new noise assessment test area, which was completed by Colas. Colsoft is developed to reduce noise pollution in urban areas and alleviate environmental problems. Laid as thin asphalt layer using crumb rubber from recycled vehicle tyres (half a tyre to each m2) as part of a discontinuous graded aggregate, the product also incorporates the high performance SBS modified binder, Colflex.

Recent tests in France showed that Colsoft made pavement gave typical noise values of between 4 to 7 dB (A) lower than hot rolled asphalt (equivalent to a 50 % - 70 % reduction in traffic) and to generate lower noise than porous asphalt.

The success of rubber modified bitumen leads to use of other polymer in pavement construction and maintenance to fight with climatic factors that are the main enemy to pavement and that cause premature failure of pavement. PMB is less susceptible to temperature and can endure wide range of temperature fluctuation. The Mojave Desert in the USA, where the average air temperature in hottest month is 42°C and 0°C in the coldest month. This fluctuation of temperature associated with heavy traffic result in extremely rapid distress in the pavement. The quick failure of pavement was prevented and pavement life was increased by building road with SBS [World Highways, 1999] modified bituminous binder in this region.

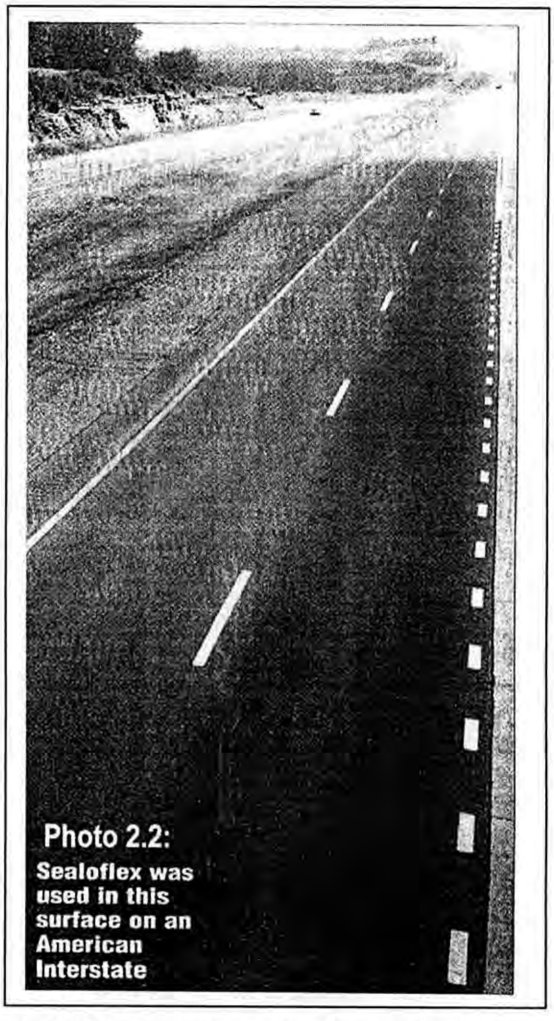


Photo 2.2: Sealoflex was used in this surface on an American Interstate

Photo 2.2 shows the use of "Sealoflex" in surface treatment in an American interstate highway. As seen on the photo the road surface with Sealoflex Modified Binder is in excellent condition even after several years of construction. A Dutch company, Ooms Avenhorn, works with sealoflex, SBS, rubber and resin modified asphalt binders, says that application of these binders in asphalt pavements provide products with characteristic properties such as considerably lower temperature susceptibility, elastic recovery, improved resistance to fatigue, high flexibility and high stability. It claims that sealoflex products prevent cracking, rutting and corrugations and can be used in heavy duty pavements such as runways, taxiways, highways and truck lanes, prolonging the life span of asphalt and reducing maintenance frequency and maintenance cost.

Sealoflex has been used on roads and airports around the world including Schipol, Amsterdam and both Kuala Lumpur international airport and Cairo international airport, where sealoflex SFB5 JR, a jet fuel resistant polymer modified asphalt binder was chosen for constructing and upgrading runways and other heavy duty asphalt pavements.

In recent years, the use of PMB has begun in other countries of the world. The temperature of major cities of Russia fluctuates between 40°C to –30°C. This wide range of temperature needs special attention for selecting the binder and the Russian successfully did it. Most of the city roads in Russia are smooth, waterproofing, crack sealing, skid resistant and durable. The achievement of this quality in pavement was possible by using PMB.

Photo 2.3 PMB Application in Moscow

Photo 2.3 shows the application of PMB in a highway of Moscow. The E30 (see Photo 2.3) road runs through Great Britain, the Netherlands, Germany, Poland, Belarus and

Russia needed repairing along 60 km stretch connecting Brest on the Polish/Belarus border with the Russian border. The region is subject to harsh winters and very hot summer, so the road pavement was constructed with KRATON polymer modified bitumen which could create a long lasting road surface able to withstand such temperature extremes, thus reducing long term maintenance costs. The construction company used granulated KRATON D-1101 polymer to provide a modified bitumen with improved aging characteristics and superior all-round performance. Over 800 tons of the polymers were used to resurface the top layer of the highway and the work was completed in the summer of 1998. Experimental use of polymer in bitumen has been started in Portugal in order to find out a way of reducing pavement rehabilitation costs. A new road network to link with Lisbon and its airport was needed to construct to celebrate Expo 98, a 100-day festival. Local constructors used Caribit SP from Shell Bitumen (Portugal), a bitumen modified with KRATON D-1101 polymer in the construction of tunnels and road surfaces for part of new road network. [World Highways, September 1998].

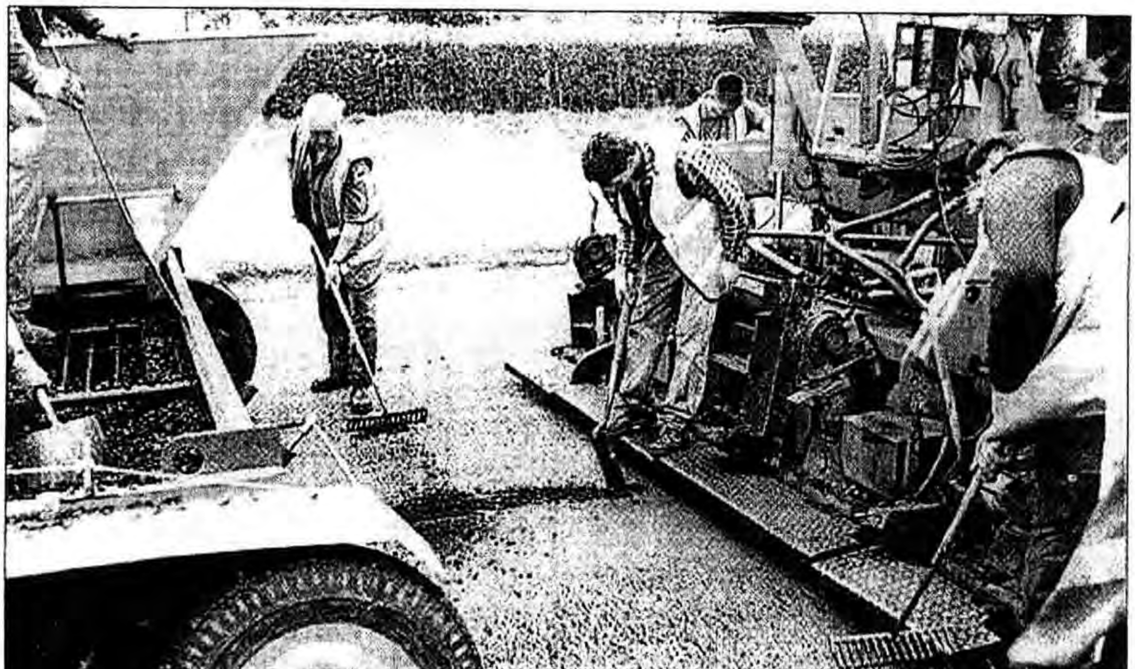


Photo 2.4: Use of KRATON Polymer in Portugal

Photo 2.4 represents the use of KRATON D-1101 polymer in the construction of road surfaces for part of a new road network. Added to the bitumen mix, the polymer improves flexibility at low temperature and increases resistance to aging and cracking fatigue in the finished road surface. Cairo, one of the busy international airports in the world exhibit cracks and irregularities in the 4 km long runway-2 and the authority decided to extend the runway to meet todays wide-bodied jets. The work of repair was recently carried out by the joint venture of Saudi Bin Laden co., Jeddah and Hassan Allam, Cairo. Firstly the bituminous layer was removed to a depth of 6 cm. The new surfaces consisting of a bituminous binder course and a wearing course of bitumen with polymer modified binder each 6 cm thick have been laid hot-to-hot in order to reduce the longitudinal joints to a minimum.

A construction team working with PMB in Cairo airport can be seen in Photo 2.5. The runway of Kuala Lumpur international airport also constructed with PMB to make it suitable to carry heavy wheel load of boaing type aircraft. Here "Sealoflex" polymer modified bitumen was chosen to construct and upgrade runways. The binder is jet fuel resistant.

Photo 2.5: Use of PMB at Cairo International Airport.

The roadway pavement in different countries of Middle East (Saudi Arabia, Qatar, Kuwait, Bahrain, Oman, UAE) is excellent because binders for pavement construction are very cheap. Recently these countries are using polymer-modified binder to reduce bleeding of binder at too hot weather that normally exists in this region. The PMB stops bleeding at high temperature and keep pavement rigid compared to normal binder. The polymer modified hot mix application is seen in Photo 2.6

PMB is being used successfully in our neighboring countries, Thailand, China and India. India is using scrap polyethylene with binder. Scrap polyethylene specially shopping bags create severe environmental hazard, cause drainage problem and pollute the land. The performance of scrap polymer modified bituminous binder should be studied to manage this hazardous waste material properly.

Photo 2.6: Application of Polymer Modified Hot Mix Over Geotextile

2.9 Mix Design of Rubber Modified Binder

2.9.1 General

Mix design procedure for hot mix paving mixtures depend upon the aggregate gradation, maximum size of aggregate, wheel load and its frequencies and on the rheology of binder. Modified binder may need slight modified method of mix design. The mixing and compaction temperature may be different for PMB/RMB depending on the improvement of viscosity. Marshal mix design method for dense graded paving mixtures using rubber modified bituminous binder is shortly described in this article.

2.9.2 Methods of Mix Design

Both Marshall and Hveem methods with simple modification can be used for designing hot mixes with PMB. Mix design procedure will depend on the rheological properties i.e. viscosity, elasticity etc. of RMB. When low percentage of polymer /rubber is used (up to 5%) unmodified mix design procedure can be followed. Higher amount of modifier (crumb rubber or polymer) make significant changes in physical and mechanical properties of RMB. In this case a modified mix design method needs to be followed.

2.9.3 Aggregate Requirement

Aggregate should meet the same quality required for conventional bituminous pavement. For crumb rubber content 10-25% (by weight) the aggregate gradation for dense graded mixes should be maintained on the course side of the gradation band.

2.9.4 Binder Content

The binder content needs to increase as the crumb rubber content in the binder increases. Approximately 25% more binder is required in case of RMB.

2.9.5 Specimen Mixing

The Rubber Modified Bitumen (RMB) should be heated using indirect source of heat. The recommended heating temperature for binder is 177±5°C and for aggregate is 150±3°C. Binder should be stirred to avoid local over heating. Mixing of the RMB and aggregate should be performed using standard mechanical mixer. Vigorous manual mixing may be acceptable also. Mixing should be performed immediately after the addition of binder to the aggregate. Maximum mixing time should not exceed two minutes. If complete coating of aggregate cannot be achieved within mixing time, one or more of the following parameters can be adjusted.

- ◊ The content of binder should be increased.
- ◊ Increase binder temperature to reduce viscosity.
- ◊ The rubber content in bitumen should be decreased.

2.9.6 Specimen Compaction

Rubberized bituminous mixture is more viscous than conventional mixtures. The compacting temperature should be maintained carefully. The recommended compaction temperature can be between 135°C-150°C. Compacted specimen should be allowed to cool to ambient temperature (minimum for four hours) prior to removal from the molds.

2.9.7 Specimen Testing

Standard procedures should be followed to test the specimens to evaluate stability, flow, and density and air voids result.

2.10 Evaluation of Rubberized Pavement

Rubberized asphalt has many advantages over conventional asphalt. These advantages involve cost, performance and environmental aspects [L. W. Swaney, Street Superintendent, Public Works Department, San Buena Ventura, California]. To evaluate rubberized pavement a test road was built in Flagstaff, Arizona, where a two-inch resurfacing with crumb rubber asphalt was placed on one side of the road and the other side was paved with a four-inch resurfacing using traditional asphalt. Over a seven-year

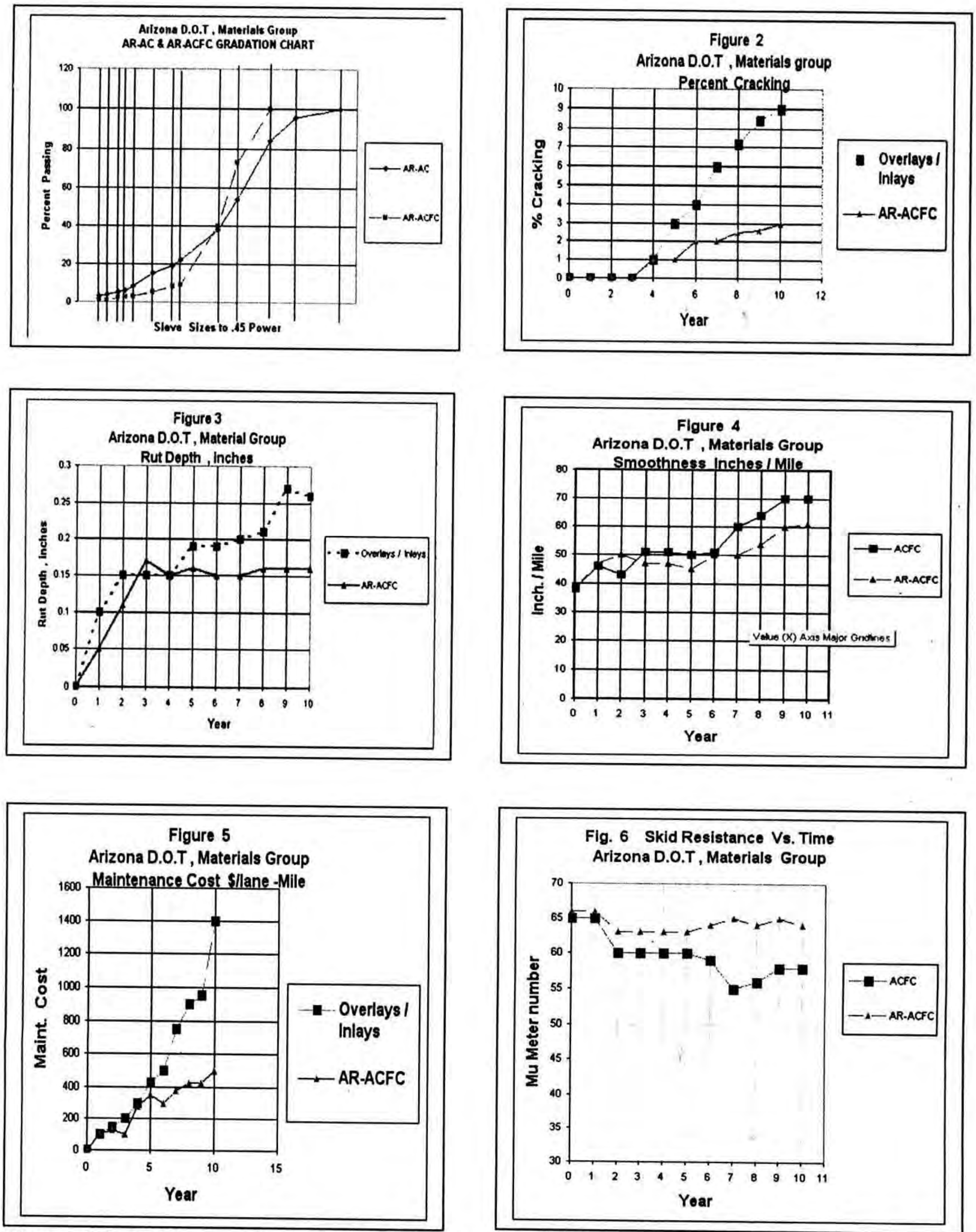


Figure 2.3: Rubberized Pavement Evaluation Graphs [Source: Arizona Department of Transportation].

period the side of the road laid with crumb rubber has experienced virtually no cracking, while the conventional side began to crack the first year. Over twelve hundred miles of road have been built using crumb rubber asphalt in Arizona with very good results. Numerous studies have been conducted in the city of Phoenix, County of Sacramento and San Buena Ventura to attest the various advantages of crumb rubber asphalt.

It has been shown that crumb rubber asphalt, if blended in the ways used in Arizona, requires half the material of traditional asphalt and lasts twice as long. The graphs in the figure 2.3 showing the performances of rubberized pavement against conventional asphalted pavement were produced through a study conducted through the Arizona Department of Transportation. It can be seen from the above figure that the field performances of polymer modified asphalt pavement is better than that of conventional pavement in all observed parameters like cracking, rutting, maintenance cost and skid resistance.

2.11 Construction Practices

2.11.1 General

Polymer Modified Bitumen (PMB) has a wide ranged application possibilities in construction of new pavement as well as in rehabilitation and maintenance of old pavements. All conventional bituminous works can be replaced by PMB. It may require slight modified mix design procedure if PMB posses higher viscosity than that of traditional binder. Some construction practices with PMB are: 1) Hot mix pavement, 2) Surface Treatment, 3) Crack and joint sealant.

2.11.2 Hot Mix Pavement

The main use of PMB/RMB is in hot mix pavement. Two widely used technologies for hot mix are McDonald and Plus Ride technology. These two methods use Rubber Modified Bitumen (RMB) and Crumb Rubber (CR) and known as wet process and dry process respectively. The technologies are described below.

McDonald Technology - Charles Mc. Donald (1964) a material engineer of Arizona developed this method of blending crumb rubber with bitumen and provided a modified mix design technique. According to his name this technology is known as Mc. Donald technology. It can be used in the dense graded, open graded and gap graded aggregate mixtures. The binder content depends on the aggregate gradation, rubber content in the binder and its rheological properties i.e. viscosity, elasticity and softening point. Higher binder content (up to 10% - 11%) is required for high viscous RMB. Higher RMB content creates thicker binder film around the aggregate and durable pavement is possible to obtain by proper compaction.

Plus Ride Technology - It is a very recent technology of mix design. It does not follow the conventional Marshall and Hveem method of mix design. The process uses crumb rubber as rubber aggregate, which is incorporated in to a gap-graded aggregate prior to mixing with the bitumen. The coarse rubber particles act as elastic aggregate in the gap graded aggregate mix and produces a more flexible and ice-debonding pavement surface. The process recommends the maximum size of granulated rubber is less than ¼ inch and the targeted air void is 2 to 4 percent. As specified in the design the crumb rubber amount is about 3 percent by weight of the total mix. The binder content generally varies from 7.5% to 9%.

2.11.3 Surface Treatment

Most of the pavement failures initiated from the surface of pavement. So surface treatment in roadway maintenance is very important. Treating surface with PMB, cracks and bleeding can be reduced as well as stripping can be minimized [M. Hussein et al, 1999, E. Hoque, 1996]. Intrusion of water, which is a major cause of "pot holes", can be prevented by improving the impermeability of surface coarse. The type of surface treatment is dependable on extend of pavement failure. Road surface treated with modified asphalt can extend pavement life and reduce maintenance costs

Slurry Seal: Slurry Seal is applied on cracked pavement. Polymers can extend the performance of slurry in the context of adhesion and cohesion, abrasion resistance,

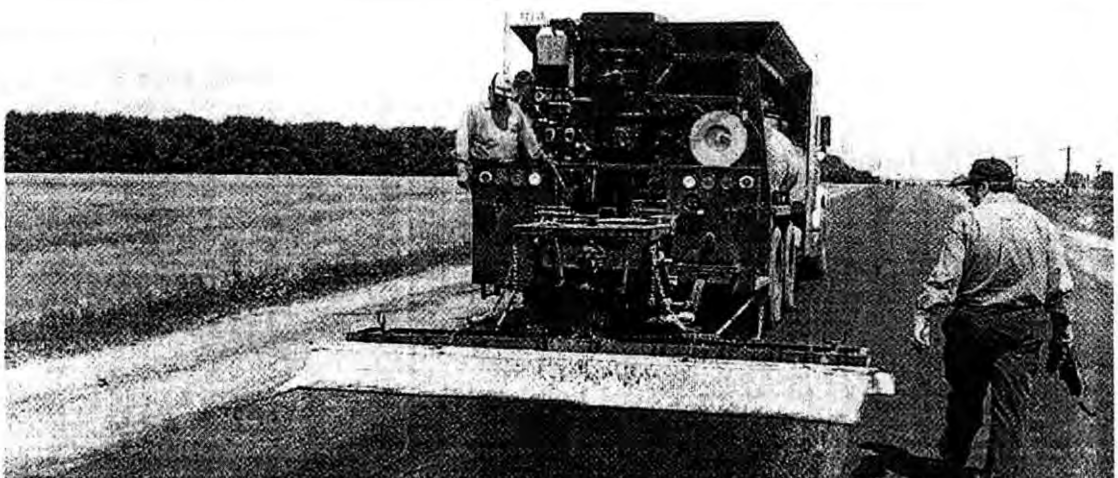


Photo 2.7: Application of Slurry Seal in Surface Treatment

bleeding resistance and durability. Slurry Seal consists of four materials, binder (emulsion), water, aggregate and set control agents or retarders. The thickness of slurry seal generally maintained between 1 to 1.5 inches. Its performance is affected by not only PMB but also quality (hardness, durability, resistance to polishing) and size of aggregate. According to Holleram and Ristic (1999), its lifetime is five to ten years. So it is powerful tools in crack preventive maintenance. The application of slurry seal is seen in Photo 2.7. A rubberized slurry seal was applied in five local airports of Los Angeles, in 1990, where ½ pound of crumb rubber was used in one gallon of emulsified bitumen. Finer graded and low percentage of aggregate was used to reduce the tendency for the propellers of Jet to lift the aggregate from the surface and damage the aircraft.

Chip Seal: Chip Seal is an overlay used to fill rut and seal cracks. A rubberized chip seal is carried out as followed.

The binder may consist of 18-20% rubber. An extender oil is often used at a level of up to 3%. The binder is blended in a propeller mixer. Blending is continued for about an hour and used within a few hours of manufacture. The binder is sprayed at 195°C-215°C at a rate of 2.5 litre/m^2 by a sprayer. The pre-coated aggregate with bitumen is then applied at a temperature of 45°C-60°C with automated sprayer.

Micro Surfacing: Micro surfacing can be used to mitigate flushing and rock loss problems and provide a quiet, skid resistance for cracked and deteriorated surface. Micro surfacing is laid in multiple layers. It is often laid on high-volume, high traffic roads where toughness and resistance to tearing becomes more important. The micro surface mix, which essentially consists of 9.5 mm screenings bonded by polymer modified bituminous emulsion, is economical and can be placed very swiftly. It is also aesthetically pleasing because of its resemblance to hot mix bituminous pavement.

In 1990 and 1991 Georgia Department of Transportation (GDOT) conducted an evaluation of micro surface mixes in test road [World Highways/Routes Du Monde, Feb 1998]. Two different micro surface mixes were used, containing different polymer modifier. Both the mixes showed little deterioration after two years.

SAM (Stress Absorbing Membrane): It is a surface treatment in which rubberized bitumen is applied with a sprayer. The construction of SAM is similar to any other surface treatment. The use of SAM has particular benefits toward the performance of the pavement. The elasticity and temperature susceptibility of the modified binder increases the ability of the surface to resist the stresses induced by the climatic factors and traffic. A SAM can resist and delay the development of reflective cracks. Generally 20 to 30 percent (by weight of binder) of crumb rubber is used in the production of SAM. Cover aggregate is preferably of uniform size (3/8 to ¼) and hot pre-coated with binder.

SAMI (Stress Absorbing Membrane Interlayer): SAMI is not directly a surface treatment, but it has benefits similar to SAM. The principle utility of providing a SAMI is to place a membrane beneath the overlay that can resist the deflective cracks and delay propagation of cracks [E. Hoque, 1996] through the new overlay. The SAMI is best used where the roadway is structurally sound but oxidation on the surface has resulted in mild to severe alligator cracks.

2.11.4 Crack and Joint Sealant

Rubberized bituminous binder is widely used as crack and joint sealant in maintenance work. In crack sealing application the RMB must have the property of less temperature susceptibility and high elasticity to resist cracks that induced in the pavement at low temperature. Additionally PMB should be flexible enough to keep pavement flexible at cold weather. High penetration grade bitumen with a high amount of crumb rubber can satisfy both the requirement. The choice of sealant for a particular location depends on many factors. The main factors are; type of pavement, type of crack and joint, shape and size of the crack or joint and degree of pavement distress [E. Hoque, 1996].

2.12 Overview

The preceding articles presented a brief but reasonably comprehensive review of polymer modified bitumen. It has intended to present polymer modification as a viable cost effective technique of improving pavement performance. From the literature review it is found that in many countries, modified binders are being used in all paving and maintenance applications including hot mix, warm mix, cold mix, chip seals, hot and cold crack filling, patching, slurry seals and even airport pavement. They are being used extensively wherever extra performance and durability are desired. In consideration of improved stability, durability and elasticity, modified binders are gradually being replacing the conventional bituminous binder.

Literature review revealed that now-a-days many countries are exploiting the potential of polymer modification particularly to tackle pavement distresses due to extreme hot and cold temperature and in some counties to reduce their waste disposal problems. But little study document is found emphasizing its potential to reduce drainage induced pavement failure. This may be due to the fact that in developed countries this mode of pavement failure is not a serious problem. The later issue is very significant in Bangladesh, particularly in built-up areas, due to acute drainage problems coupled with extended monsoon period. As such, there is a strong need to study on the polymer modified bituminous binder and mixes in particular relation to its performance under submerged condition.

From the review of studies conducted in Bangladesh, it is learnt that previously two attempts have been made on this issue [A. S. Chowdhury, 2001; M. Hussein, 2002]. But they were unsuccessful because blending of polymer with bitumen could not be performed properly. That is why it is a main target of the proposed research study, to know the technique of blending process and thereby to see if polymer modification of bitumen is possible using low cost device.

Based on the literature review presented in this chapter, the important observations emphasizing on blending process and technique, is summarized as following:

- Only thermoplastic polymers are suitable for modification of bitumen.
- It is possible to blend scrap tyres, tube, rubber and polythene bags with bitumen.
- SBS (Styrene Butadiene Styrene), KRATON, POLYBILT are the commercially produced polymers for the modification of bitumen.
- Blending depends on compatibility of polymer with bitumen and compatibility depends on the type of polymer and chemical composition of bitumen.
- Successful blending of polymer with bitumen depends on
    - Contact of polymer and bitumen (i.e. mixing)
    - Blending temperature
    - Blending time
    - Application of shear force
- Cooling characteristics of prepared blend may affect the storage stability of blend. Quick cooling has less effect on storage stability of blend.
- In the developed countries, specific blending plants are used for the mass production of polymer modified binder.
- Conventional equipment and procedures is used for the mixing, lay down and compaction of polymer modified mixes.
- Marshall and Hveem mix design methods with slight modification is used for designing hot mixes with polymer modified binder.
- Polymer reduces temperature susceptibility, increases viscosity, imparts elasticity and improves other rheological properties of bitumen.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Bituminous materials are used extensively for roadway construction. As a road material its performances are evaluated by some properties. Polymer changes these properties when it is blended with bitumen. Polymer brings how much and what kind of changes in the behavior of bitumen is one of the main objectives of this investigation. To investigate this a set of examinations of reference binder and polymer-modified binder is required. This chapter includes the planned experimental design which is outlined in Art.1.5. The design includes selection of blending technique, searching compatible polymer to blend, process of evaluation of polymer modified binder and mixes. This chapter also includes the test procedure which are performed.

The performances of compacted mixes depend not only on binder quality but also on mechanical and physical properties of constituent material. Besides binder, aggregate is the main constituent of paving mixes. A short description of the properties of aggregate that would be used in the experiment is also included in this chapter.

3.2 Method of Blending

The proposed project work encompasses two distinct phases of activities, blending of polymer with bitumen and the laboratory performance evaluation of polymer-modified binder (PMB) and mixes. The successful blending of polymers depends on the compatibility of them with binder. It is very difficult to blend polymer, which is chemically incompatible to bitumen. As such, the compatibility is the prime consideration in the preparation of PMB.

There are two methods of blending polymer with bitumen, the dry blending method and wet blending method. In the wet blending method, polymer is added to the hot bitumen prior to adding the resulting binder to the aggregate. This method is termed as "Cooking method" [M. Hossain, 1995]. The method requires a simple cooking device. The device comprises a container, a stirrer and a heater. The stirrer should have fins to produce required shear force in the mixer during blending process. The shear force required to mix polymer with bitumen depends on the polymer types.

Blending can be performed in three ways by using:

- ❑ Commercial automated blending system
- ❑ Laboratory milling machine
- ❑ Manual cooking device

Commercial automated blending system: There are some chemical companies viz. HEATEC and Exxon that supply polymer-bitumen blending system. Various types of polymers such as SBS and ground rubber can be blended with bitumen in this blender. It is useable at both asphalt terminals and hot mix asphalt plant. The blending system may be portable or stationary. Picture of these plants can be seen in the Photograph 3.1.

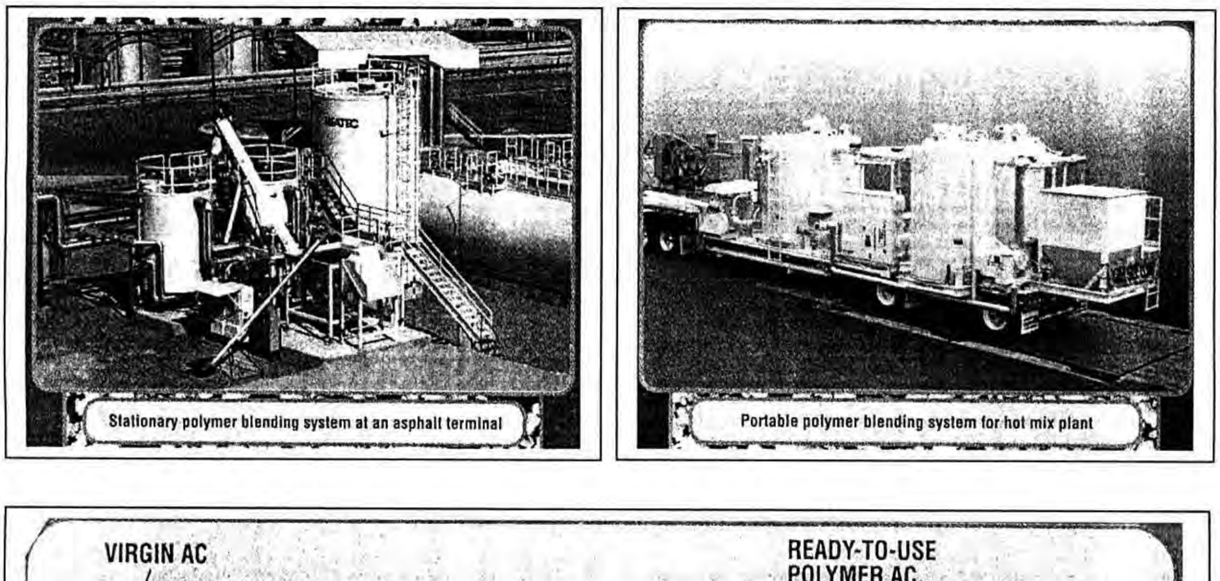


Photo 3.1. Stationary and Portable Polymer Blending System.

Laboratory milling machine: This milling machine is used in the laboratory to blend polymer with bitumen for experimental purpose. It comprises a rotor to produce shear force, an electric heater and a container. Blending temperature and applied shear force can be controlled properly in this machine. Most of the compatible polymer including recycled polymer (scrap polymer, crumb rubber and polyethylene bags) can be blended in this machine.

Manual cooking device: It is a manual method of blending polymer with bitumen. It works in the same principle as that of a commercial blending system. In this device the required shear force is produced by means of manual stirring. Since it is difficult to control the blending temperature and produce the required shear force, all type of polymer cannot be blended in this process. Some selected polymers, which require low shear force can be blended in this device.

Limitation of manual cooking method

- Difficult to control temperature.
- Cannot produce high shear force
- May produce smoke.

Advantages of manual cooking method

- Low cost
- Easy to manufacture
- Suitable for small scale production.

It is proposed that in this study, manual-cooking device would be used to blend polymer due to unavailability of alternative methods and considering the cost of procuring such equipment. A number of trials would be performed to find out the suitable polymer to modify bitumen.

3.3 Mixing Compatibility Test

In order to find a suitable modifier, compatibility test would be performed on several types of locally available pure form of polymers viz. LDPE, PP, EVA and PVC. The objective of this compatibility test is to identify the appropriate polymer that can be used as a modifier of bitumen.

3.4 Process of Evaluation of Modified Binder and Mixes

In order to evaluate the properties of polymer-modified binder, a sample of unmodified bitumen would be taken as the reference binder. The reference binder would be modified by various proportion of the selected polymer. A comparative study would be performed on the reference binder and modified binder. The physical and engineering properties of both the binders (reference and modified) would be investigated by performing Specific gravity, Softening point, Penetration, Ductility, Viscosity and Loss on heating tests.

Marshall test would be performed to evaluate the properties of mixes prepared with modified and unmodified (reference) binder. Several sets of Marshall test specimen would be prepared at different proportions of binder in order to determine the effect of polymer modification of bitumen. The mixes prepared with reference binder (unmodified bitumen) would be consider as reference mixes and the properties of the mixes prepared with modified binder would be compared with that of reference mixes. In preparing the mixes, other factors such as the type of aggregate, gradation of aggregate, mixing and compaction temperature would be kept constant. Stripping and coating test would be performed with both the binders to compare the ability to withstand the effect of moisture.

Besides these, a non-conventional test would also be performed in order to measure the film thickness of coating on aggregates. Description of the test is given in the Article 3.5.8.

3.5 Tests on binder

3.5.1 General

The tests which would be performed in order to evaluate the properties of binders (reference and modified) are Softening point, Specific gravity, Penetration, Ductility, Viscosity and Loss on heating, Film thickness and Stripping of coating. These tests would be carried out following the ASTM standard procedures. A brief summary of these tests methods and their significance are presented here.

3.5.2 Softening Point

The Softening point of a bituminous binder is the measure of its consistency. It does not indicate binder's melting point. It is a temperature of binder at which the binder changes its state from semi-solid to liquid gradually. It is a useful characteristic of semisolid materials. The temperature susceptibility of binder can be evaluated by softening point. Between two binders having the same penetration, one will be less susceptible to temperature, which have higher softening point.

The Ring and Ball softening point test is widely used to determine the consistency of bituminous binders. It is a very simple test. In this test a steel ball is put on a sample of binder placed on a steel ring. After immersing the arrangement in to a water bath, heat is applied gradually at the specified rate. The temperature of water at which the ball just crosses the ring is stated as the softening point.

3.5.3 Penetration

The "Penetration" of a bituminous binder is measured by the distance in tenth of a millimeter that a standard needle penetrates vertically into a sample of the binder under specified condition of temperature, load and duration (time). It is a measure of consistency of binder. The higher values of penetration indicate softer consistency. To determine the penetration, the sample should be melted properly and cooled and maintained specified temperature. The penetration is measured with a Penetrometer.

3.5.4 Ductility

The ductility of a material is the measure of its cohesion. A material having this property can be elongated without fracture or breaking. It is an important property of binder. Binders should be sufficiently ductile to prevent fracture in the pavement. The distance to which it will be elongated at a specified temperature measures the ductility of bitumen.

3.5.5 Specific Gravity

The specific gravity of a semi-solid 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.

3.5.6 Viscosity

There are two types of viscosity, kinematic and absolute viscosities. Kinematic viscosity is the measure of resistance to flow of a liquid under gravity. ASTM D2170-85 (AASHTO T201) describes the determination of kinematic viscosity of liquid asphalt at 60°C and semi-solid asphalt at 135°C in the range from 6 to 100,000 centistokes. Absolute viscosity of bituminous material is measured following ASTM D2171 (AASHTO T202) designation. This method is applicable to bitumen with viscosities in the range from 0.036 to 200,000 poises.

Viscosity is one of the important terms to describe the properties of bitumen. The mixing and compacting temperature of hot asphalt paving mixes depends on viscosity of binder.

3.5.7 Loss on Heating

It is the measure of mass of oil and asphaltic compounds that are lost (evaporation) during the process of heating of binders. It is a significant property of bitumen.

3.5.8 Film Thickness

This test is designed to observe the film thickness of binder coating on aggregate. In general, aggregates have greater affinity to water than that of bitumen. If the coating of bitumen on aggregates is thin, water can easily come into contact with the aggregates and thereby breaks the inter-particular bond. As such, greater film thickness of bitumen would be more effective to fight against water.

The objective of measuring film thickness of coating is to see the improvement of coating thickness due to increased viscosity of polymer-modified bitumen. Since it would be difficult to measure the film thickness of binder on aggregate due to irregular shape of aggregate, a solid steel ball of uniform shape would be used for measuring coating thickness on it. Comparing the coating thickness of both unmodified and modified bitumen on a spherical steel ball an indirect evaluation of film thickness would be made.

3.5.9 Stripping and Coating

Stripping can be defined as the separation of bitumen coating from the surface of aggregate in the presence of water and temperature. Stripping is one of the main causes of pavement failure in Bangladesh. Stripping can occur in six ways: emulsification, detachment, displacement, film-rupture, pore pressure and hydraulic scouring. Water is the principal factor that causes stripping and destroys the bond between aggregates and bitumen. To measure the effectiveness of binders against stripping, the static immersion test would be performed in the laboratory. The static immersion test is used to determine the retention of a bituminous film on aggregate in presence of water. It is applicable to cutback, emulsified asphalt, semi-solid asphalt and to tars. It is termed as "go no go" test at the 95% level because its precision is not satisfactory for application at lower levels.

3.6 Tests on Mixes

3.6.1 General

The purpose of performing tests on compacted mixes is to determine the mix properties that are important for the performance of pavement at service condition. The standard Marshall mix design method would be followed in the laboratory. A set of Marshall test specimens would be prepared and tested. A volumetric analysis would also be performed on the test specimens.

3.6.2 Marshall Stability and Flow Test

Stability and flow values of compacted mixes depend not only on the physical and mechanical properties of aggregates but also on the quality as well as quantity of binder. Thus, if the properties of aggregates are kept unchanged in the mixes, by measuring stability and flow values the quality of binder could be evaluated.

In Marshall Test, the maximum load at which test specimen fails is termed as stability. 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 pavement. Pavement should have reasonable flexibility that also depends on the quality of binder.

3.6.3 Volumetric Analysis of Compacted Mixes

Density, air voids, void in the mineral aggregate and void filled with asphalt of compacted mixes are known as the volumetric properties of paving mixes. The volumetric properties of compacted paving mixes provide some indication of pavement's performance in service condition. A volumetric analysis would be performed on the compacted paving mixes prepared with polymer modified bitumen and unmodified bitumen.

3.6.3.1 Density

Density can be determined multiplying the specific gravity of mixture by the density of water. Two types of specific gravity - bulk specific gravity and maximum theoretical specific gravity would be determined. Specific gravity can be defined as the ratio of the weight of specimen in air to the weight of equal volume of water. The density of compacted mixes depends on the level of compaction if other parameters are kept constant.

3.6.3.2 Air Void

The air spaces bitumen the coated aggregate of paving mixture is known as air void. It is a considerable factor in pavement performance. Too much air voids in paving mixture may cause stripping allowing water to stay in it. Air void of compacted mixes is determined using the following formula.

$$V_a = 100 \times (G_{mm} - G_{mb})/G_{mm}$$

Where,

V_a = air void in compacted mixture percentage of total volume.

G_{mm} = maximum specific gravity of paving mixture.

G_{mb} = bulk specific gravity of paving mixture.

3.6.3.3 Void in the Mineral Aggregate

The void in the mineral aggregate (VMA) is defied by the intermolecular spaces between the aggregate particles in compacted paving mixtures that includes the air voids and the effective asphalt content. VMA is calculated on the basis of 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 is measure as follows:

$$VMA = 100 - (G_{mb} \times P_s)/G_{sb}$$

Where,

VMA = voids in mineral aggregate, percent of bulk volume.

G_{sb} = bulk specific gravity of total aggregate

G_{mb} = bulk specific gravity of compacted mixture

P_s = aggregate content, percent by total weight of mixture.

3.6.3.4 Void Filled With Asphalt

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. It is measured in the following way:

$$VFA = 100 \times (VMA - V_a)/VMA$$

Where,

VFA = voids filled with asphalt percent of VMA.

VMA = voids in mineral aggregate, percent of bulk volume.

V_a = air voids in compacted mixture, percent of total volume.

3.7 Material Properties

3.7.1 General

Flexible pavement consists of major two materials. These two materials are aggregate and binder. The performance of pavement is greatly influenced by binder. Generally bitumen is used as binder in pavement construction. The properties of Polymer Modified Bitumen (PMB) would be studied in this research work. The study work would require unmodified bitumen, polymer and aggregate as raw materials. In order to study only the effect of polymer on binder and mixes other ingredients need to be maintained same throughout the whole experiment process. Here a short description of these ingredients and there characteristics are presented below.

3.7.2 Bitumen

Bitumen is a cementing material. It holds the aggregate together in a bituminous pavement. The quality of bitumen depends on its crude source, refining process and chemical composition. The chemical composition affects the compatibility of bitumen with polymer. Bitumen is normally designated by "grade" though it does not indicate the overall qualities of bitumen. The characteristics of base bitumen affect the quality improvement of the modified bitumen. In this study 80/100 penetration grade bitumen is used. It is obtained from the laboratory stock. The chemical composition of the bitumen is unknown. The viscoelastic properties of unmodified bitumen are shown in Table 3.1.

Table 3.1 Viscoelastic Properties of Unmodified Bitumen.

Properties of bitumen	Specific gravity	Softening point (^0C)	Penetration (1/10th mm, 25^{0}C)	Ductility , (cm)	Loss on heating (%)	Viscosity (centistokes at 135^{0}C)
Test method	AASHTO T228-93/ ASTM D 70-76	AASHTO T47-8/ ASTM D6-80	AASHTO T49-93 / ASTM D5-86	AASHTO T53-92/ ASTM D36-89	AASHTO T51-93/ ASTM D113-79	AASHTO T49-93/ ASTM D5-86
Test results	1.030	45	87	100+	0.06	331

3.7.3 Polymer

The use of polymer with bitumen has been started at least 40 years ago in California of USA. Crumb rubber was then used on the road surfaces to make it less susceptible to temperature and fit to fight with weathering action. The better performance of rubberized roads leads researchers to research in this sector of road material. Later many chemical companies invented special polymers to use as modifier of bitumen. SBS and POLYBILT polymers are marketed by Shell and Exxon chemicals respectively. These two polymers are widely used in bitumen modification.

Polymers are grouped according to their chemical composition. The members of a polymer group are classified by their structure, molecular weight and density. Generally linear, low-density polymers have high compatibility to bitumen. In this investigation, compatibility test would be performed with low-density polyethylene (LDPE), polypropylene (PP), ethylene vinyl acetate (EVA) and polyvinyl chloride (PVC). LDPE, PP, EVA and PVC are available in the local market in pellet form. Some of the properties of the polymers are shown in Table 3.2

Table 3.2 Physical Properties of Some Selected Polymers

Type of Polymers	Physical Form	Density (pcf)	Specific Gravity	Melting Temp. (°C)	Melt flow index (g/600s, 190°C)
LDPE	Pellet	59.56	0.953	115.1	36.07
HDPE	Pellet	59.50	0.952	129.1	31.4
EVA 1802	Pellet	58.75	0.94	--------	---------
CPP	Pellet	56.875	0.91	163.8	3.65 (at 230^{0}C)
PVC	Pellet	--------	--------	--------	--------

3.7.4 Aggregate

3.7.4.1 General

Aggregate is a major constituent of bituminous pavement. It imparts strength to the pavement. The physical properties (i.e. gradation) as well as mechanical properties (i.e. hardness, toughness, durability) of aggregate have great influence on the mix properties. The procedure of mix design, binder content, mixing and compaction of mix depend on aggregate gradation to some extent. In this research, same aggregate with same gradation would be used for both mixes prepared with unmodified bitumen and polymer modified bitumen in order to keep the behavior of aggregate constant in the mixes. The properties of coarse aggregate, fine aggregate and mineral filler, which are important for mixes, are presented below.

3.7.4.2 Coarse Aggregate

Coarse aggregate occupies major part of the total volume of the mix. The behavior of bituminous mixes is highly affected by the gradation and quality of coarse aggregate. Degree of compaction and the value of Marshall stability of the mix depend on the characteristics of coarse aggregate used. Hence, the selection of appropriate coarse aggregate of desired gradation is important.

Mechanically crushed boulder would be used as coarse aggregate in the mix. The boulder is available in Bhola Ganj, Sylhet. The maximum size of coarse aggregate that would be used in the mix is ¾ inch. The physical and mechanical properties of coarse aggregate are presented in Table 3.3.

Table3.3 Physical and Mechanical Properties of Aggregates

Physical properties	Test method	Test results		
		Bulk specific gravity	**Bulk specific gravity (SSD)**	**Apparent sp. gravity**
Specific gravity		2.71	2.72	2.74
Density (lb/cft)		169	170	171
Water absorption (%)		0.48		
Flakiness Index (%)	BS812, Part 1; Clause 7.3, and 7.4	19		
Elongation Index (%)	BS812, Part 1; Clause 7.3, and 7.4	27		
Agg. Impact Value (%)	BS812, Part 3, 1975	26		
Agg. Crushing Value (%)	BS812, Part 3, 1975	22		
Los Angeles Abrasion Value (%)	ASTM C-131	29		

3.7.4.3 Gradation

The aggregate gradation that which is used in this study is shown in Table 3.4. This gradation is recommended by the California Department of Transportation (CalTrans), for surface course. The same graded aggregate would be used for both mixes prepared with unmodified bitumen and polymer modified bitumen (PMB). The grain size distribution of combined aggregate is shown in the Figure 3.1.

Table 3.4 Gradation of Combined Aggregate.

Sieve Size	Percent Finer by Weight	Average Percent Finer	Percent Retained	Type of Aggregate
1"	100	100	0	
¾"	95-100	97.5	2.5	Coarse Aggregate 62.5%
3/8"	65-85	72.5	27.5	
No.4	45-60	52.5	47.5	
No.8	30-45	37.5	62.5	
No.50	5-20	12.5	87.5	Fine Aggregate 32.5%
No.200	3-7	5.0	95	
Pan	2.5-7.5	5.0	100	Mineral filler 5%

3.7.4.4 Fine Aggregate

Fine aggregate occupies the interspaces of coarse aggregate. Stone screenings would be used as fine aggregate. The screening is produced when stones are crushed with mechanical crusher. The specific gravity of the fine aggregate is 2.75. The specific gravity is determined according to ASTM C128. In the Marshall mixture, the proportion of fine aggregate and coarse aggregate would be kept at 32.5% and 62.5% of total aggregate.

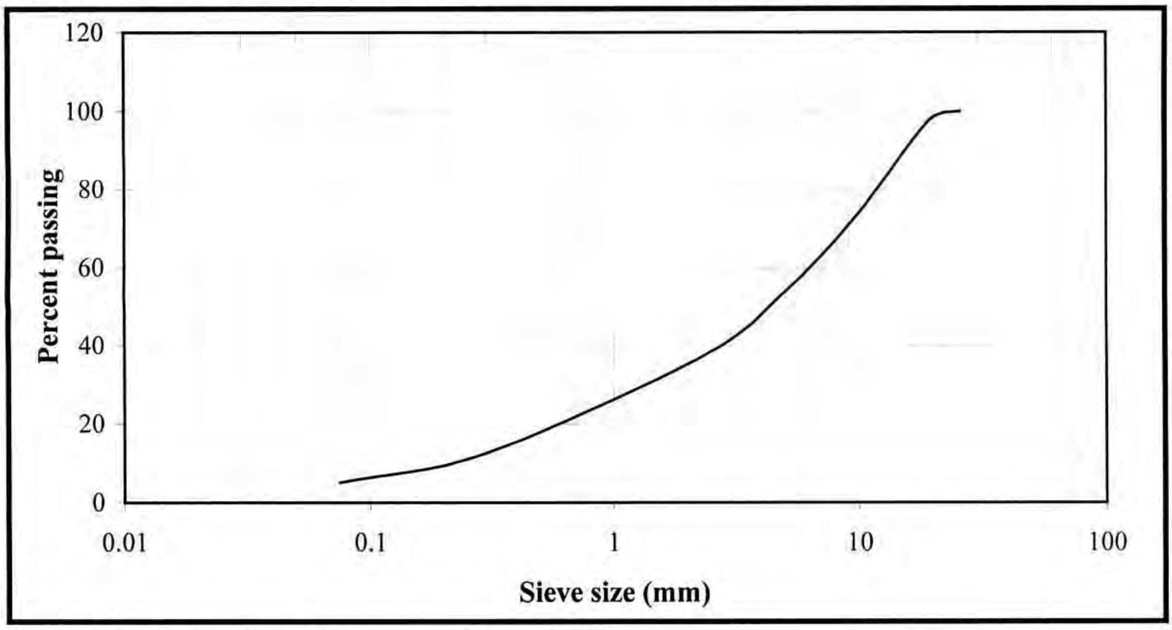


Figure 3.1: Grain Size Distribution Curve of Aggregates.

3.7.4.5 Mineral Filler

Mineral filler is not compulsory for bituminous mixes. Mineral filler fills the void in the aggregate and increases density of the compacted mixes. Percent void in the mineral aggregate can be controlled by the use of mineral filler. Stone dust obtained from the Los Angeles abrasion test of stone has been sieved by #200 sieve and would be used as mineral filler in the mix. The specific gravity of mineral filler is 2.77.

3.8 Overview

In this chapter different methods of blending, compatibility test of polymer and evaluation of prepared blend and mixes have been discussed. Considering the unavailability of blending system and as well as economic ground, the manual method of blending is proposed for this research work. Blending device need to be fabricated locally. Four types of polymers (LDPE, PP, EVA and PVC) are primarily selected for compatibility test. It is expected that these polymers could be blend with bitumen manually. Based on the compatibility test results, one of the four polymers would be selected to use as modifier of bitumen. This polymer would be used to prepare the final blend on which tests would be performed. The production of blend, preparation and testing of samples are described in the next chapter.

CHAPTER 4

SAMPLE PREPARATION AND TESTING

4.1 Introduction

This chapter includes compatibility test of polymer, selection of modifier, preparation of blend, process of blending, description of blending device, tests on binders and tests on mixes. The properties of reference binder and modified binder are evaluated by performing tests on binders and mixes. The tests that are performed on the binders are Specific gravity, Softening point, Penetration, Ductility, Viscosity, Loss on heating, Film thickness and Stripping and coating. This chapter also contains a brief description of these tests. Marshall mix design method is followed in order to determine the properties of mixes prepared with reference binder and modified binder. In this research work two different types of specimen namely (a) reference specimen using unmodified bitumen and (b) modified specimen using varying proportion of LDPE are prepared. For the preparation of fresh specimen conventional procedure is followed. But for the preparation of specimen using modified binder a special method and blending device is used.

4.2 Compatibility Test

It is stated earlier that incompatible polymer cannot be blended with bitumen. To find out the compatible polymer trial blending are made with four different pure forms of locally available polymers viz. low density poly ethylene (LDPE), poly propylene (PP), ethylene vinyl acetate (EVA) and polyvinyl chloride (PVC) and few reclaimed forms of waste polymers viz. tyres, tube, polythene bags. Trial blends are prepared with 5% polymer of unmodified bitumen. The duration of mixing time is 25-30 minutes and the mixing temperature is kept between 160°C-180°C. The process is carried out in a can having the capacity of 125 gm, taking 50 gm of bitumen. Mixing is performed by stirring manually and heat is applied by a gas burner. The homogeneity of the blend is examined by visual inspection under floodlight and sieving the blend by #100 sieve.

From the trial experiment it is observed that PVC and other waste polymers are not compatible with bitumen if manual method of mixing is adopted. Other three pure forms of polymers such as EVA, PP and LDPE are visually compatible with the bitumen i.e. any of these three polymers could be used to blend with bitumen by applying mixing force manually. However, considering the scope of the study and as well as relative cost of polymers only LDPE is selected as a modifier. LDPE is available in the local market in the pellet form and cost of one-pound LDPE is Tk. 24. This polymer in raw form could be seen in Photo 4.1. The physical properties of LDPE are presented in Table 3.2.

4.3 Production of Blend

4.3.1 General

Considering the fact that previous studies on polymer, attempted by local researchers [A.S. Chowdhury 2001, M. Hossain 2002] failed, as they were not successful in blending any forms of polymer with bitumen. Critical review of literature revealed that three factors affect the success of blending process. Without adjusting these three factors one cannot be able to prepare polymer-bitumen blend. The factors are blending temperature, blending time and shear force. The factors vary from polymer to polymer. Crumb rubber and recycled polyethylene needs high shear force (2500-2800 rpm) and long blending time (30-120 minutes) and relatively higher blending temperature. Blending time should be kept as less as possible, because too long blending time may change the rheology of modified binder. From the trial blending with different sources of polymer it is observed that the low-density polymers require less shear force and complete blending is possible by using manual stirring. Accordingly, in order to prepare the polymer-modified binder, a simple manual blending device is developed.

Photo 4.2: Locally Fabricated Blending Equipment

4.3.2 Blending Device

The blender consists of three parts, a tripod stand having clamping facilities, a container and a stirrer. The container is made of brass and having the capacity of 2.5 litre of liquid bitumen. The container is cylindrical and its internal diameter is 14 cm and height is 15 cm. A steel rod flattened at one end is used as stirrer. A loop is formed at the other end of the stirrer to make it easy to hold. The container can be clamped on the tripod stand firmly, so that it does not overturn during vigorous stirring of mixture. The fabricated blending device could be seen in Photo 4.2.

4.3.3 Preparation of Blend

Initially, a number of trials are made in order to get a'homogeneous binder, as a result of which the following procedure is adopted. About 1200 gm of bitumen is taken in the container. Then the container with the bitumen is placed on the tripod stand and heated with a gas burner. An asbestos net is used below the container to ensure uniform distribution of burner flame. Moreover, bitumen is heated for five minutes and stirred continuously to avoid local overheating. As the bitumen attained 160°C, the required quantity of selected polymer (LDPE) is added and mixed manually. The mixture is then vigorously stirred for 25-35 minutes keeping the temperature between 160°C-180°C depending on the amount of polymer.

At this stage it is observed that a uniformly dispersed binder is formed in the container. It is also found that the prepared binder was remained physically unchanged during the test period (3 months) and the binder may be stored for long time for future use. Photo 4.3 shows the blending operation.

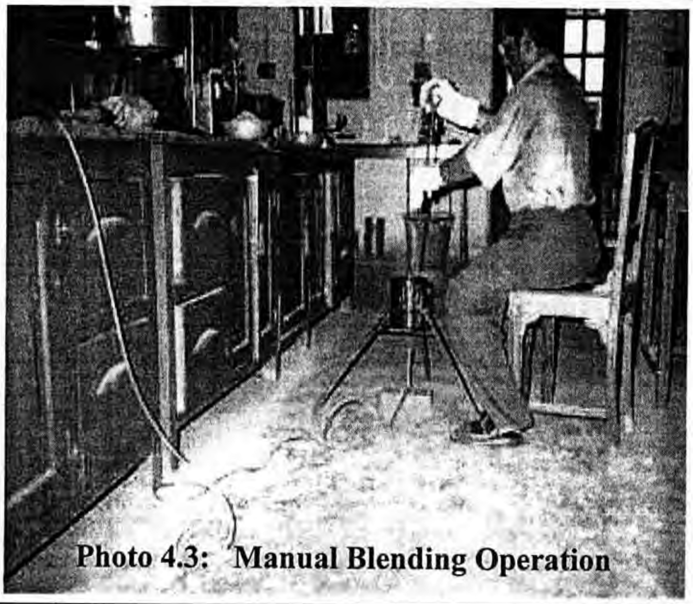


Photo 4.3: Manual Blending Operation

Following the above blending procedure, a total of four blends are prepared with 2.5%, 5%, 7.5% and 10% of LDPE. For each percentage of LDPE the required blending time is almost same. But the applied shear force and blending temperature needed to increase with the increase of LDPE content. But it was not possible to record the change of applied shear force and blending temperature in this manual blending device. It requires thermostatically and mechanically controlled blending system to observe the change of these factors.

4.4 Binder Test Procedures

4.4.1 General

Six conventional and one non-conventional tests are performed on the five sample of binder (one reference and four modified) in order to investigate the effects of LDPE on the bitumen properties. All of the tests are carried out following the AASHTO/ASTM designation. A new test, named as "film thickness" is carried out with reference-bitumen and LDPE modified bitumen in order to observe the film thickness characteristics on aggregates. Though, the film thickness test is not a standard one, it is performed in order to get an indirect measure of coating thickness on aggregates.

In order to obtain representative test results, the specimen preparation and testing are carried out as precisely as possible following the AASHTO/ASTM standards. In case of abnormal or unexpected results, the tests are repeated. In spite of this, due to some instrumental constraint or problem a few tests have shown inconsistent results. For instance, the results obtained from the Loss on heating test are found to be abnormal due to absence of high sensitive balance in the laboratory.

4.4.2 Penetration

Test Method: Penetration test of the binders is performed as per AASHTO DESIGNATION T 49-93 (ASTM DESIGNATION D5-86).

Summary of the Method: The sample is melted and cooled under controlled condition. The penetration is measured with a Penetrometer by means of which a standard needle is applied to the sample under the specified condition.

Test Condition: The accuracy of the test result is dependent upon closely controlled temperature condition. The test is performed at 25°C. The test load and loading time are 100 gm and 5 seconds respectively.

4.4.3 Softening Point

Test Method: Softening Point test is carried out as per AASHTO DESIGNATION T 53-92 (ASTM DESIGNATION D36-89).

Summary of the Method: The sample is melted and stirred thoroughly to avoid incorporation of air bubbles in it and to ensure homogeneity in case of PMB. Then the sample is poured into the ring that is rested on an amalgamated brass plate. After cooling for 1 hr, the excess material is cut off with a slightly heated knife.

Test Condition: The temperature of the distilled water in the glass vessel is maintained at 5°C for 15 minutes. The sample (ring) is placed 2.54 cm above the bottom of the glass. The rate of heating is 5°C per minute.

4.4.4 Ductility

Test Method: AASHTO DESIGNATION T 51-93 (ASTM DESIGNATION D113-79).

Summary of the Method: The sample is melted, stirred and molded as per specification. After cooling to room temperature for 30-40 minute, the excess material is cut off with a slightly hot knife. The mold is then set in the testing apparatus and ductility is measured at standard test condition.

Test Condition: Test is performed at 25°C, at pulling rate 5 cm/minute.

4.4.5 Specific Gravity

Test Method: AASHTO DESIGNATION T 228-93 (ASTM DESIGNATION D70-76).

Summary of the Method: The sample is heated and stirred above the expected softening point to be sufficiently fluid to pour. The fluid binder is poured into a clean, dry and warmed Pycnometer to the three-fourth of its capacity. The Pycnometer with its contents is allowed to cool to ambient temperature for a period not less than 40 minutes. The rest portion of the Pycnometer is filled with distilled water at test temperature. All weights are taken carefully.

Test Condition: Test is performed at 25/25°C condition.

4.4.6 Viscosity

Test Method: AASHTO DESIGNATION T201-93, ASTM DESIGNATION D2170-85.

Summary of the Method: ASTM D2170 (AASHTO T201) method is used to measure the viscosity of unmodified bitumen and modified bitumen. The viscosity machine has two major parts---oil bath and viscometer. The sample is heated and poured carefully into the viscometer at specified volume. The viscometer with the sample is set into the oil bath and heated for half an hour at test temperature (135^{0}C). Then the flow of bitumen is made to start by applying air pressure. Flow continues due to siphoning action of the system. The test arrangement can be seen in Photo 4.4. The time required to produce the specified head is recorded with a stopwatch. The kinematic viscosity is then calculated by multiplying the afflux time (in seconds) by viscometer calibration factor.

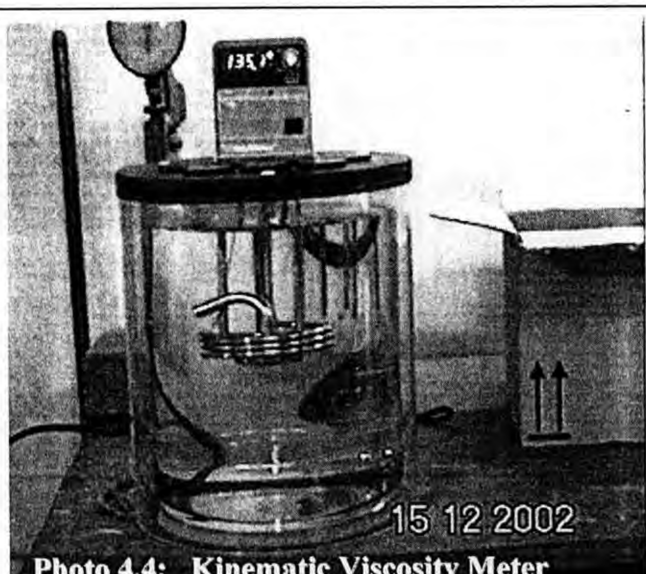


Photo 4.4: Kinematic Viscosity Meter

Test Condition: Test is performed at 135°C condition.

4.4.7 Loss on Heating

Test Method: AASHTO DESIGNATION T 47-83 (ASTM DESIGNATION D6-80).

Summary of the Method: 50 gm of the water free sample is taken in a container and cooled it to room temperature and weighed. The container with the sample is placed in the oven at 163°C. The temperature of the oven is maintained at 162°C±1°C for 5 hrs.

Test Condition: The test is performed at 163°C for 5 hrs.

4.4.8 Film Thickness Test

Test Method: Non-conventional.

Summary of the Method: Two steel spheres of suitable size are used to determine the binder film thickness on it. The sphere is heated in the oven at 150°C and the binder is heated separately at 150°C-155°C. The heated spheres are placed into the binder in a container and stirred for 2-3 minutes. The spheres are brought out and rested on a thin ring. The coated spheres are cooled to room temperature. The coated spheres can be seen in Photo 4.5. The lower portion of the spheres is smoothened with a slightly hot knife. Then the weight of the coated spheres are taken. The difference of the weight of the coated spheres and uncoated sphere is the weight of binder adhere to it. Coating thickness is calculated by using the following equations:

Photo 4.5: Coating Test on Solid Spheres

Volume of the binder = Weight of binder/Density of binder

Film thickness = Volume of binder/Surface area

Test Condition: Film thickness is determined at 25°C.

4.4.9 Stripping and Coating Test

Test Method 1: AASHTO DESIGNATION T 182-84 (ASTM DESIGNATION D1664-80).

Summary of the Method: Representative amount of aggregates are selected and sized in such a way that 100% passes through 9.5 mm (3/8 inch) sieve and retained on a 6.3 mm (1/4 inch) sieve. The aggregates are washed and dried at 135°C-149°C to a constant weight and stored in an airtight container. Then 100 gm of oven dry aggregates are taken in the mixing container. The container is placed in an oven for 1hr at constant temperature between 135°C-149°C. The binder is heated separately to 135°C-149°C. Then 5.5 gm of heated binder is added to aggregates and mixed vigorously with a spatula for 2-3 minutes until the aggregates are completely coated with binder. The coated aggregates are allowed to cool to room temperature.

Five samples of coated aggregate are prepared with the five samples of binder. Each sample is tested creating following four test conditions consecutively.

Cycle 1: The coated aggregates are transferred to a 600 ml glass container and covered immediately with 400 ml of distilled water at room temperature. The coated aggregates are allowed to remain immersed in the water for 18 hrs. The stripped area is estimated by visual inspection.

Cycle 2: The sample in the glass beaker is covered with distilled water. Then the beaker with contents is kept in an oven for 18 hr at 40°C. The stripping area is estimated by visual inspection.

Cycle 3: To create severe weathering condition, the sample is allowed to cool at room temperature without contact of water (at dry condition) for 72 hours. The sample is then immersed in water as per above procedure and kept in the oven at 40°C for 18 hrs. The change of coating characteristics is observed.

Cycle 4: Cycle 3 is repeated at 60°C.

4.5 Mix Design

Marshall method of mix design is adopted in the laboratory for evaluating the compacted paving mixes. The mix design method is formulated by Bruce Marshall, a former bituminous Engineer of the Mississippi State Highway Department. The Marshall test procedure has been standardized by the American Society for Testing and Materials (ASTM). The original Marshall method is applicable to hot-mix asphalt paving mixtures containing aggregates with maximum sizes of 25 mm (1 inch) or less. The method is intended for laboratory design and field control of asphalt hot-mix dense-graded paving mixtures. The method is empirical in nature. The standard shape of Marshall test specimen is cylindrical. The height of the sample is 64 mm (2.5 inch) and diameter is 102 mm (4 inch). In this experiment a total of 50 (5x5x2=50) specimens are prepared following the specified procedure of heating, mixing and compacting the asphalt-aggregate mixtures. Two different types of specimen namely (a) reference specimen using unmodified bitumen and (b) modified specimen using varying proportion of LDPE are prepared in this research.

4.5.1 Preparation of Test Specimens

4.5.1.1 Determination of Expected Design Binder Content

The "expected design" binder content can be determined from experiences, computational formula or by performing the centrifuge kerosene equivalency and oil soak test in the Hveem procedure. Another quick method to arrive at a starting point is to use the dust-to-asphalt ratio guideline. The expected design asphalt content, in percent by total weight of mix, could then be estimated to be approximately equivalent to the percentage of aggregate in the final gradation passing the 75 μm (No.200) sieve. In this test the computational formula is used to estimate the expected design asphalt content [Asphalt Concrete Mix Design; Asphalt Institute Manual Series No.2 (MS-2), Sixth Edition, 1997].

$$P = 0.035a + 0.045b + Kc + F$$

Where,

- P = approximate asphalt content of mix, percent by weight of mix
- a = percent of mineral aggregate retained on 2.36 mm (No. 8) sieve
- b = percent of mineral aggregate passing the 2.36 mm (No. 8) sieve and retained on the 75 μm (No.200) sieve
- c = percent of mineral aggregate passing 75 μm (No.200) sieve
- K = 0.15 for 11-15 percent passing 75 μm (No.200) sieve
  0.18 for 6-10 percent passing 75 μm (No.200) sieve
  0.20 for 5 percent or less passing 75 μm (No.200) sieve
- F = 0 to 2.0 percent. Based on absorption of light or heavy aggregate. In the absence of other data, a value of 0.7 is suggested.

The gradation of combine aggregates indicates, a = 62.5%, b = 32.5%, c = 5%. Using K = 0.2 and F = 0.7, the calculated expected design asphalt content is 5.37%. Using 0.5% increment of asphalt content the specimen are prepared with 4.5%, 5%, 5.5%, 6% and 6.5% of binder. Each specimen is prepared with 1.2 kg of aggregate.

4.5.1.2 Number of Specimens

The Marshall method recommends, preparing at least three specimens for each combination of aggregate and binder content. In this study though, two specimens for each combination of aggregate and binder content are prepared to minimize the laboratory work. Considering this specimen reduction, during sample preparation and testing the specification of the mix design method is strictly and carefully followed in order to get representative results.

4.5.1.3 Determination of Mixing and Compaction Temperature

Mixing and compaction temperature depend on viscosity of binder. In this experiment mixing and compaction is performed at 160°C ± 5°C and 145°C ± 3°C respectively to produce binder viscosity of 170 ± 20 centistokes kinematics and 280 ± 30 centistokes kinematics respectively.

4.5.1.4 Preparation of Mold and Hammer

The mold assembly and the face of the compaction hammer are cleaned thoroughly. They are heated in a water bath to a temperature between 95°C and 150°C. Filter paper is used in the bottom of the mold before the mixture is placed in the mold.

4.5.1.5 Preparation of Mixture

The required quantity of aggregates for each specimen is weighed into separate pans and the pans are heated in the oven at specified temperature. The heated aggregates are placed in the mixing bowl and are mixed thoroughly. Binder is heated separately at specified temperature. The required amount of heated binder is mixed with aggregates in the mixing bowl. Mixing is performed quickly and thoroughly by a trowel. Mixing temperature is kept at 160°C ± 5°C.

4.5.1.6 Packing the Mold

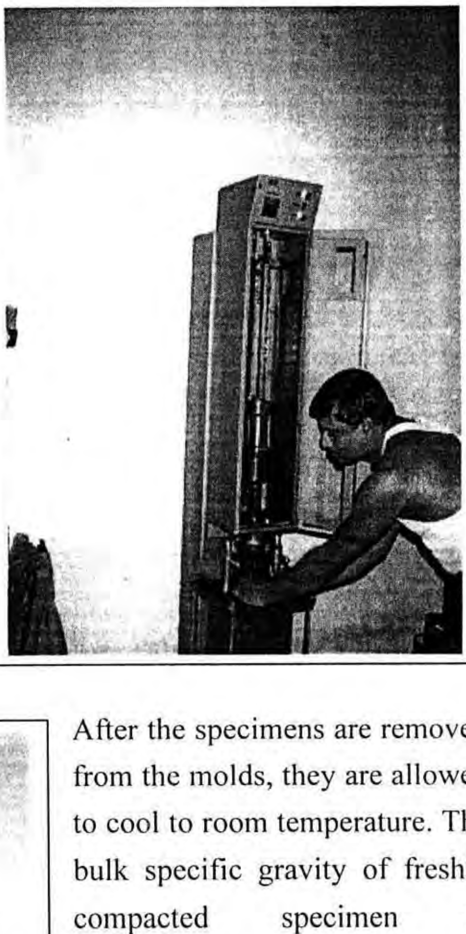
The entire batch is placed in the prepared mold. Filter papers are used in the bottom of the mold. The mixture is spaded vigorously with a heated spatula for 15 times around the perimeter and ten times over the interior. The surface is smoothened to a slightly rounded shape. The temperature is maintained within the compaction temperature.

4.5.1.7 Compaction of Specimen

Compaction is performed by a mechanical compactor at 145°C ± 3°C. A total of 50 blows are applied at each face of a specimen. The compacted specimens are allowed to cool overnight. Compaction of specimen could be seen from Photo 4.6.

4.5.2 Testing of Specimens

Photo 4.6: Specimen Compaction



4.5.2.1 General

The Marshall tests are conducted on compacted specimens to find stability and flow values of different mixtures. For volumetric analysis of compacted mixes (specimens), it is necessary to know the bulk and maximum specific gravity of the mixes. The maximum specific gravity of each specimen is determined after the completion of stability and flow test. Photo 4.7 shows removing of compacted specimen from the molds and Photo 4.8 shows assembly of prepared specimens.

4.5.2.2 Determination of Bulk Specific Gravity

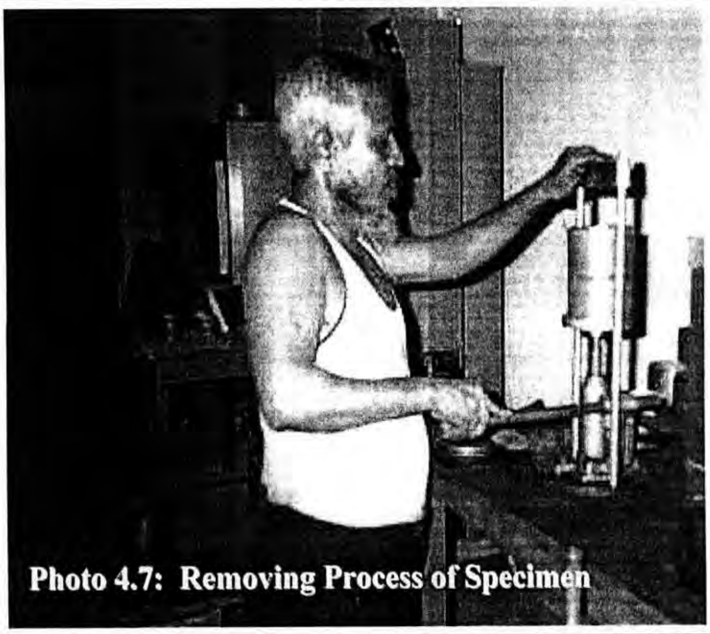


Photo 4.7: Removing Process of Specimen

After the specimens are removed from the molds, they are allowed to cool to room temperature. The bulk specific gravity of freshly compacted specimen is determined as quickly as possible. The test is performed according to the ASTM D 1188 method of testing.

4.5.2.3 Stability and Flow Test

After the determination of bulk specific gravity the specimens are immersed in a water bath at 60°C for 30 minutes. The inside surface of the testing head is cleaned maintaining the temperature between 21.1°C and 37.8°C. The guide rod is lubricated with oil and "zero" setting is checked in the flow meter and proving ring dial gauge. Ensuring the testing apparatus ready, the test specimen is removed from the water bath and the surface of specimen is dried carefully with a cloth. Then the specimen is placed in lower testing head and centered. The upper testing head is fitted in to position and the complete assembly is centered in loading device. Flow meter is placed over marked guide rod and again "zero" is checked. Load is applied to the specimen at constant rate of deformation (2 inch per minute) until failure occurred. The point of failure is defined as the maximum load. The total force required to produce failure is marked as Marshall Stability. When load began to decrease, the reading of flow meter is recorded. This is the reading of flow for the specimen. The flow value is expressed as 1/100 inch. The entire procedure for both stability and flow measurement are completed within the specified time of 30 seconds. Testing of Marshall specimen can be seen in Photo 4.9.


Photo 4.8: Assembly of Marshall Specimens

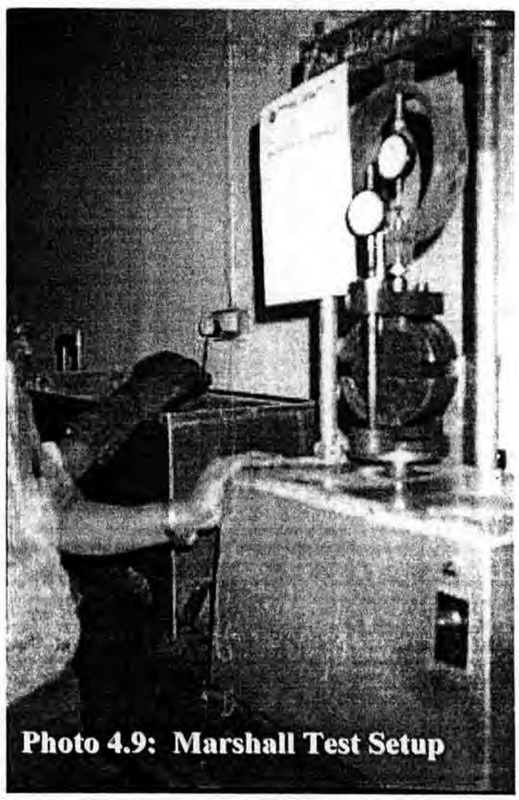


Photo 4.9: Marshall Test Setup

4.5.2.4 Determination of Maximum Specific Gravity

After stability and flow test, the specimens are stored for the determination of maximum specific gravity. To determine the maximum specific gravity, the specimen is broken and the material is weighed in air. Then it is placed in a container and water is poured to submerge the sample sufficiently and vacuum pressure is applied to remove void from the mixes. Then the weight of the sample is taken in water. Maximum specific gravity is determined to calculate the air void of the mixes.

4.5.2.5 Density and Void Analysis

After completion of stability and flow test, a density and void analysis is made for each series of test specimen. The bulk specific gravity values for two test specimens of a given binder content are averaged. The unit weight for each binder content is determined, multiplying the average bulk specific gravity of binder by the density of water. The effective specific gravity of total aggregates is calculated from the maximum specific gravity. The effective and bulk specific gravity of the total aggregates, the average bulk specific gravity of the compacted mixes, the specific gravity of binder and the maximum specific gravity of the mixes are used to calculate percent absorbed binder content by weight of aggregate, percent air void (Va), percent void filled with binder (VFA) and percent voids in mineral aggregate (VMA).

4.6 Overview

In this study, LDPE is selected as a modifier of bitumen considering its compatibility with bitumen and low price as compared to other compatible polymers. LDPE requires low shear force to blend with bitumen, which was possible to produce manually. Four blends were prepared by mixing 2.5%, 5%, 7.5% and 10% of LDPE with bitumen. From the trial experiment it is observed that to make homogeneous mix with waste polymers, high-speed mechanical blender would be required.

In order to study the characteristics of modified binder all standard routine tests and one non-conventional test were carried out. Marshall mix design method was followed in order to determine the properties of mixes prepared with reference binder and modified binder. All test results are presented in the next chapter.

CHAPTER 5

ANALYSIS OF RESULTS AND DISCUSSION

5.1 Introduction

The main objectives of the project work were to investigate the quality improvement of bituminous binder after adding polymer to it. For the assessment of quality improvement and comparison of reference binder (unmodified bitumen) with LDPE modified binder, Softening point, Penetration, Ductility, Specific gravity, Loss on heating, Viscosity, Film thickness and Stripping and coating tests were carried out on both unmodified bitumen (UB) and LDPE modified bitumen. Marshall tests were also performed on the compacted paving mixes prepared with reference bitumen and LDPE modified bitumen. This chapter contains all the results of these tests in tabular and graphical forms, analysis and comparison of results and discussion on them.

5.2 Binder Test Results

5.2.1 General

The tests that were performed on the binders are very conventional. Some common but important properties of binder such as temperature susceptibility, consistency, adhesive quality, viscosity etc. are assessed from these test results.

5.2.2 Penetration Test Results

In general the penetration is used to measure the consistency of semisolid and solid bituminous materials. It is used to classify semisolid bituminous materials into standard consistency grade. Since grade does not signify quality, the penetration test has no relation to quality of binder. It is an empirical test.

The results of penetration test on unmodified bitumen and LDPE-modified bitumen are shown in Table5.1. A plot of penetration versus LDPE content is shown in the Figure 5.1.

Penetration test was performed at 25°C. From the Figure 5.1, it can be noticed that the value of penetration decreases almost uniformly from a value of 87 in case of pure bitumen to 24 in case of the binder containing 10 percentage of LDPE content. This means that LDPE increases the consistency in a way stiffness of bitumen.

The bituminous binder provides cohesion or tensile strength in the bituminous paving mixtures. Generally, higher values of penetration are preferable for bitumen to use in tropical countries to prevent bleeding in pavement. On the other hand, in the field bitumen gradually hardens due to aging or oxidation process and penetration value decreases with time. Serious cracking may occur when penetration value falls below 20. This characteristic of binder causes bleeding to new pavement and cracking to aged pavement. The polymer-modified binder may be the solution of this problem. Since polymer is a non-biodegradable substance, initially its presence in the binder decreases the penetration of modified bitumen but it has the potential to retards the time dependent hardening process or further decrease of penetration of binder. Thus, it enhances the performance of pavement.

Table 5.1: The Results of Penetration Test on Unmodified and LDPE Modified Bitumen.

Test Method	LDPE Content (%)	Penetration (1/10th mm)
AASHTO T49-93 ASTM D5-86	0.0 (Unmodified Bitumen)	87
	2.5	65
	5.0	55
	7.5	35
	10.0	24

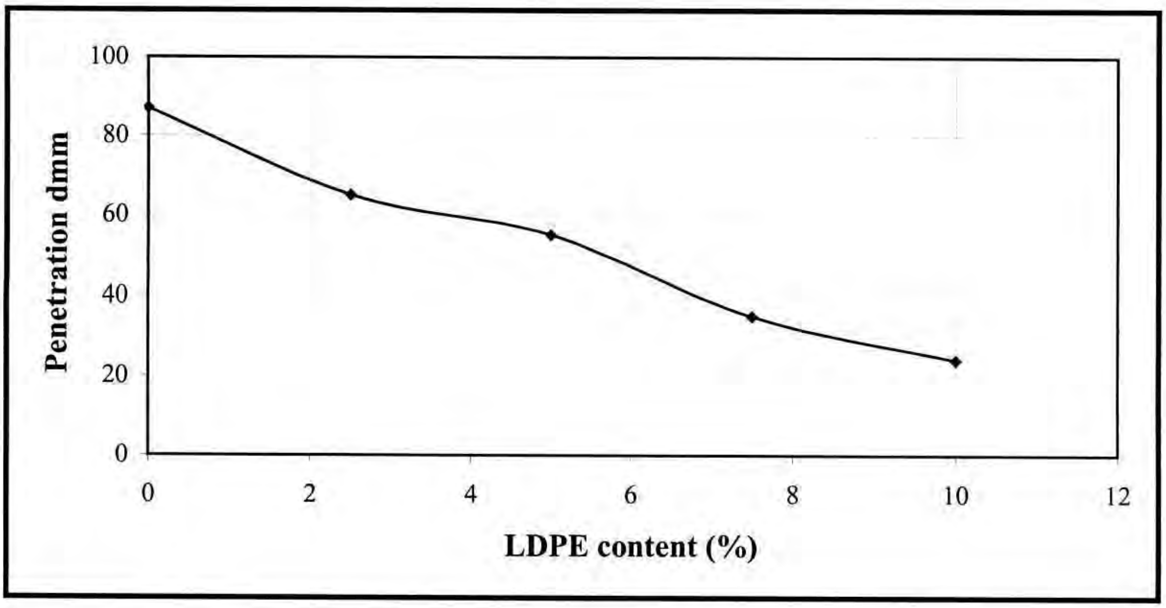


Figure 5.1: Variation of Penetration with LDPE Content in Bitumen.

5.2.3 Softening Point Test Results

The softening point test results are presented in Table 5.2 and Figure 5.2. Softening point is a measure of temperature at which binder reaches at flowing condition under the weight of a standard steel ball. It is not a measure of melting point. From the Figure 5.2, it can be seen that softening point increases from 45°C in case of unmodified bitumen to 68°C in case of the binder containing 10 percent LDPE content. It can be explained in this way that as polymer content increases consistency of the binder, higher temperature will be required to make the modified binder soft. From the Table 5.2 it can be calculated that addition of 10% LDPE with the unmodified binder, softening point increased by more than 51%. Which indicates that temperature susceptibility of binder significantly decreased with polymer content. This improvement of binder property will reduce the pavement-bleeding problem during hot season, which is one of the important modes of pavement distresses in tropical countries like Bangladesh.

Table 5.2: The Results of Softening Point Test on Unmodified and LDPE Modified Bitumen.

Test Method	LDPE content (%)	Softening Point (°C)
AASHTO T53-92 ASTM D36-89	0.0 (Unmodified Bitumen)	45
	2.5	48
	5.0	54
	7.5	61
	10.0	68

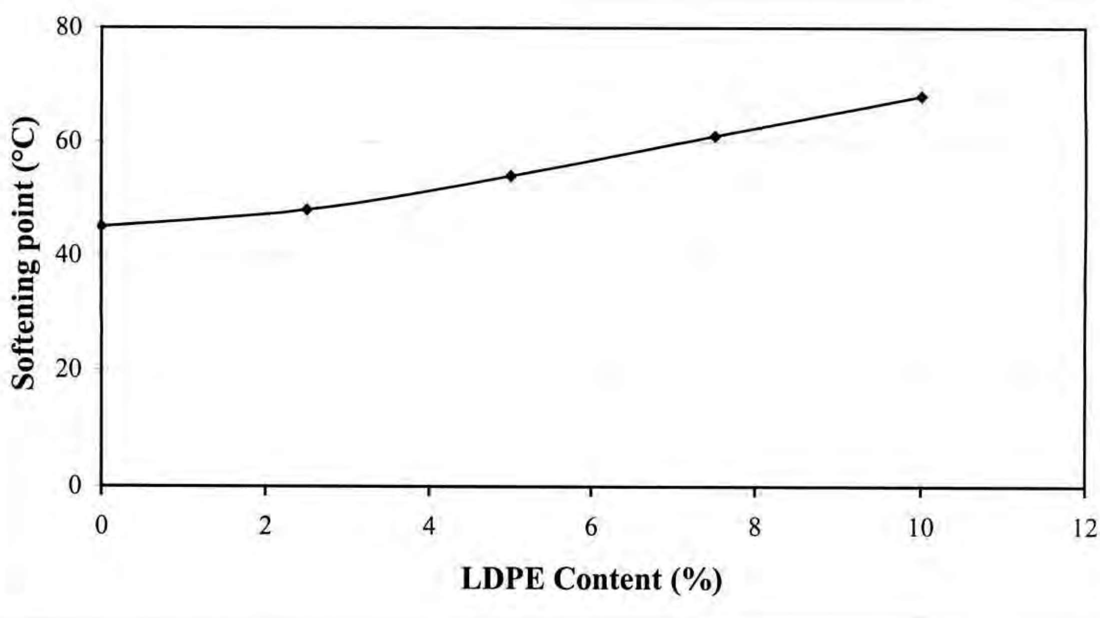


Figure 5.2: Variation of Softening Point with LDPE Content in Bitumen.

5.2.4 Ductility Test Results

Table 5.3 and Figure 5.3 represent the ductility test results. The results indicate that ductility sharply decreases with the increase of LDPE content in binder. The ductility of original bitumen was 100+ cm. This value of ductility is decreased to 19 for 10% of LDPE content (Specifications for standard bitumen as per AASHTO are shown in Table 4A and Table 5A of appendix). Resulting loss of ductility with this LDPE content is more than 425% as compared to the reference bitumen with ductility value of 100+ cm. This implies that use of LDPE polymer as a modifier has pronounced effect on the ductility property of the unmodified bitumen. From the Figure 5.3 it can also easily be seen that the change of ductility value with LDPE content is not linear. The rate of change of ductility property increases with LDPE polymer content.

Table 5.3: The Results of Ductility Test on Unmodified and LDPE Modified Bitumen.

Test Method	LDPE Content (%)	Ductility (cm)
AASHTO T51-93 ASTM D113-79	0.0 (Unmodified Bitumen)	100+
	2.5	94
	5.0	70
	7.5	45
	10.0	19

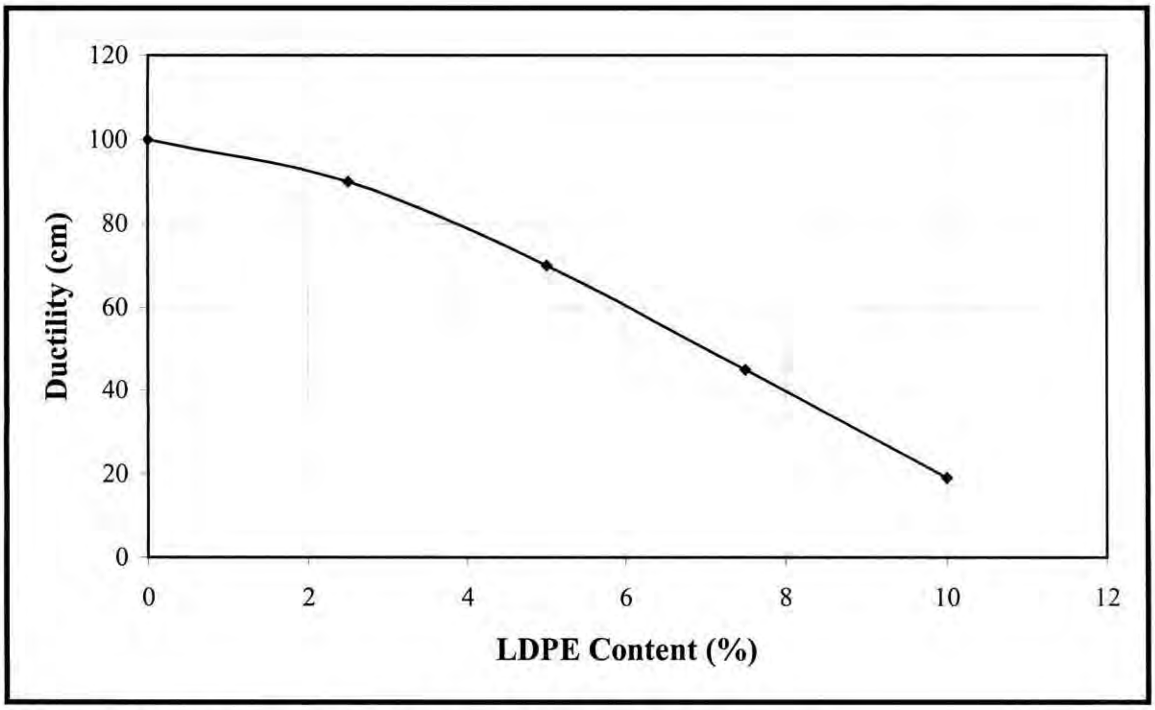


Figure 5.3: Variation of Ductility with LDPE Content in Bitumen.

Ductility is the measure of internal cohesion of the binder. It is an important quality of binder, which imparts cementing property in bituminous mixes. It is generally thought that bituminous materials with high ductility value have good binding properties. But bituminous materials with high ductility could perform differently. As initial ductility alone does not indicate whether the binder will perform better in service period or not. Generally, ductility of bitumen decreases with time and the rate of decrease are not same for all types of binders. Using LDPE with bitumen can decelerate the rate of change of ductility value, though LDPE initially reduces the original ductility of bitumen. As too much reduction of ductility may cause the binder unfit as pavement material, selection of maximum LDPE content may be limited by the ductility value of modified binder. Though from the literature it is learned that in one hand polymer decreases ductility on the other hand it increases elasticity of the binder. In this consideration modified binder with lower ductility value could be used safely in the bituminous mixes. In this regard elastic recovery test would be the most appropriate test, but due to unavailability of this experimental setup in the laboratory it could not be performed.

The effect of LDPE on ductility, penetration and softening points could be seen from the combined Figure 5.3a.

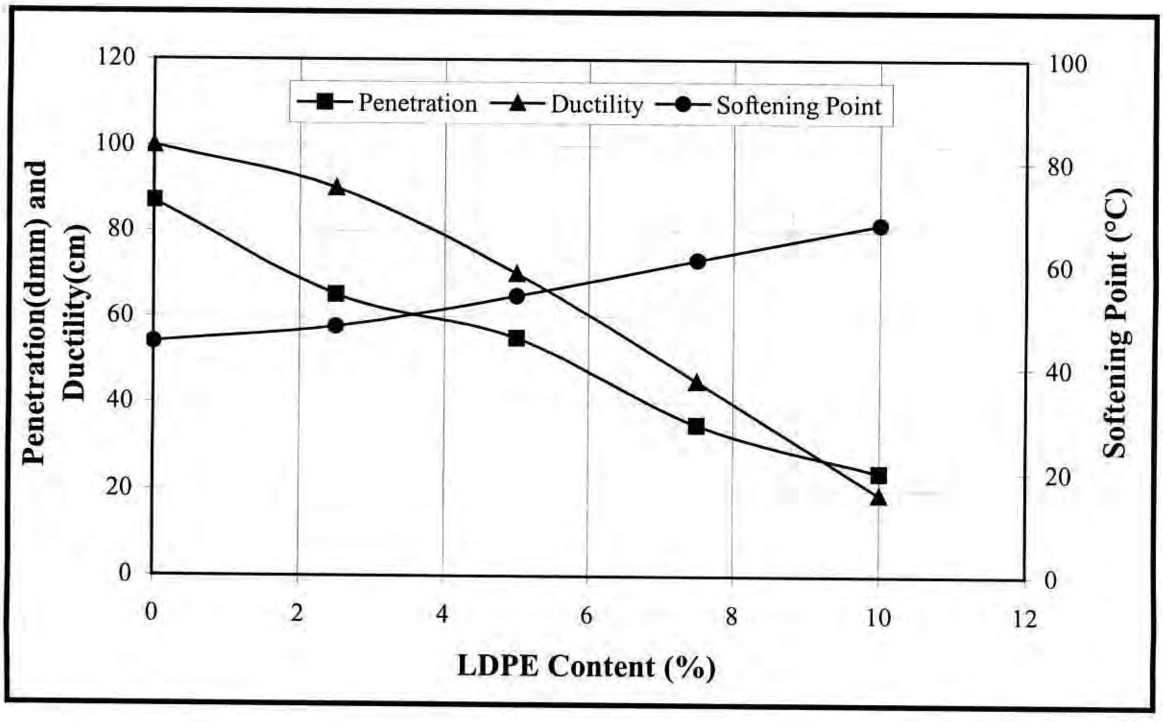


Figure 5.3a: Variation of Penetration, Ductility and Softening Point with LDPE Content in Bitumen.

The results of penetration, ductility and softening point tests show that the stiffness of the binder increases with addition of increasing quantity of polymer

5.2.5 Specific Gravity Result

The results of specific gravity test are shown in Table 5.4. and Figure 5.4. From these Table and Figure, it is seen that specific gravity of LDPE modified bitumen decrease with the percentage of LDPE content. The specific gravity of unmodified bitumen was 1.030. For 10% LDPE content, this value of specific gravity decreased to 1.018. Since the specific gravity of LDPE is less than that of bitumen, expectedly the value of specific gravity of modified binder decreases with the increase of LDPE content in bitumen.

Table 5.4: The results of Specific Gravity Test on Unmodified and LDPE Modified Bitumen.

Test Method	LDPE Content (%)	Specific Gravity
AASHTO T228-93 ASTM D70-76	0.0 (Unmodified Bitumen)	1.030
	2.5	1.025
	5.0	1.020
	7.5	1.019
	10.0	1.018

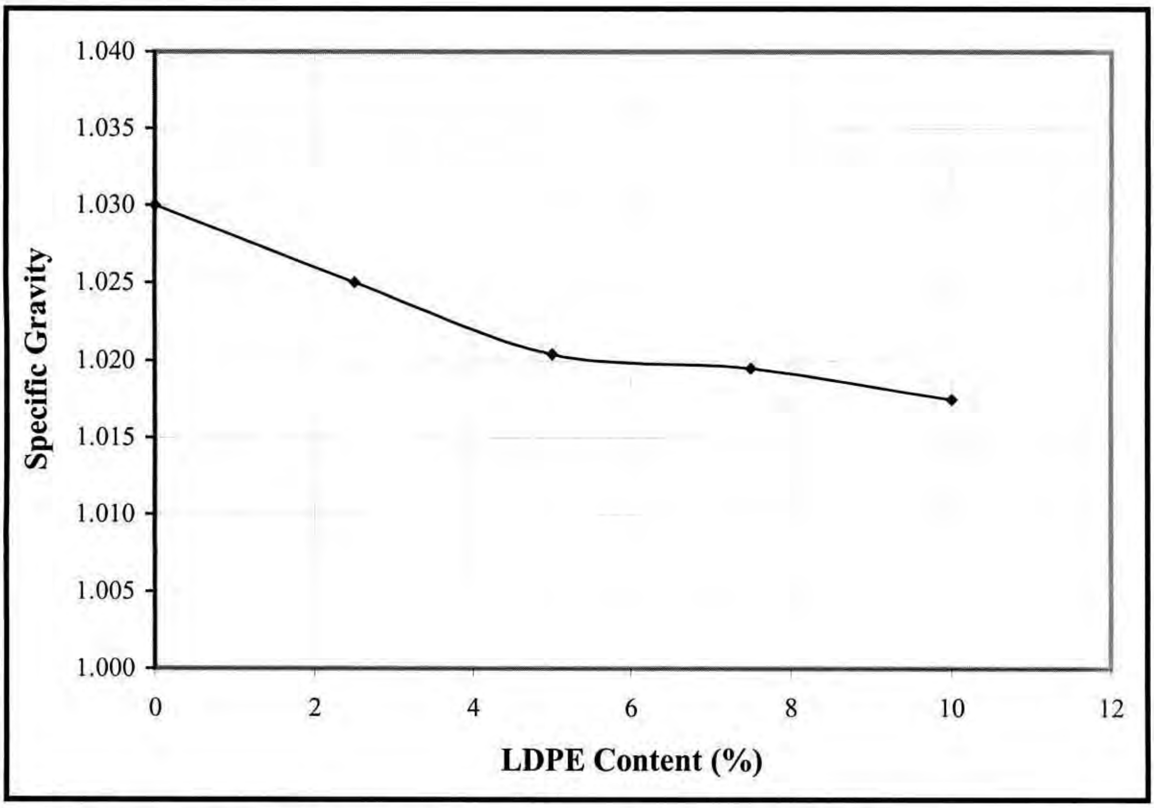


Figure 5.4: Variation of Specific Gravity with LDPE Content in Bitumen.

5.2.6 Loss on Heating Results

The results of loss on heating test are shown in Table 5.5. This test requires very sensitive balance to weigh the material. But due to unavailability of sensitive balance in the laboratory this test could not be performed accordingly. From the results presented in the Table, no definitive effect of LDPE on loss of heating of modified binder could be inferred. Though for few instances the tests were repeated but the results obtained were anomalous. The loss of material for reference bitumen is 0.06% and that for 5.0% and 7.5% LDPE modified bitumen are found to be 0.04% and 0.06% respectively. Variation of loss on heating with LDPE content in bitumen is graphically presented in Figure 5.5.

Table 5.5: The Results of Loss on Heating Test on Unmodified and LDPE Modified Bitumen.

Test Method	LDPE Content (%)	Loss on Heating (%)
AASHTO T47-83 ASTM D6-86	0.0 (Unmodified Bitumen)	0.060
	2.5	0.065
	5.0	0.040
	7.5	0.060
	10.0	0.053

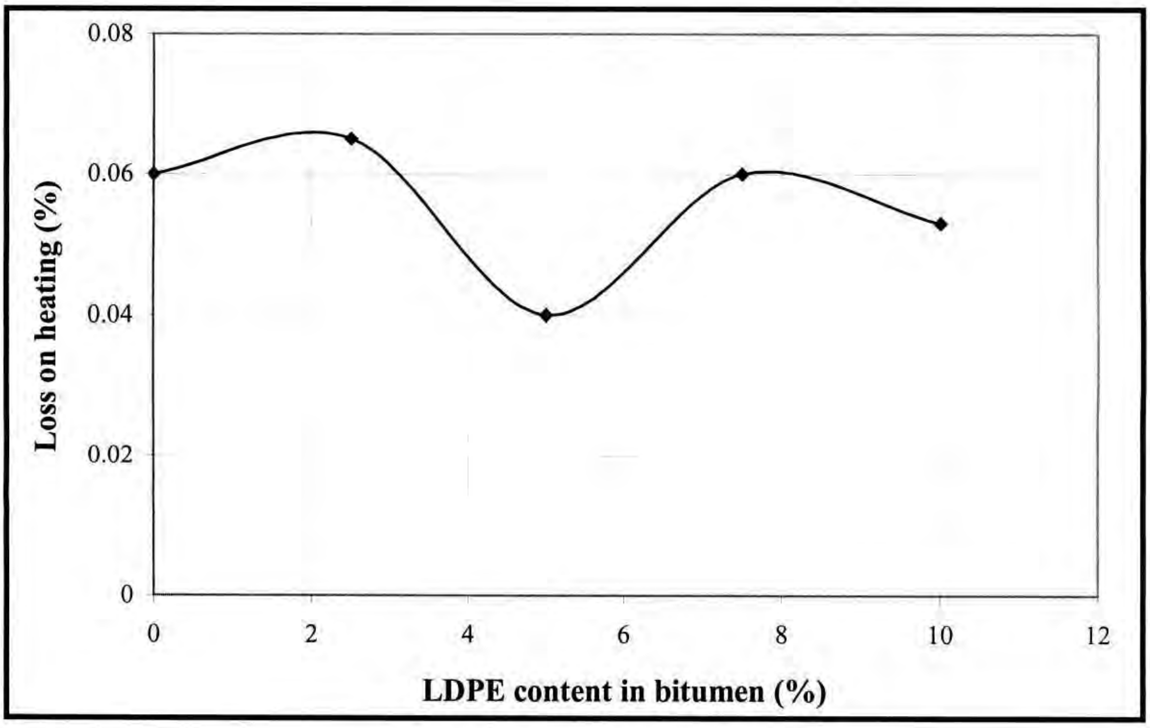


Figure 5.5: Variation of Loss on Heating with LDPE Content in Bitumen.

5.2.7 Viscosity Test Results

Viscosity is an important property of bituminous binder. It indicates performance of bitumen with temperature. As such the classification based on viscosity is considered better than that of based on penetration. Moreover, mixing and compaction temperature of hot asphalt paving mixtures depends on the viscosity of binder. Binders having higher viscosity increase the thickness of coating on aggregates and can minimize stripping in pavement.

In this research, the Kinematic test was performed to determine the viscosities of the binders. The results of viscosity test are summarized in Table 5.6 and graphically presented in Figure 5.6. It is seen from the results that the viscosity of LDPE modified binder increased substantially with the increase of LDPE content.

In general, binder with higher viscosity is necessary to build pavement in the tropical region. Though with the traditional binder it becomes very difficult to select harder bitumen meeting with other important specification such as ductility. In this respect, the use of LDPE modified binder in the paving mix could be a better solution.

Table 5.6: The Results of Viscosity Test on Unmodified and LDPE Modified Bitumen.

Test Method	LDPE Content (%)	Viscosity (centistokes)
AASHTO T49-93 ASTM D5-86	0.0 Unmodified bitumen	331
	2.5	630
	5.0	1117
	7.5	1572
	10.0	9494

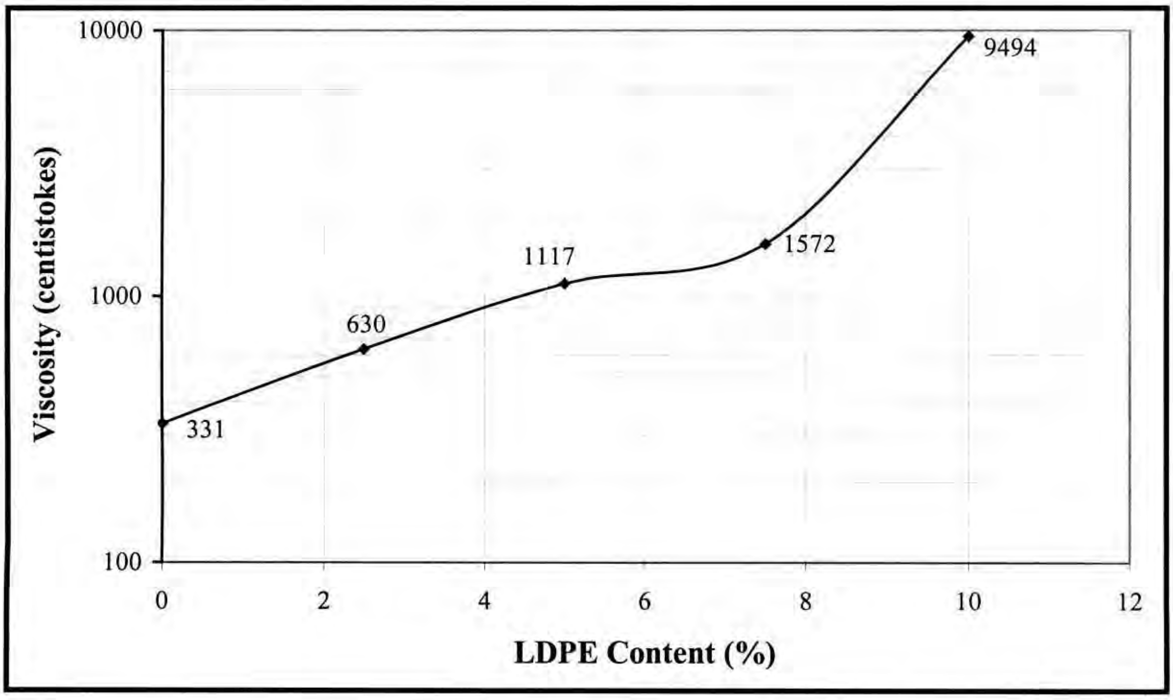


Figure 5.6: Variation of Viscosity with LDPE Content in Bitumen.

5.2.8 Film Test Results

This unconventional test was performed with a solid steel sphere, in order to study the film or coating thickness of binder on aggregates when polymer is added with bitumen. As the surface texture of the sphere is quite different from that of aggregates, it would be a very indicative type of test. Moreover, as aggregates are porous and irregular in shape, the amount of binder and the nature of film thickness on aggregates would be different from that of solid sphere.

The experimental results as shown in Figure 5.7, it can be observed that the thickness of film or coating on smooth surface increases with the increase of LDPE content. Expectedly, the polymer due to the extra viscosity imparts this increase of film thickness. From the Table 5.7 it is clear that the increase of coating thickness even with the smooth spherical surface is very significant. With 10% LDPE content the increase of film thickness is about 150% as compared to the original binder. It is obvious that this coating thickness of modified binder would be more with aggregates.

From the above results it could easily be inferred that the thicker film on aggregates would be helpful in preventing water to enter into the aggregates. Thus with polymer modified pavement mixes, the bond between aggregates and binder would be more strong and thereby pavement performance would be better especially under submerged conditions. The study results in this regard are presented in the following article.

Table 5.7: Binder Film Thickness on Spherical Surfaces for Different LDPE Content.

Binder Type	Sp. Gr.	Sphere No.	Surface Area (mm)	Wt. of Coating (gm)	Volume of Coating (cm^3)	Film Thickness (mm)	Average Thickness (mm)
Unmodified bitumen	1.0300	1	5674.5	0.295	0.2864	0.0504	0.0481
		2	5489.1	0.26	0.2524	0.0459	
Bitumen + 2.5% LDPE	1.0250	1	5674.5	0.297	0.2897	0.0510	0.0549
		2	5489.1	0.331	0.3229	0.0588	
Bitumen + 5.0% LDPE	1.0204	1	5674.5	0.470	0.4606	0.0811	0.0790
		2	5489.1	0.431	0.4220	0.0769	
Bitumen + 7.5% LDPE	1.0195	1	5674.5	0.513	0.5031	0.0886	0.0891
		2	5489.1	0.502	0.4923	0.0897	
Bitumen + 10.0% LDPE	1.0175	1	5674.5	0.688	0.6762	0.1192	0.1190
		2	5489.1	0.673	0.6614	0.1205	

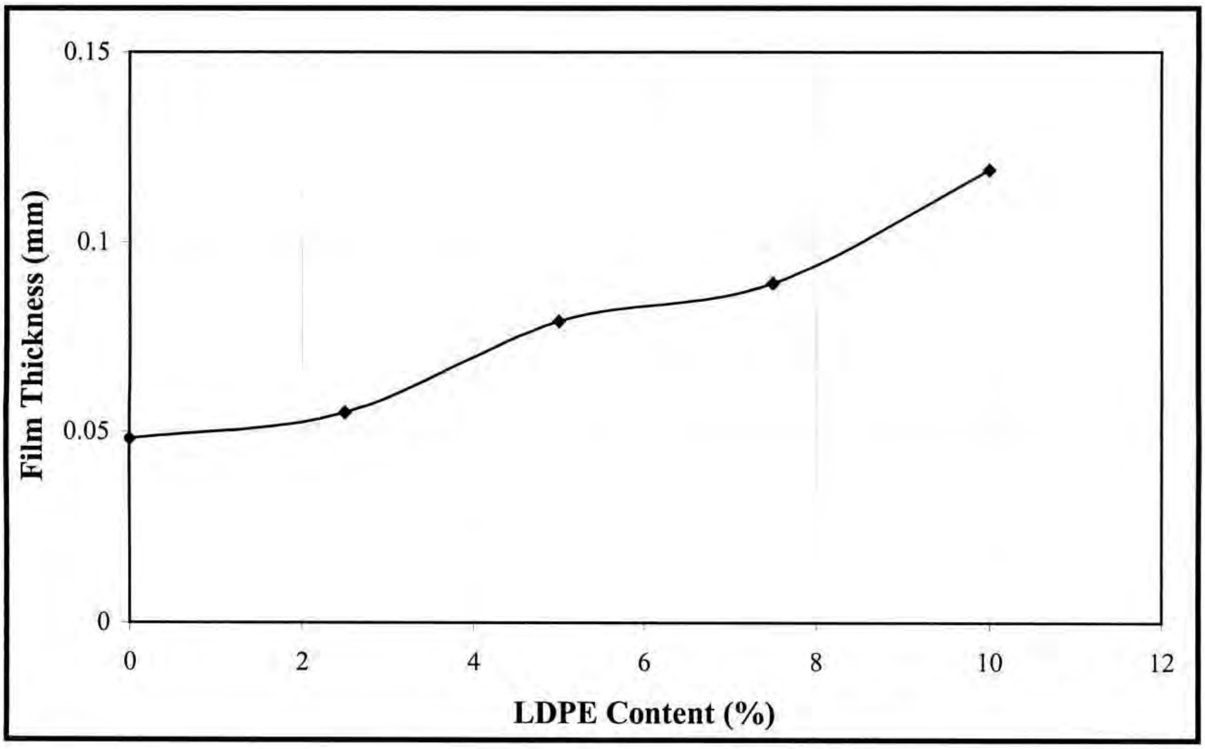


Figure 5.7: Variation of LDPE Modified Binder Film Thickness on Steel Sphere.

5.2.9 Stripping and Coating Test Results

Stripping and coating test of binder was performed at four different test conditions. In order to get a meaningful comparative result, the test was conducted progressively for up to four cycles with changing test condition. In the first cycle, the test was carried out according to the ASTM standards for all the test binders including unmodified and modified binder. Observation was made qualitatively after 18 hrs of immersion at room temperature. Getting no significant results for any of the test binders, the experiment was repeated for three times successively by gradually accelerating the harshness of test conditions.

In the second cycle, observation was made on the same test materials after further 18 hrs submergence at 40°C. Third cycle test was conducted after allowing 72 hrs drying of the test materials at room temperature and further 18 hrs submergence at 40°C. The final observation was made after 72 hrs drying at room temperature and further 18 hrs submergence at 60°C. Though according to the test method, stripping and coating test results are need to be expressed as "below 95%" or "above 95%" but in order to make a meaningful comparison among binders with and without polymer, the experimental results are also expressed in different ways.

The stripping and coating test results are presented in Table 5.8. Comparing the test results, it can be concluded that the affect of stripping is less with LDPE modified bitumen as compared to that of unmodified bitumen. Test results show that the retention of binding material on aggregates for reference bitumen is less than that for LDPE modified bitumen. Moreover, it can be seen that stripping decrease with higher proportion of polymer content. It is observed from the Table that even after 4^{th} cycle of aggressive test conditions, with 5% LDPE content the stripped area is only 5% which is 20% for unmodified bitumen. It implies that the increased film thickness of modified binder make it more water resistance and thereby imparts more endurance than that of unmodified binder.

Table 5.8: The Results of Stripping and Coating Test on Unmodified and LDPE Modified Bitumen.

Polymer content in bitumen (%)	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**
	18 hrs under water at room temperature	18 hrs under water at 40°C	72 hrs at drying at room temperature and 18 hrs under water at 40°C	72 hrs at drying at room temperature and 18 hrs under water at 60°C
0.0	Above 95%	Below 95%	Below 95%	Below 80%
2.5	Above 95%	Below 95%	Below 95%	Below 85%
5.0	Above 95%	Above 95%	Above 95%	Above 95%
7.5	Above 95%	Above 95%	Above 95%	Above 95%
10.0	Above 95%	Above 95%	Above 95%	Above 95%

5.3 Marshall Test Results

5.3.1 General

In order to study the performance of unmodified and modified binders a comparative analysis is presented here. For the performance evaluation of PMB mixes, all the descriptive parameters of Marshall test are used as a measure of index. Besides Marshall stability and flow tests, volumetric analysis of the test specimens is also presented here. Raw data of Marshall test and related calculations are included in the Appendix.

5.3.2 Marshall Stability

Table 5.9 and Figure 5.8 represent the stability test results. The Figure 5.8 shows the stability versus binder content curves. As can be seen from the Figure, the trend of stability curves for the mixes with modified binders is similar to that of bituminous concrete with pure bitumen. There are five curves in this Figure. The lower most curve is for the unmodified bitumen and the upper most one is for modified bitumen with 10% LDPE. The upward trend of five consecutive curves clearly indicates that the stability increases with the increment of LDPE content in bitumen. From the Table 5.9, the maximum stabilities for binders containing 0, 2.5, 5, 7.5 and 10 percent polymer are found to be 2256, 2583, 2803, 2959 and 3018 lb respectively. For all the cases the maximum stabilities occurred at 5 percent binder content.

Further calculation of percent improvement of stability value revealed that due to use of 10% polymer in the binder, the stability has increased in the order of 34%. This finding indicates that high strength bituminous mixes could be produced by using PMB and without changing other ingredients. Which implies that with this extra strength, thin wearing course or overlay could be design in pavement construction as well as in rehabilitation works and thereby a significant cost saving could be possible. In this consideration it is very important for Bangladesh.

Table 5.9: Marshall Stability for Mixes with Unmodified and LDPE Modified Bitumen.

Binder Content (%)	Marshall Stability (lb)				
	0.0% LDPE	2.5% LDPE	5.0% LDPE	7.5% LDPE	10% LDPE
4.5	2082	2443	2678	2905	2933
5.0	2256	2583	2803	2959	3018
5.5	2184	2420	2572	2763	2934
6.0	2094	2283	2442	2610	2715
6.5	1994	2116	2391	2573	2649

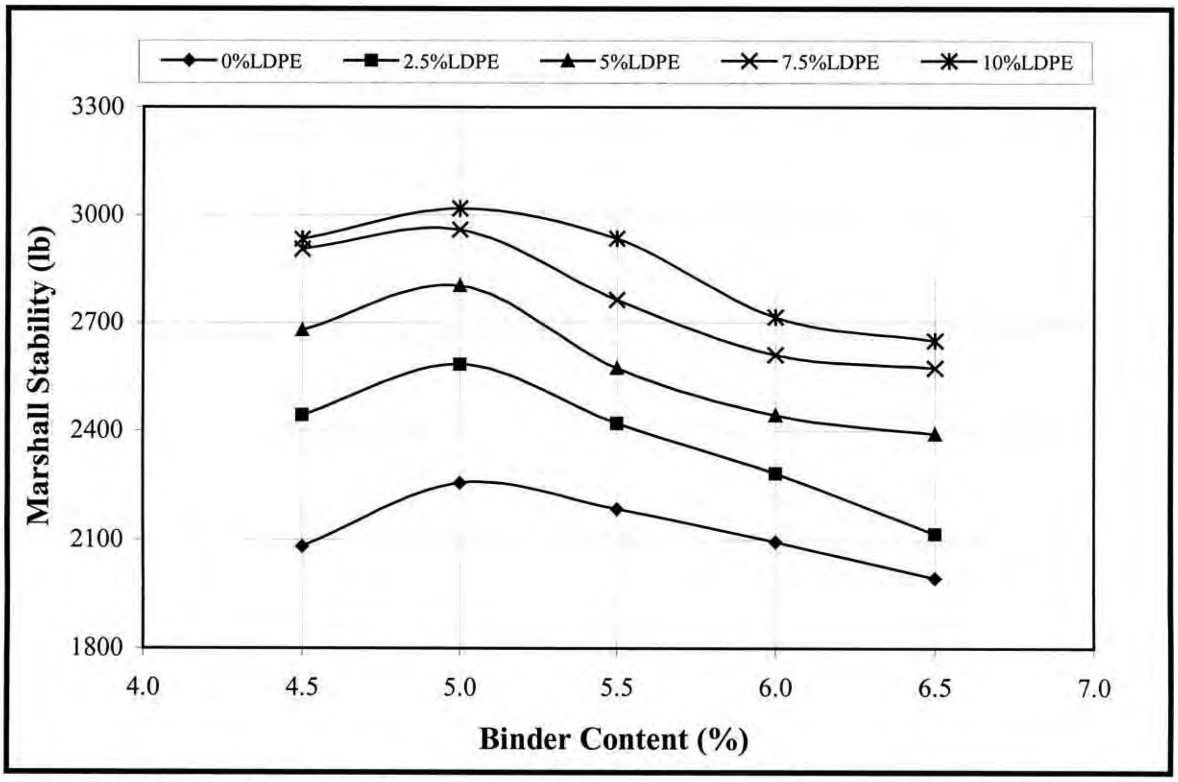


Figure 5.8: Marshall Stability Results for Mixes with Unmodified and Modified Binder.

In order to see the overall effect of binder modification, the Figure 5.9 is drawn averaging the stability values corresponding to each percentage of LDPE content. From the continuous increasing pattern of stability value with increasing LDPE content indicates that there is a possibility of blending more quantity of LDPE type polymer with bitumen.

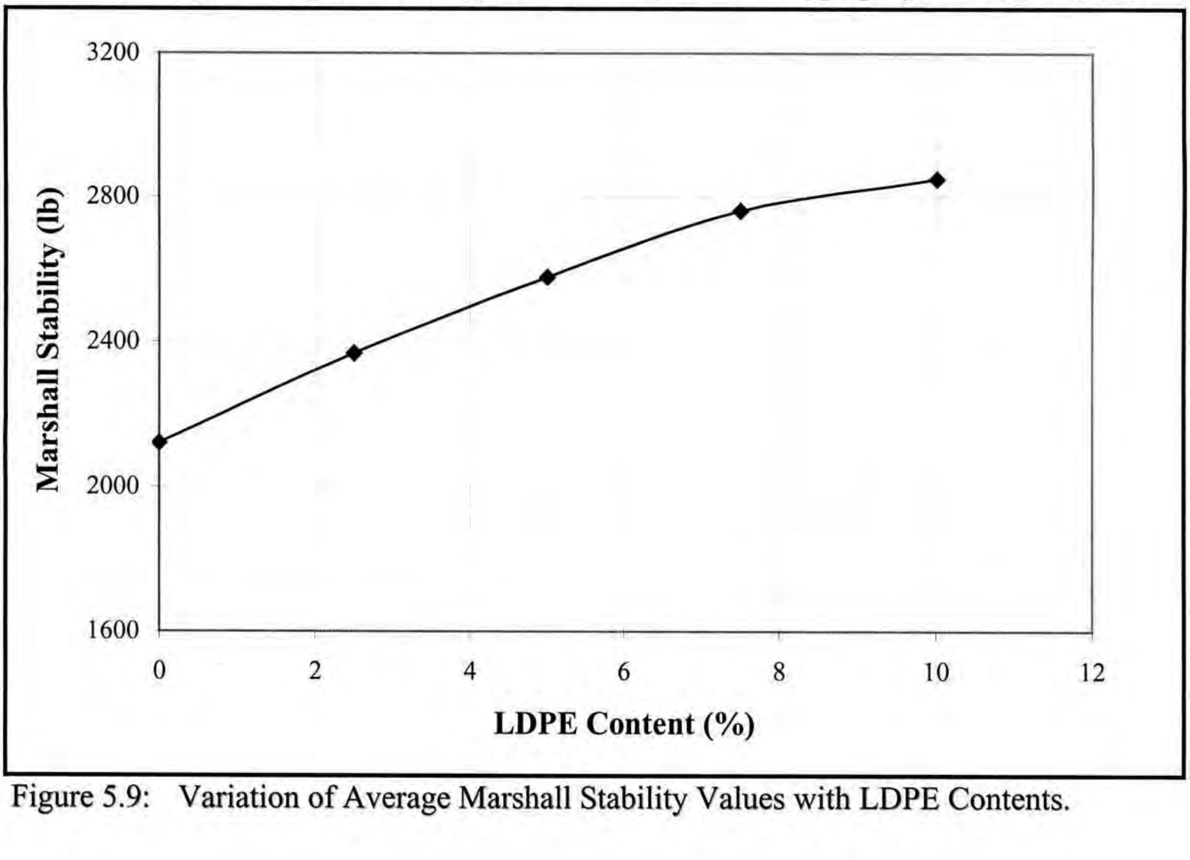


Figure 5.9: Variation of Average Marshall Stability Values with LDPE Contents.

5.3.3 Flow Value

Flow value is a measure of deformation. The maximum deformation at which a Marshall specimen fails is termed as the flow value. For unmodified bitumen higher flow value of bituminous pavement indicates lower rigidity.

The variation of Marshall flow values with binder content is presented in Table 5.10 and Figure 5.10. From the results it can be observed that for all the bitumen contents the flow values increase with the increase of LDPE content, though the rate of increase of flow values is quite low. Figure 5.11 is drawn by averaging the flow values for each percentage of polymers content in the binder. The same increasing pattern could also be observed from this Figure.

In consideration of this increasing trend of flow values with LDPE, it can be said that LDPE could not be used in high proportion to modify binder. But other research results [Shell Chemicals] revealed that though due to application of polymer in bitumen increases the flow values but at the same time it significantly improves the elastic property of the modified binder. This revelation implies that bituminous mix with high proportion of LDPE would not create any functional problem as long as other Marshall mix design criteria are satisfied.

The main criterion of Marshall mix design is that bituminous pavement should have sufficient stability to sustain wheel loads without any significant deformation. In general conventional bituminous pavement with high stability values lacks flexibility. And with time this type of pavement becomes brittle and develops cracks. In this regard LDPE (or any suitable modifier) could be a better solution as it has the potential to improve both the pavement stability as well as the flexibility.

Table 5.10: Marshall Flow Values for Mixes with Unmodified and LDPE Modified Bitumen.

Binder Content (%)	Flow Value (1/100 inch)				
	0% LDPE	2.5% LDPE	5% LDPE	7.5% LDPE	10% LDPE
4.5	12.50	12.10	15.50	17.00	18.00
5.0	13.00	13.00	16.00	17.75	17.50
5.5	13.75	13.50	17.00	18.50	19.25
6.0	14.25	15.25	17.75	19.00	18.50
6.5	15.50	17.00	19.50	20.25	20.75

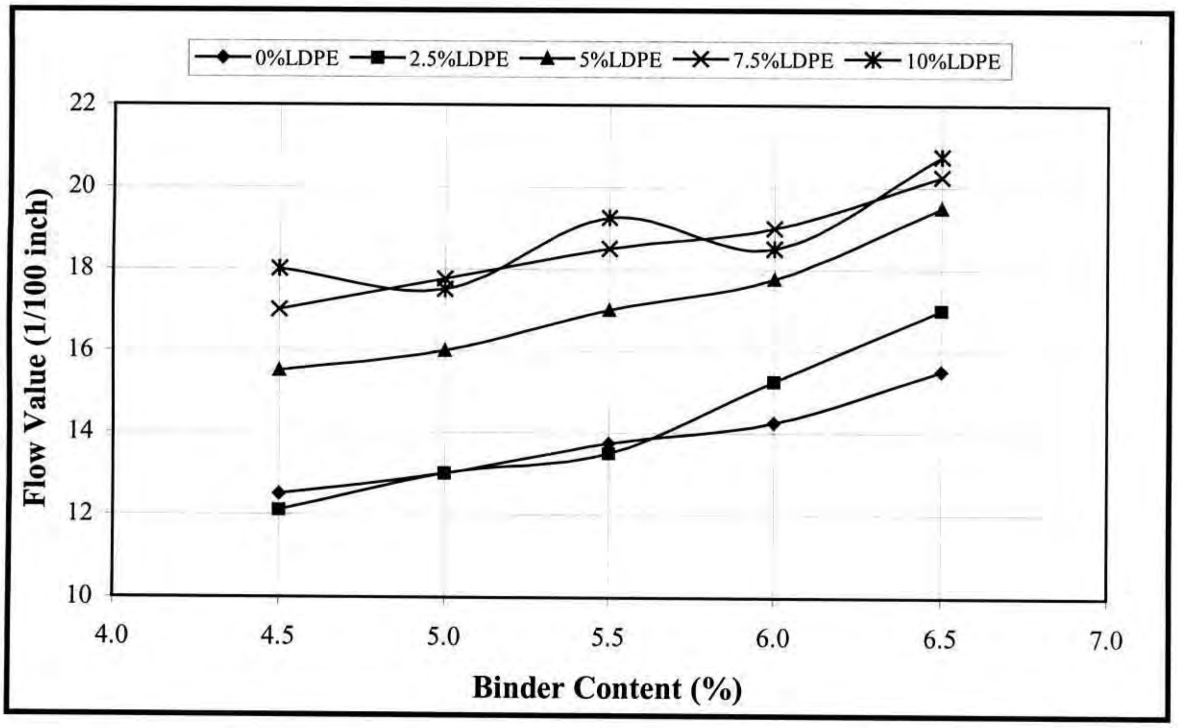


Figure 5.10: Flow Value Results for Mixes with Unmodified and LDPE Modified Binder.

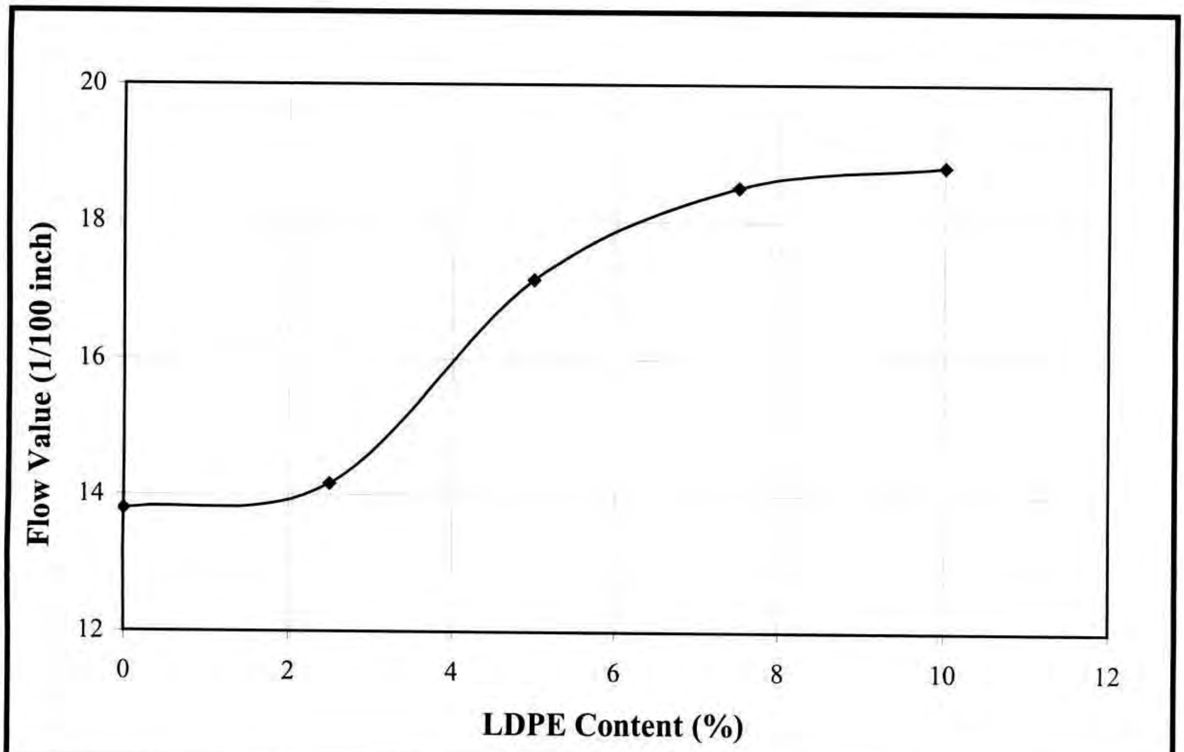


Figure 5.11: Variation of Average Flow Values with LDPE Contents.

5.3.4 Density

The results of density analysis are shown in Table 5.11 and Figure 5.12. The lower most of the five curves in Figure 5.12 stands for 10% LDPE content. From the close observation of the results it can be seen that unlike stability the density of compacted mixes slightly decreases with the increase of LDPE concentration in bitumen. This may be due to the fact that LDPE is a low-density type polymer. Though the closeness of the curves implies that the impact of binder modification is not significant. For all the mixes, the maximum unit weight is obtained at 6 percent bitumen content.

Table 5.11: Unit Weight Results for Mixes with Unmodified and LDPE Modified Bitumen.

Binder Content (%)	Unit Weight (lb/cft)				
	0% LDPE	2.5% LDPE	5% LDPE	7.5% LDPE	10% LDPE
4.5	144.64	146.05	145.17	145.06	145.23
5.0	146.75	146.73	146.91	146.76	146.11
5.5	148.21	148.08	148.42	148.48	147.83
6.0	148.69	149.48	149.07	149.26	148.61
6.5	148.89	149.01	149.37	149.15	148.58

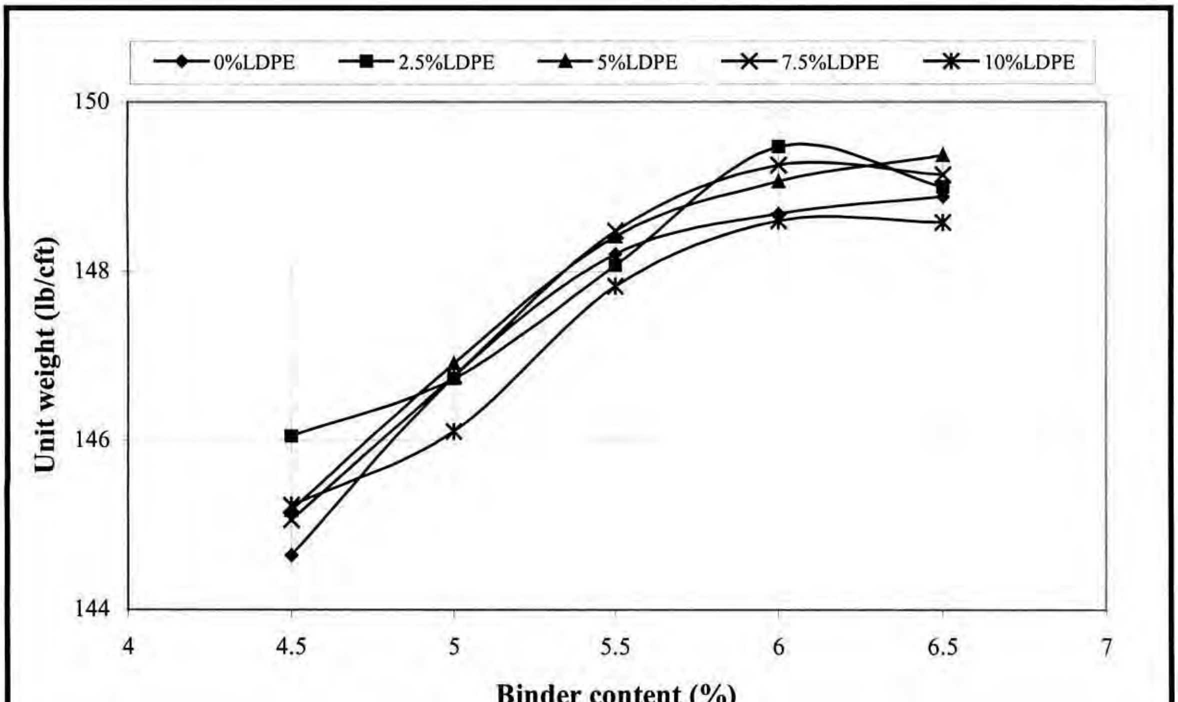


Figure 5.12: Unit Weight Results for Mixes with Unmodified and LDPE Modified Bitumen.

5.3.5 Air Void (Va)

The amount of air voids present in the mix is a very important design criterion. There should be enough air voids in the pavement mix so that binder can adhere the aggregate particles properly and at the same time it would not create bleeding problem at elevated temperature. The results of air void analysis are presented in Table 5.12 and Figure 5.13. By observing the results it can be said that the variation of air void due to change of LDPE concentration in bitumen is insignificant. From close observation of the Table 5.12, it can be revealed that air voids slightly decreased with increasing concentration of LDPE in the mixes. This may be due to the fact that increased viscosity of modified binder may have caused less infiltration of binder in to the voids of mineral aggregates, resulting less air voids in the mixes. All the curves in Figure 5.13 are closely spaced. This close contact of these curves implies less impact of LDPE on air void in compacted mixes. From the Figure it can also be observed that the general shape of the curves for modified binders is very similar to that of unmodified bitumen.

Table 5.12: Air Void Results for Mixes with Unmodified and LDPE Modified Bitumen.

Binder Content (%)	Air Void (%)				
	0% LDPE	2.5% LDPE	5% LDPE	7.5% LDPE	10% LDPE
4.5	8.58	7.64	8.14	8.21	8.08
5.0	6.53	6.49	6.33	6.41	6.81
5.5	4.89	4.91	4.63	4.58	4.98
6.0	3.87	3.29	3.49	3.35	3.75
6.5	3.02	2.87	2.56	2.69	3.03

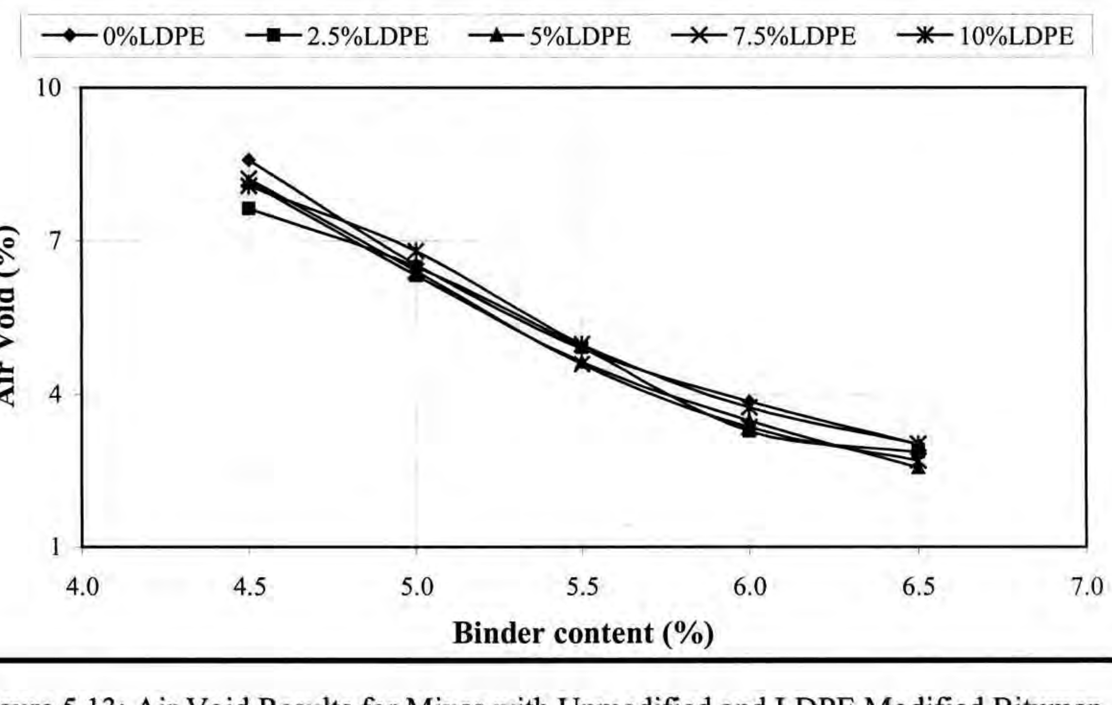


Figure 5.13: Air Void Results for Mixes with Unmodified and LDPE Modified Bitumen.

5.3.6 Void in Mineral Aggregate (VMA)

In general, the shape of VMA curve for polymer less binder is concave upward (flattened U-shape) and the value of VMA decreases with the increase in binder content to a minimum and then increases again. The results of VMA analysis are shown in Table 5.13 and Figure 5.14. As can be seen that the Figure 5.14 satisfies the general shape of VMA curve and it does not clearly show any significant effect of LDPE content in bitumen.

Table 5.13: VMA Results for Mixes with Unmodified and LDPE Modified Bitumen.

Binder Content (%)	Void in Mineral Aggregate (%)				
	0% LDPE	2.5% LDPE	5% LDPE	7.5% LDPE	10% LDPE
4.5	17.84	17.04	17.54	17.60	17.50
5.0	17.08	17.09	16.99	17.07	17.44
5.5	16.69	16.77	16.57	16.54	16.91
6.0	16.87	16.43	16.65	16.55	16.91
6.5	17.20	17.13	16.93	17.05	17.37

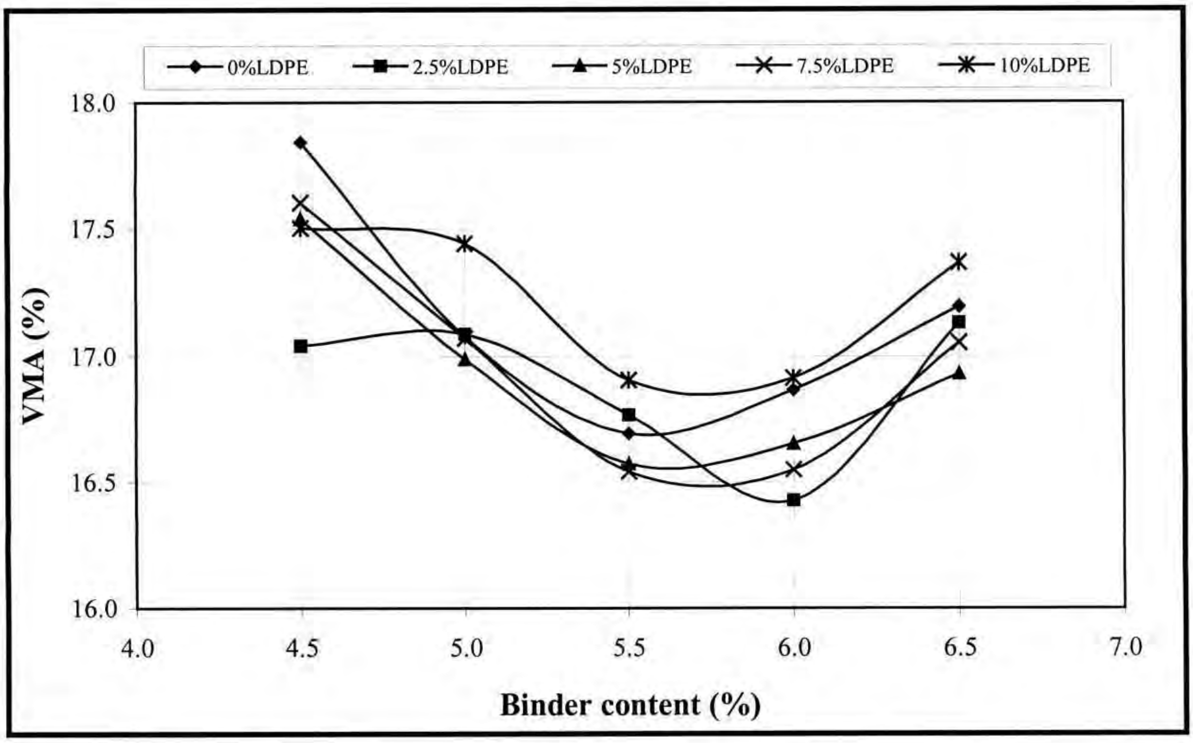


Figure 5.14: VMA Results for Mixes with Unmodified and LDPE Modified Bitumen.

5.3.7 Void Filled with Asphalt (VFA)

VFA (Void Filled with Asphalt), VMA (Void in Mineral Aggregate) and AV (Air Void) are closely interrelated. The purpose of VFA analysis is to limit the maximum levels of VMA and subsequently maximum level of bitumen content. VFA also controls the air void content in compacted mixes. Table 5.14 and Figure 5.15 represent the VFA analysis results. From the results, like air voids no significant effect of LDPE content on VFA in bituminous mixes could be found.

Table 5.14: VFA Results for Mixes with Unmodified and LDPE Modified Bitumen.

Binder Content (%)	Void Filled With Asphalt (%)				
	0% LDPE	2.5% LDPE	5% LDPE	7.5% LDPE	10% LDPE
4.5	51.99	55.19	53.58	53.39	53.86
5.0	61.81	62.02	62.78	62.47	60.99
5.5	70.71	70.72	72.05	72.29	70.59
6.0	77.08	80.05	79.07	79.73	77.84
6.5	82.48	83.27	84.87	84.20	82.56

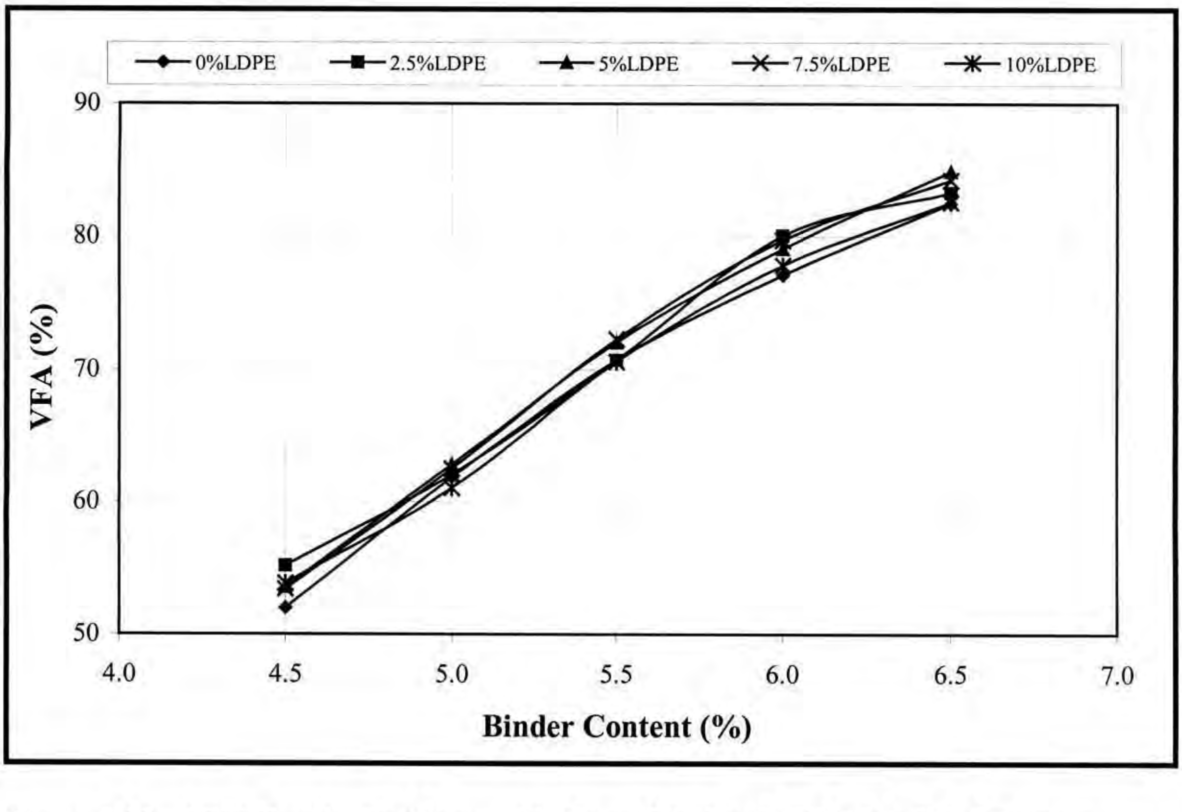


Figure 5.15: VFA Results for Mixes with Unmodified and LDPE Modified Bitumen.

5.4 Overview

This chapter presented the analysis of experimental results. The tests that were performed for the evaluation of PMB and mixtures are very conventional. Test result indicates encouraging results. From the test results, it can be commented that adding LDPE type polymer with bitumen improves the inherent weakness of the traditional bitumen such as temperature susceptibility. It also improves consistency, stiffness properties of bitumen and stripping of aggregates. These findings may be significant in particular relation to Bangladesh where pavement requires frequent maintenance. It is also evident from experiment results that high strength bituminous mixes is possible using PMB. Summary of finding of the thesis is presented in the following chapter.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The preliminary objective of this study was to find out compatible polymers to blend with bitumen and to fabricate a simple low cost blending device. A manual blending device is fabricated accordingly. In this investigation a total of four pure forms of synthetic polymers viz. low density poly ethylene (LDPE), poly propylene (PP), ethylene vinyl acetate (EVA) and polyvinyl chloride (PVC) are tested to check their compatibility with bitumen.

According to other objectives of the research, the blended binder and mixes prepared with LDPE were investigated through laboratory experimentation. A comparative analysis of polymer-modified binder and bituminous mixes prepared with this modified binder was carried out. The qualitative improvement of polymer modified binder and mixes are studied by comparing their characteristics with that of unmodified bitumen. The summary of the test results and important findings are presented in the following articles.

6.2 Conclusion on Experimental Results

6.2.1 Polymer Blending and its Compatibility

The success of blending of polymer with bitumen depends on their compatibility and affinity to mix with one another. An incompatible polymer cannot be blended with bitumen. Mutual compatibility test is the first step of polymer-bitumen mix. From the compatibility tests of LDPE, PP, EVA and PVC, findings of research are summarized below:

- Blending of bitumen with pure forms of polymer can be done by using manual stirring device. With the exception of PVC, polymers such as LDPE, PP and EVA become compatible with bitumen if the shear force (2500-3000 rpm) required for the blending operation is applied manually.

- It is observed that the blending of these compatible polymers requires vigorous stirring and a uniformly dispersed binder formed when the temperature and the time of blending exceed about 160°C and 25 minutes respectively. The duration of blending and the range of temperature for these three polymers are found to be 25-35 minutes and 160°C-200°C respectively, depending on the polymer content in the binder.

- LDPE required a lower blending temperature as compared to the other compatible polymers. The range of blending temperature for LDPE is found to be 160°C - 180°C and the maximum time required for the binder to react with bitumen is about 30 minutes.

- It is found that for the production of polymer modified binder in small quantity, the manual method of blending is quite suitable.

- During the preparation of the modified binder in the laboratory, no objectionable fumes are noticed from the heated polymer.

- It is also observed no physical change in the prepared blend during the test period (3 months). The prepared binder may be stored for future use.

6.2.2 Characteristics of Polymer Modified Binder

The comparative qualities of binders (unmodified bitumen and modified bitumen) was evaluated by such tests as softening point, specific gravity, penetration, ductility, viscosity, loss on heating, film thickness and stripping and coating. The following conclusions are drawn by analyzing the test results on the binders :

- The penetration, the ductility and the specific gravity of the LDPE modified binder decrease while the softening point and viscosity increase with the increase in the concentration of LDPE in the bitumen.

- Experimental results reveal that the LDPE polymer reduces the binder's temperature susceptibility and improves consistency by significant amounts.

- The film thickness experiment conducted with solid steel spheres shows that the binder coating thickness increases significantly with the increase of the LDPE content in the bitumen. With 10% LDPE content, the increase of film thickness was about 150% as compared to that of the original binder. It is obvious that the coating thickness of the modified binder would be more with aggregates in the bituminous mix.

- Coating and stripping tests show that the coating of the LDPE modified bitumen on aggregate is stronger than that of unmodified bitumen on aggregate. From the static immersion test it is also observed that better adhesive property of the modified binder makes the bituminous mixes more impermeable to water and delays the stripping process.

6.2.3 Characteristics of Polymer Modified Bituminous Mixes

The properties of compacted mixes prepared with unmodified bitumen and LDPE modified bitumen were studied. The tests on the mixes reveal that :

- The stabilities of the compacted mixes increase significantly with the increase of the LDPE content in bitumen. The continuous increasing pattern of the stability value up to 10% LDPE content indicates that there is a possibility of blending more amount of LDPE with bitumen.

- From the stability test of Marshall specimens it is found that 10% polymer in the binder increases mixture stability by about 34%. This implies that high strength bituminous mixes may be made simply by adding LDPE type polymer and without changing any other mix ingredient.

- The flow values as obtained in the Marshall tests show slightly increasing pattern with LDPE type polymer content, whereas unlike stability, the density of the compacted mixes slightly decreases with the increase of LDPE content in the bitumen. The effect of LDPE on air void (Va), void in mineral aggregate (VMA) and void filled with asphalt (VFA) is found insignificant.

- From close observations of the trend of Marshall characteristics curves (stability, flow, unit weight, AV and VMA) for modified binder, it is found that the patterns and shapes are very similar to that of mixes with pure bitumen. These observations imply that the optimum quantity of modified binder could be determined following the same Marshall procedure and criteria.

6.3 General Conclusions

The use of polymers as modifier of bitumen has yet to start in Bangladesh. The results obtained from this research work are found to be encouraging. As such, there is a bright prospect of using not only new polymers but also recycled polymer as a modifier of bitumen. In consideration of frequent submergence problems, high summer temperature and poor pavement construction practice in Bangladesh, the use of polymers in pavement may bring economical as well as environmental benefits in the following ways:

- In case of traditional binder the use of optimum amount of binder in the mix is a very important issue. In general excess binder content causes bleeding and heaping problems especially at high temperature, whereas any deficient amount of binder may cause cracking, loss of aggregates and potholes problems. In Bangladesh due to prevalence of manual mixing, it is very difficult to control the correct amount of bitumen in the mix; thereby pavement serviceability and life suffer from so called different binder induced problems. In this regard polymer modified binder could be a better solution due to its low ductility, high softening point and presumably enhanced elastic properties.

- Moreover, as polymer modified binder (PBM) is less susceptible to temperature, bituminous mixes could be designed with minimum air void criteria. The resulting benefits would be decelerated aging process due to less circulation of air as well as less infiltration of surface runoff. Additionally, due to its improved susceptibility, the polymer modification would be helpful to use softer grades of bitumen in pavement construction.

- Extra film thickness of modified binder is beneficial not only to deter stripping process but to ensure more flexible and smoother pavements. These attributes are very important for pavements in urban as well as residential areas where drainage problem is very common and pavement induced noise is a serious issue.

- As the modification of binder increases pavement strength by a big margin, pavement thickness could be reduced significantly and thereby a considerable cost saving could be achieved in pavement construction.

- Since polymer modified bituminous binder has the potential to make pavement long lasting, to reduce construction cost and maintenance frequency, it holds a huge potential and a great prospect in prevailing weather conditions and road construction practices in Bangladesh.

6.4 Limitation of the Study

Though this investigation was an attempt to incorporate polymer with bitumen with the aim of producing high performance binder and partly solving the undesirable stockpiling of non-biodegradable waste. In the absence of any thermostatically and mechanically controlled blending system, the study is conducted with one of the pure forms of low-density polymer instead of reclaimed or waste polymer. Though, experimental results show that high strength mixes are possible using this polymer, besides being costly, it would not solve any undesirable environmental waste deposition problem.

Moreover, the observations of this research are limited in their scope, within the range of variables investigated, the type of tests employed and the nature as well as the number of specimens tested. For example, only one type of polymer has been used throughout this laboratory investigation, keeping the compaction energy unchanged for all the specimens that have been tested. The durability is determined only on the basis of static immersion tests. Due to lack of laboratory facilities, elastic and ductility recovery tests could not be performed. The latter tests are most important measures of indices to study the time dependent behavior of binders.

6.5 Recommendations for Future Study

In this research commercially available branded LDPE is used as a modifier of bitumen. No doubt, the results of this study are encouraging and polymer modified binder (PMB) will lengthen pavement service life. As imported LDPE is costly, modification of bitumen with LDPE may not be commercially beneficial from economic considerations. An economical feasibility analysis should be done before the practical use of pure LDPE with bitumen.

The use of reclaimed waste/scrape polymers as modifiers of bitumen may produce economical and environmental benefits. Hence further continuous study is essential in this respect.

In order to ascertain the complete behavior of the modified binder, a comprehensive test program including fatigue and permanent deformation tests with varying parameters such as test temperatures and loading conditions need to be conducted in order to determine the life of the mixes and the resistance to plastic deformations.

Above all, if the polymer-modified binder is to be applied in pavement construction and in rehabilitation works, first of all a complete blending system should be procured or locally developed to facilitate large scale production of PMB. A simplified version of commercially available plants is schematically shown in Figures 6.1a and 6.1b in order to fabricate a milling/blending device, using local resources.

In order to observe actual field performance of modified binder a demonstration plot could be built alongside the traditional pavement. This test section of polymer modified pavement would also help to investigate if there is any problem in the process of mixing and compacting pavement using relatively sticker binder.

In this thesis the wet process of blending is used to modify binder. In the dry process, the shredded tyre type chips could be used as a partial replacement of aggregates, especially in the construction of base and subbase courses. This type of application is gaining popularity in western countries. The evaluation of the suitability of using shredded old tyres as a material for road pavement could be an interesting potential topic for further studies and research.

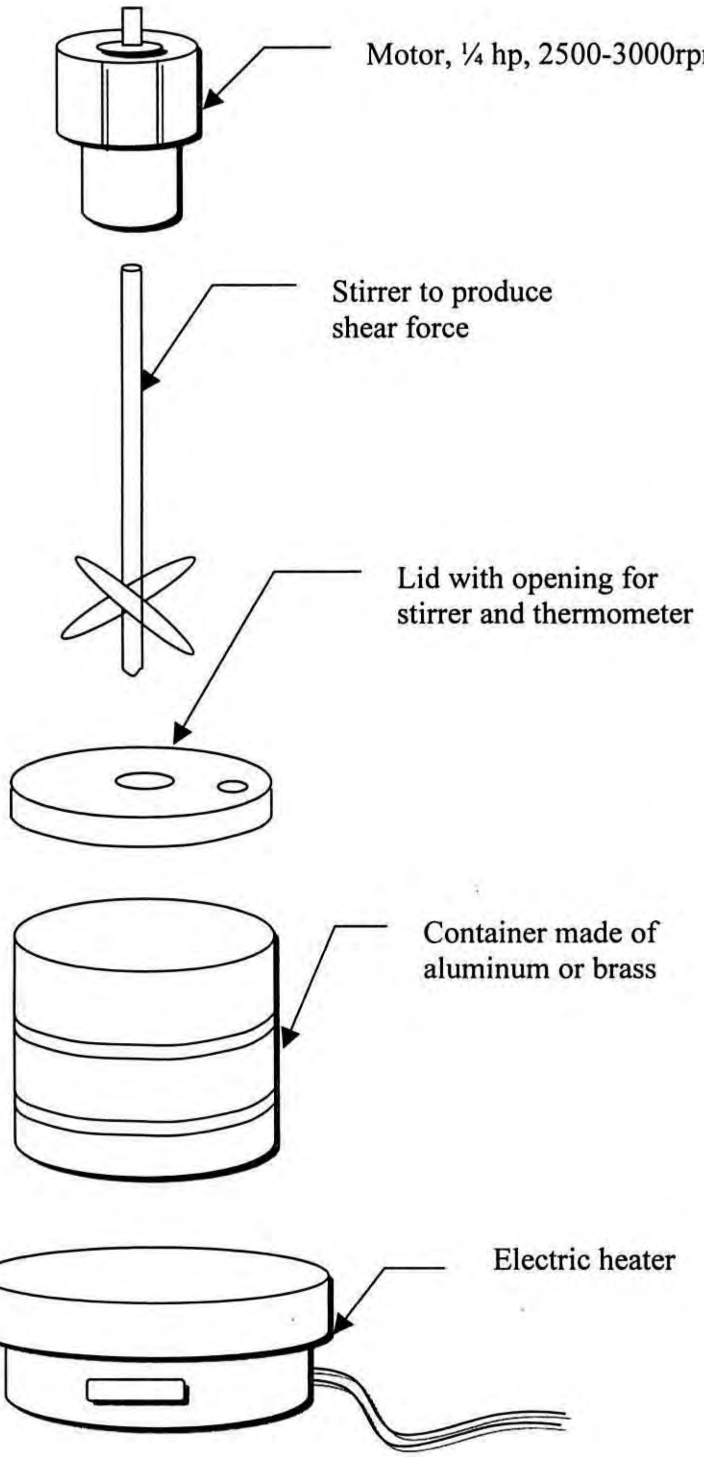


Figure 6.1a: Component of Polymer Blending System.

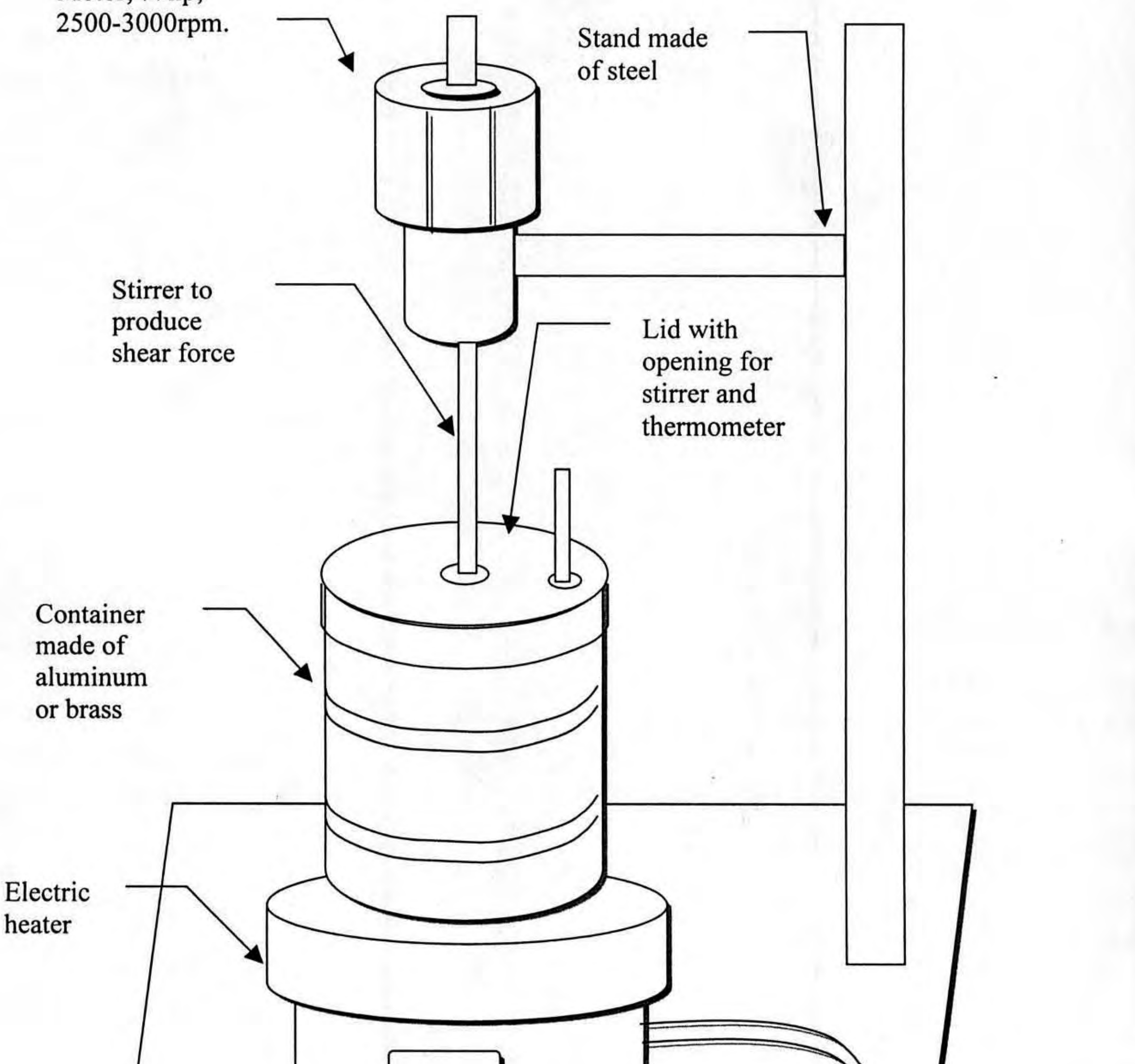


Figure 6.1b: Assembled Polymer Blending System.

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APPENDIX

Table 1A: Raw Marshall Data and Calculated Results

Binder Content (%), P_b	**Specific Gravity of Binder G_b**	**Spec. Wt. in air (gm)**	**Spec. Wt. in Water (gm)**	**Bulk Vol. (cc)**	**Bulk Specific gravity G_{mb}**	**Effective .Sp.gr. of Agg. G_{se}**	**Max. Sp.gr of mix G_{mm}**	**Unit Wt. (lb/cft)**
0 % LDPE								
4.5	1.03	1246	704	542	2.30	2.69	2.53	143.68
4.5	1.03	1237	706	531	2.33	2.68	2.53	145.60
5	1.03	1251	715	536	2.33	2.70	2.51	145.87
5	1.03	1259	726	533	2.36	2.70	2.51	147.63
5.5	1.03	1257	727	530	2.37	2.66	2.49	148.23
5.5	1.03	1259	728	531	2.37	2.73	2.49	148.19
6	1.03	1269	736	533	2.38	2.69	2.47	148.80
6	1.03	1267	734	533	2.38	2.75	2.47	148.57
6.5	1.03	1273	737	536	2.38	2.75	2.46	148.44
6.5	1.03	1276	742	534	2.39	2.75	2.46	149.34
2.5% LDPE								
4.5	1.025	1248	714	534	2.34	2.71	2.53	146.07
4.5	1.025	1250	715	535	2.34	2.68	2.53	146.03
5	1.025	1255	720	535	2.35	2.68	2.51	146.61
5	1.025	1250	718	532	2.35	2.70	2.51	146.85
5.5	1.025	1257	728	529	2.38	2.69	2.49	148.51
5.5	1.025	1252	722	530	2.36	2.73	2.49	147.64
6	1.025	1262	737	525	2.40	2.71	2.47	150.24
6	1.025	1273	738	535	2.38	2.75	2.47	148.71
6.5	1.025	1274	740	534	2.39	2.75	2.45	149.11
6.5	1.025	1277	741	536	2.38	2.75	2.45	148.90
5% LDPE								
4.5	1.0204	1241	705	536	2.32	2.68	2.53	144.71
4.5	1.0204	1249	713	536	2.33	2.68	2.53	145.64
5	1.0204	1259	725	534	2.36	2.71	2.51	147.35
5	1.0204	1242	712	530	2.34	2.71	2.51	146.46
5.5	1.0204	1257	727	530	2.37	2.73	2.49	148.23
5.5	1.0204	1265	733	532	2.38	2.73	2.49	148.61
6	1.0204	1269	738	531	2.39	2.75	2.47	149.36
6	1.0204	1264	733	531	2.38	2.73	2.47	148.78
6.5	1.0204	1278	743	535	2.39	2.75	2.45	149.30
6.5	1.0204	1284	747	537	2.39	2.75	2.45	149.44
7.5% LDPE								
4.5	1.0195	1248	709	539	2.32	2.68	2.53	144.71
4.5	1.0195	1254	715	539	2.33	2.68	2.53	145.41
5	1.0195	1264	727	537	2.35	2.71	2.51	147.11
5	1.0195	1258	721	537	2.34	2.71	2.51	146.42
5.5	1.0195	1261	731	530	2.38	2.73	2.49	148.70
5.5	1.0195	1262	730	532	2.37	2.73	2.49	148.26
6	1.0195	1268	737	531	2.39	2.76	2.47	149.25
6	1.0195	1261	733	528	2.39	2.73	2.47	149.27
6.5	1.0195	1275	741	534	2.39	2.75	2.45	149.23
6.5	1.0195	1276	741	535	2.39	2.75	2.45	149.07
10% LDPE								
4.5	1.0175	1249	711	538	2.32	2.68	2.53	145.10
4.5	1.0175	1249	712	537	2.33	2.68	2.53	145.37

Binder Content (%), P_b	Specific Gravity of Binder G_b	Spec. Wt. in air (gm)	Spec. Wt. in Water (gm)	Bulk Vol. (cc)	Bulk Specific gravity G_{mb}	Effective .Sp.gr. of Agg. G_{se}	Max. Sp.gr of mix G_{mm}	Unit Wt. (lb/cft)
5	1.0175	1256	720	536	2.34	2.71	2.51	146.46
5	1.0175	1257	718	539	2.33	2.71	2.51	145.76
5.5	1.0175	1256	727	529	2.37	2.73	2.49	148.39
5.5	1.0175	1263	727	536	2.36	2.73	2.49	147.27
6	1.0175	1271	737	534	2.38	2.76	2.47	148.76
6	1.0175	1266	733	533	2.38	2.76	2.47	148.45
6.5	1.0175	1278	739	539	2.37	2.78	2.45	148.19
6.5	1.0175	1280	743	537	2.38	2.78	2.45	148.98

Table 2A: Raw Marshall Data and Calculated Results

Binder Content (%) P_b	Agg. Content (%) P_s	Bulk Sp. Gravity of total Agg. G_{sb}	Air Void (%) (V_a)	Void in Mineral Agg. (%) VMA	Void Filled with Asphalt (%) VFA	Spec. height (mm)	Spec. diam. (mm)	Spec. volume (mm^3)
0 % LDPE								
4.5	95.5	2.69	9.18	18.39	50.06	65.23	102	533013
4.5	95.5	2.69	7.97	17.30	53.92	65.13	102	532196
5	95	2.69	7.09	17.57	59.64	66.33	102	542001
5	95	2.69	5.97	16.58	63.98	66.4	102	542573
5.5	94.5	2.69	4.88	16.68	70.77	65.8	102	537670
5.5	94.5	2.69	4.90	16.71	70.65	66.1	102	540122
6	94	2.69	3.79	16.80	77.44	65.73	102	537098
6	94	2.69	3.94	16.93	76.72	65.6	102	536036
6.5	93.5	2.69	3.31	17.45	81.02	65.4	102	534402
6.5	93.5	2.69	2.72	16.94	83.94	65.33	102	533830
2.5% LDPE								
4.5	95.5	2.69	7.62	17.03	55.23	66.73	102	545270
4.5	95.5	2.69	7.65	17.05	55.14	66.36	102	542246
5	95	2.69	6.57	17.16	61.72	66.17	102	540694
5	95	2.69	6.41	17.02	62.32	67.86	102	554503
5.5	94.5	2.69	4.63	16.52	71.96	63.3	102	517242
5.5	94.5	2.69	5.19	17.01	69.48	64.93	102	530561
6	94	2.69	2.79	16.00	82.53	64.1	102	523779
6	94	2.69	3.78	16.85	77.57	64.47	102	526802
6.5	93.5	2.69	2.80	17.07	83.60	64.51	102	527129
6.5	93.5	2.69	2.93	17.19	82.93	64.66	102	528355
5% LDPE								
4.5	95.5	2.69	8.44	17.80	52.60	65.33	102	533830
4.5	95.5	2.69	7.85	17.27	54.56	65.13	102	532196
5	95	2.69	6.04	16.74	63.90	64.4	102	526230
5	95	2.69	6.61	17.24	61.66	65.23	102	533013
5.5	94.5	2.69	4.76	16.68	71.49	63.9	102	522145
5.5	94.5	2.69	4.51	16.47	72.61	65.03	102	531378
6	94	2.69	3.30	16.49	80.00	64.76	102	529172
6	94	2.69	3.68	16.82	78.13	64.73	102	528927

Binder Content (%) P_b	Agg. Content (%) P_s	Bulk Sp. Gravity of total Agg. G_{sb}	Air Void (%) (V_a)	Void in Mineral Agg. (%) VMA	Void Filled with Asphalt (%) VFA	Spec. height (mm)	Spec. diam. (mm)	Spec. volume (mm^3)
6.5	93.5	2.69	2.61	16.97	84.63	64.83	102	529744
6.5	93.5	2.69	2.52	16.89	85.11	64.63	102	528110
7.5% LDPE								
4.5	95.5	2.69	8.43	17.80	52.66	65.86	102	538161
4.5	95.5	2.69	7.99	17.40	54.12	65.7	102	536853
5	95	2.69	6.18	16.87	63.34	65.16	102	532441
5	95	2.69	6.63	17.27	61.60	65.33	102	533830
5.5	94.5	2.69	4.44	16.42	72.94	64.16	102	524269
5.5	94.5	2.69	4.73	16.67	71.64	64.96	102	530806
6	94	2.69	3.36	16.56	79.70	64.83	102	529744
6	94	2.69	3.35	16.54	79.76	64.16	102	524269
6.5	93.5	2.69	2.64	17.01	84.47	64.66	102	528355
6.5	93.5	2.69	2.75	17.10	83.93	64.76	102	529172
10%LDPE								
4.5	95.5	2.69	7.99	17.43	54.15	66.1	102	540122
4.5	95	2.69	6.58	17.24	61.83	65.73	102	537098
5	95	2.69	7.03	17.64	60.16	66.4	102	542573
5	94.5	2.69	4.62	16.59	72.18	64.66	102	528355
5.5	94.5	2.69	5.34	17.22	69.01	65.26	102	533258
5.5	94	2.69	3.65	16.83	78.32	64.9	102	530316
6	94	2.69	3.85	17.00	77.36	65.26	102	533258
6	93.5	2.69	3.29	17.59	81.30	65.46	102	534892
6.5	93.5	2.69	2.78	17.15	83.81	65.36	102	534075
6.5	95.5	2.69	8.16	17.58	53.57	65.36	102	534075

Table 3A: Raw Marshall Data and Calculated Results

Binder Content (%) P_b	Specimen volume (cc)	Correction Factor	Proving dial Reading	Marshall. Stability (lb)	Corrected Stability (lb)	Flow (1/100 inch)
0 % LDPE						
4.5	533	0.96	312	1849	1775	12
4.5	532	0.96	420	2488	2388	13
5	542	0.93	377	2233	2077	11
5	543	0.93	442	2618	2435	15
5.5	538	0.93	403	2387	2220	16.5
5.5	540	0.93	390	2310	2149	11
6	537	0.93	421	2494	2319	14.5
6	536	0.93	339	2009	1868	14
6.5	534	0.96	341	2020	1940	15
6.5	534	0.96	360	2133	2048	16
2.5%LDPE						
4.5	545	0.93	412	2441	2270	13.5
4.5	542	0.93	475	2813	2616	10.7
5	541	0.93	465	2754	2561	14

Binder Content (%) P_b	**Specimen volume (cc)**	**Correction Factor**	**Proving dial Reading**	**Marshall. Stability (lb)**	**Corrected Stability (lb)**	**Flow (1/100 inch)**
5	555	0.93	473	2801	2605	12
5.5	517	1	437	2588	2588	12
5.5	531	0.96	396	2346	2252	15
6	524	0.96	401	2375	2280	15.5
6	527	0.96	402	2381	2286	15
6.5	527	0.96	344	2038	1957	17
6.5	528	0.96	400	2370	2275	17
5% LDPE						
4.5	534	0.96	476	2819	2706	16
4.5	532	0.96	466	2760	2650	15
5	526	0.96	508	3009	2888	16
5	533	0.96	478	2831	2718	16
5.5	522	1	475	2813	2813	17
5.5	531	0.96	410	2429	2332	17
6	529	0.96	440	2606	2502	17.5
6	529	0.96	419	2482	2383	18
6.5	530	0.96	425	2517	2417	19
6.5	528	0.96	416	2464	2366	20
7.5%LDPE						
4.5	537	0.93	575	3405	3167	17
4.5	532	0.96	538	3186	3059	17.5
5	534	0.96	503	2979	2860	18
5	524	0.96	460	2725	2616	18
5.5	531	0.96	512	3032	2911	19
5.5	530	0.96	460	2725	2616	19.5
6	524	0.96	458	2713	2604	18.5
6	528	0.96	490	2902	2786	20.5
6.5	529	0.96	415	2458	2360	20
6.5	538	0.93	480	2843	2644	17
10%LDPE						
4.5	534	0.93	530	3139	2919	19
4.5	540	0.93	535	3168	2947	17
5	537	0.93	553	3275	3046	17
5	543	0.93	543	3216	2991	18
5.5	528	0.96	512	3032	2911	20
5.5	533	0.96	520	3080	2956	18.5
6	530	0.96	490	2902	2786	18
6	533	0.96	465	2754	2644	19
6.5	535	0.93	515	3050	2837	20.5
6.5	534	0.93	447	2648	2462	21

Table 4A: Requirements for Asphalt Cement Graded by Viscosity (AASHTO M 226).

Test	Viscosity Grade					
	AC-2.5	AC-5	AC-10	AC-20	AC-30	AC-40
Viscosity, 60°C, poises	250±50	500±100	1000±200	2000±400	3000±600	4000±800
Viscosity, 135°C, Cs-minimum.	125	175	250	300	350	400
Penetration, 25°C, 100g, 5sec. minimum	220	140	80	60	50	40
Flash point, COC	162	177	219	232	232	232
Solubility in trichlorethylene, (%) minimum	99.0	99.0	99.0	99.0	99.0	99.0
Tests on residue from Thin-Film Oven Test:						
Loss on heating[2], (%), Maximum	----	1.0	0.5	0.5	0.5	0.5
Viscosity, 60°C, poises maximum	1000	2000	4000	8000	12000	16000
Ductility 25°C, cm minimum	100[1]	100	75	50	40	25

[1] If ductility is less than 100, material will be accepted if ductility at 15.6°C is 100 minimum.
[2] The use of loss on heating requirement is optional.

Table 5A: Requirements for Asphalt Specification for Asphalt Cement Graded by Penetration (AASHTO M 20).

Test	Penetration Grade									
	40-50		60-70		85-100		120-150		200-300	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Penetration, 25°C, 100g, 5sec.	40	50	60	70	85	100	120	150	200	300
Flash point, Cleveland, open cup.	450	----	450	----	450	----	425	----	300	----
Ductility 25°C, cm	100	----	100	----	100	----	100	----	100	----
Penetration of residue (%) of original.	58	----	54	----	50	----	46	----	40	----
Ductility of residue.	----	----	50	----	75	----	100	----	100	----

Table 6A: Marshall Mix Design Criteria

Marshall method mix criteria	Light Traffic Surface Base		Medium Traffic Surface Base		Heavy Traffic Surface Base	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Compaction (blows)	35		50		75	
Stability (lb)	750	----	1200	----	1800	----
Flow (0.01 inch)	8	18	8	16	8	14
Air Void (%)	3	5	3	5	3	5
Voids Filled with Asphalt (%)	70	80	65	78	65	75
Voids in Mineral Aggregates	See Table 7A					

Table 7A: Minimum Percent Void in Mineral Aggregate (VMA)

Nominal Maximum Particle size[1,2]		Design Air Voids, Percent		
		3.0	4.0	5.0
(mm)	(inch)	Minimum VMA, Percent[3]		
1.18	No. 16	21.5	22.5	23.5
2.36	No. 8	19.0	20.0	21.0
4.75	No. 4	16.0	17.0	18.0
9.5	3/8	14.0	15.0	16.0
12.5	½	13.0	14.0	15.0
19.0	¾	12.0	13.0	14.0
25.0	1.0	11.0	12.0	13.0
37.5	1.5	10.0	11.0	12.0
50	2.0	9.5	10.5	11.5
63	2.5	9.0	10.0	11.0

1. Standard specification for wire cloth sieves for testing purpose, ASTM E11 (AASHTO M92)
2. The nominal maximum particle size is one size larger than the first sieve to retain more than 10 percent.

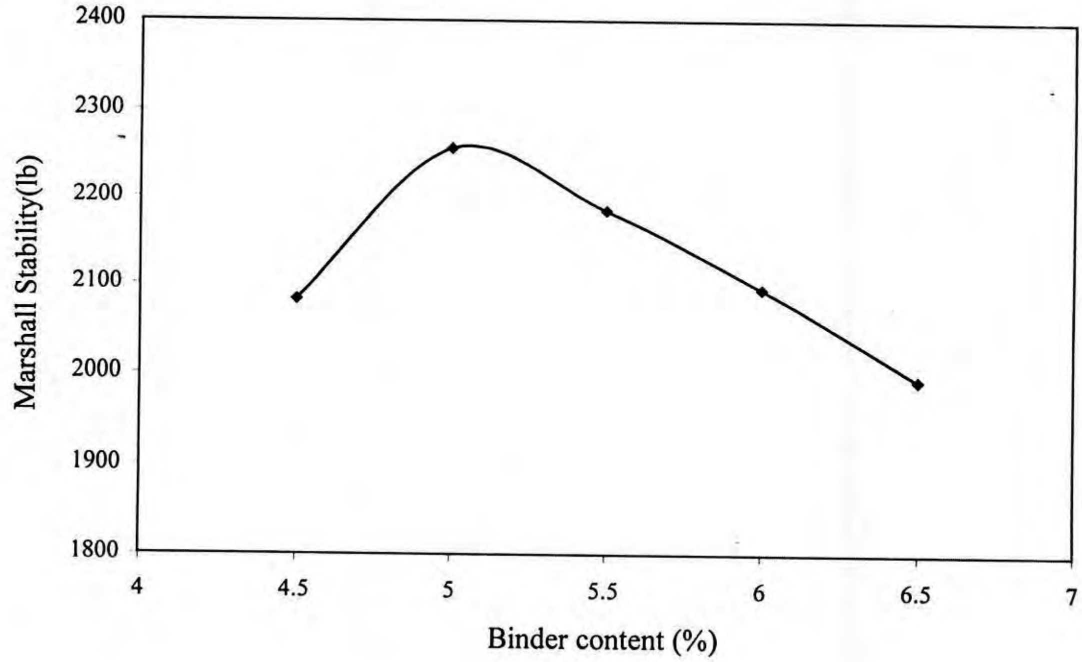

Figure 1A: Marshall Stability Results for Mixes Prepared with Unmodified Bitumen.

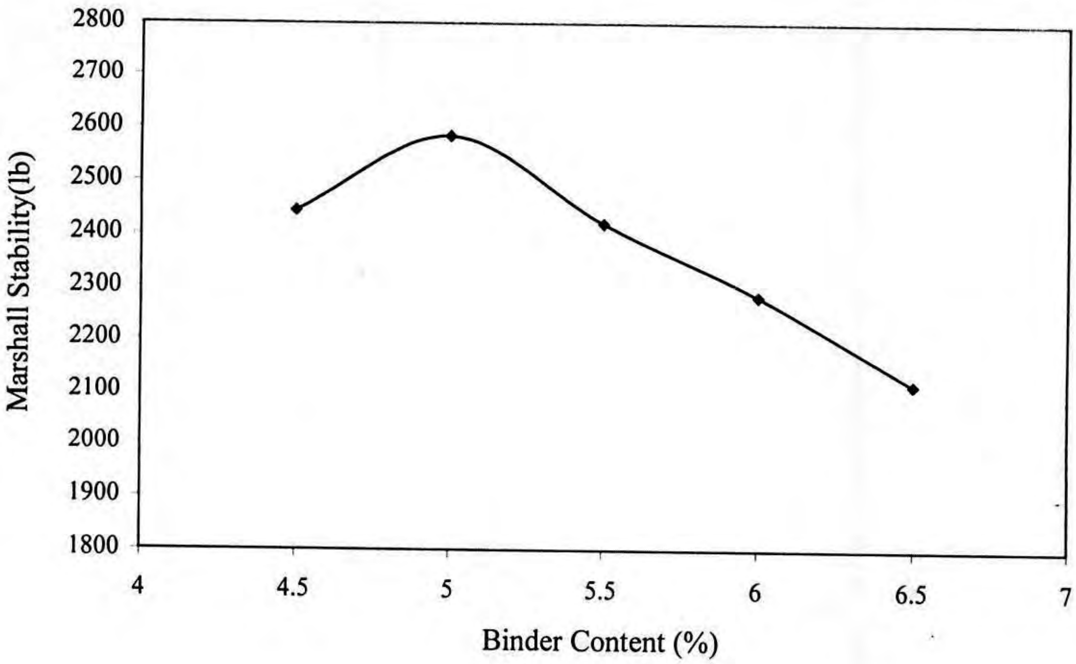

Figure 2A: Marshall Stability Results for Mixes Prepared with 2.5 % LDPE Modified Bitumen.

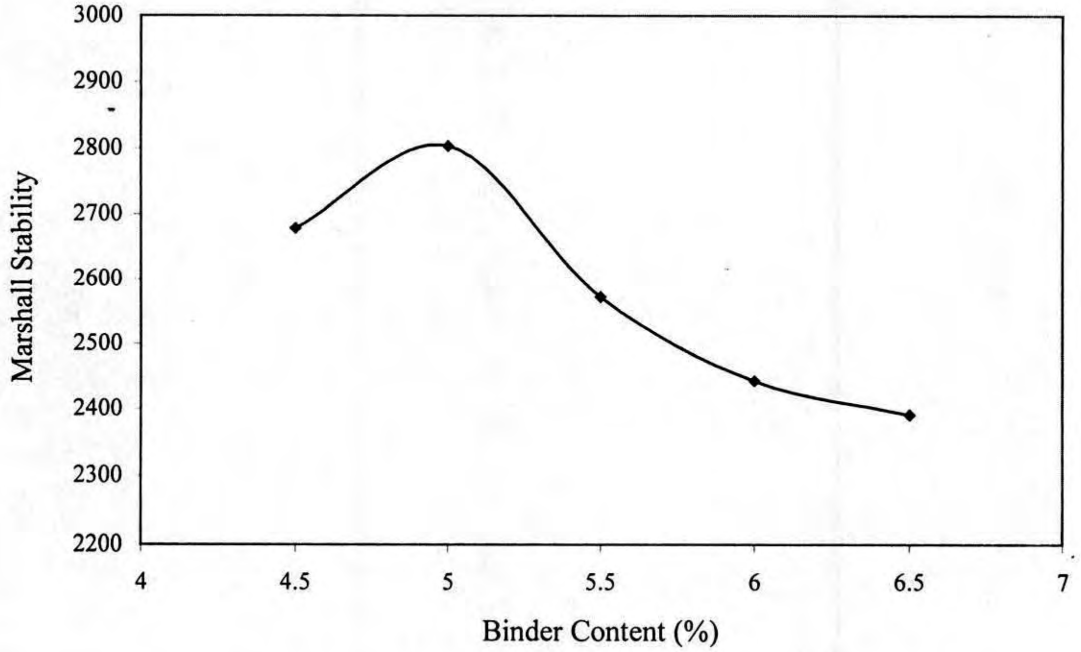

Figure 3A: Marshall Stability Results for Mixes Prepared with 5 % LDPE Modified Bitumen.

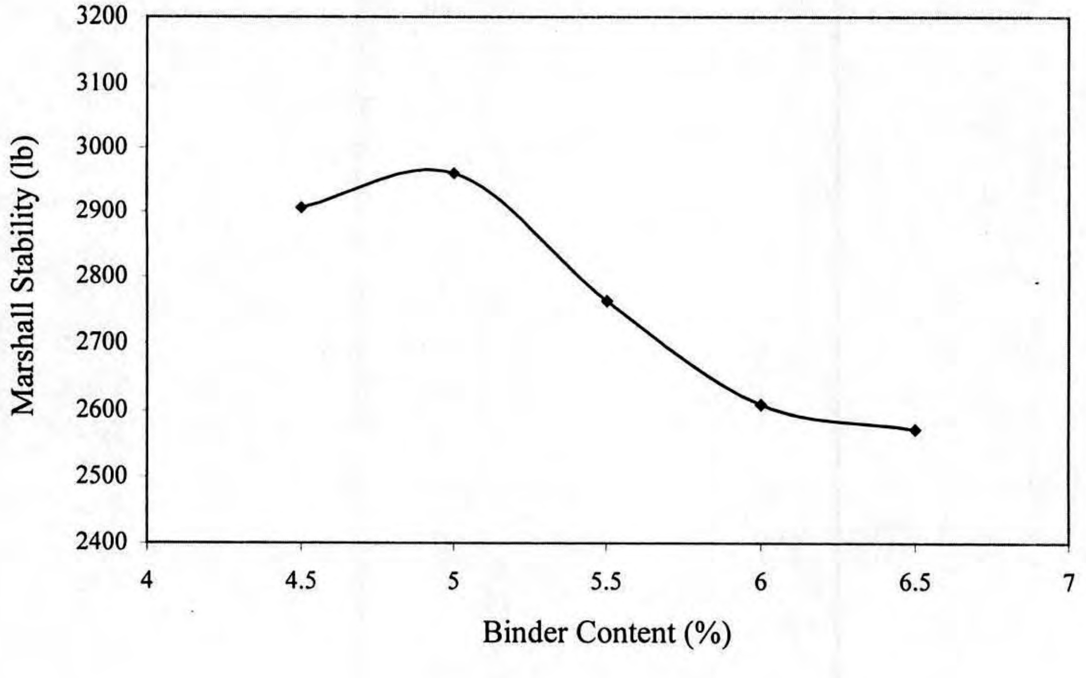

Figure 4A: Marshall Stability Results for Mixes Prepared with 7.5 % LDPE Modified Bitumen.

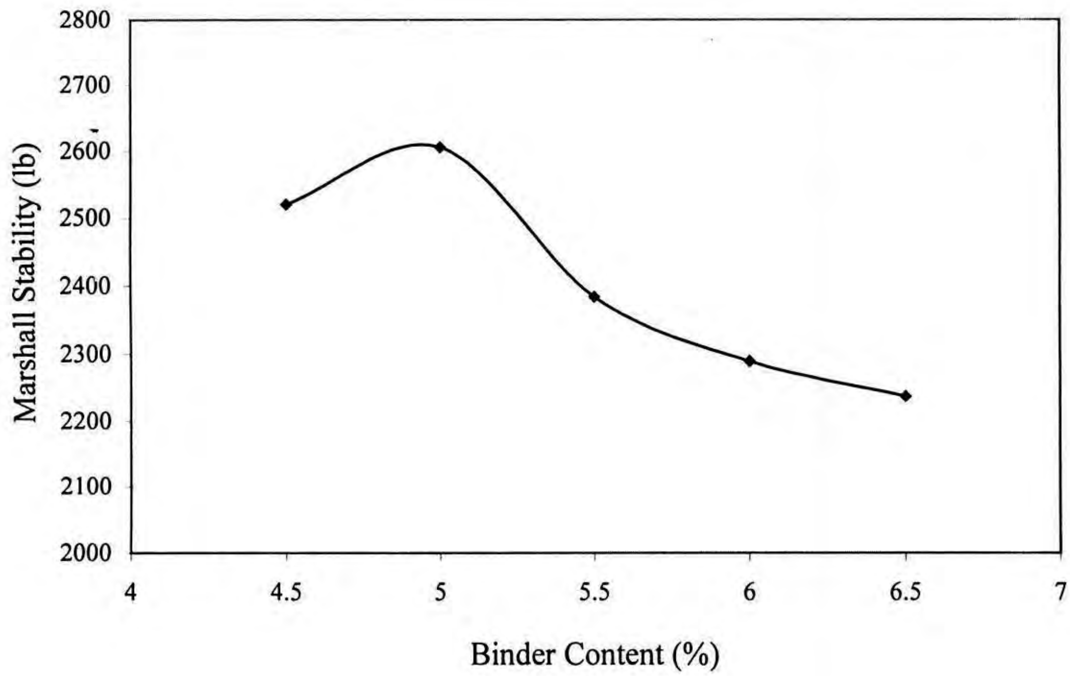

Figure 5A: Marshall Stability Results for Mixes Prepared with 10 % LDPE Modified Bitumen.

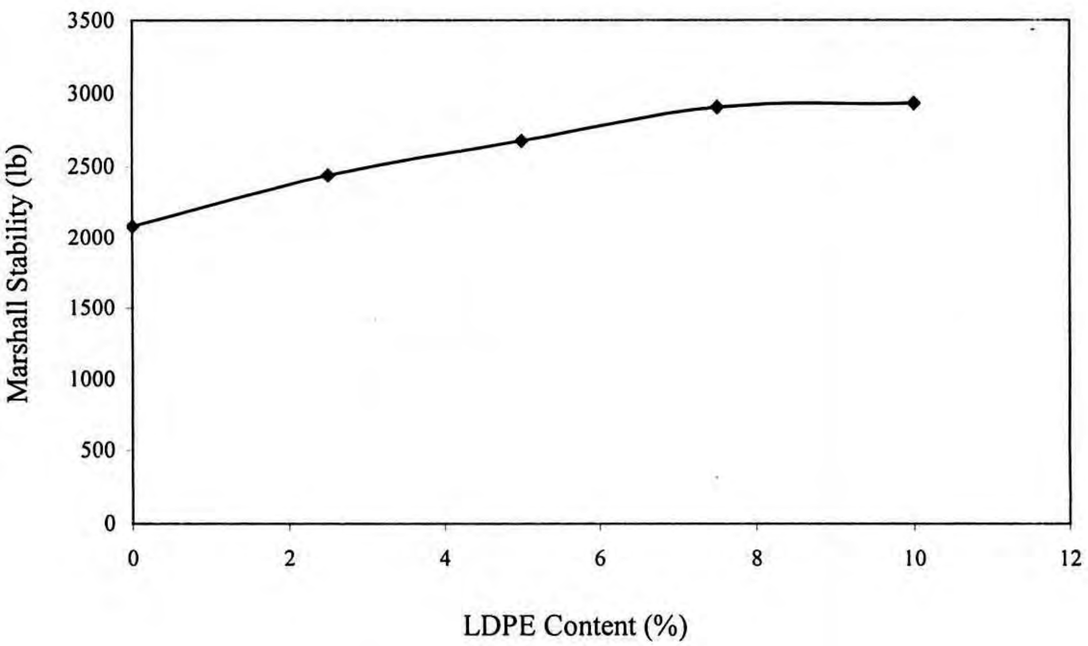

Figure 6A: Variation of Marshall Stability with LDPE Content for Mixes Prepared with 4.5 % Binder Content.

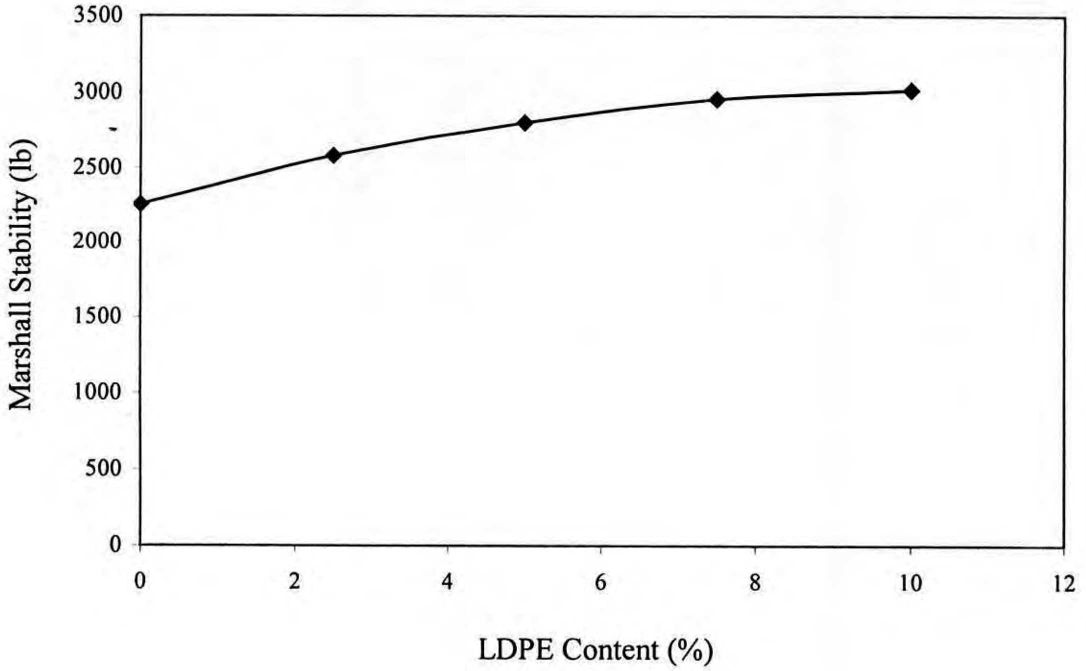

Figure 7A: Variation of Marshall Stability with LDPE Content for Mixes Prepared with 5 % Binder Content.

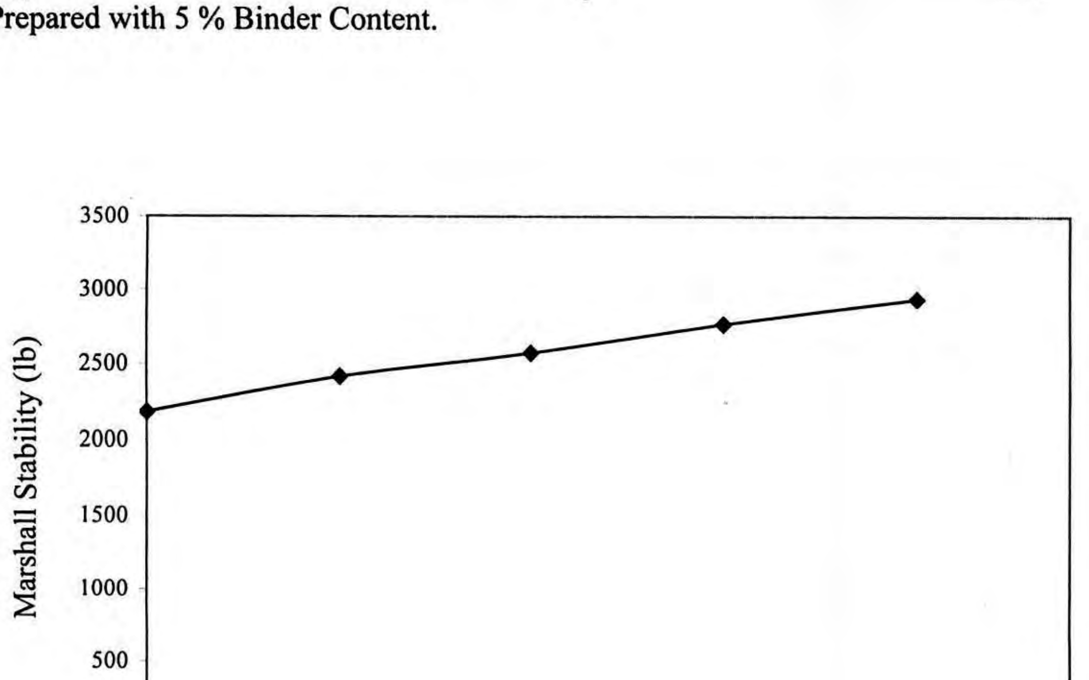

Figure 8A: Variation of Marshall Stability with LDPE Content for Mixes Prepared with 5.5 % Binder Content.

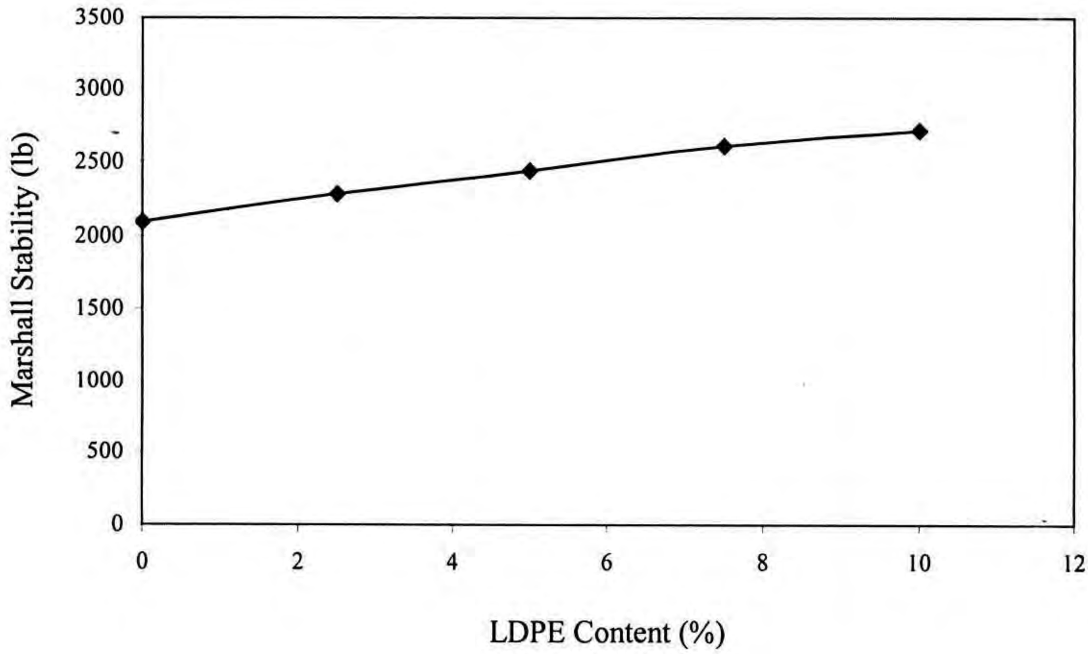

Figure 9A: Variation of Marshall Stability with LDPE Content for Mixes Prepared with 6 % Binder Content.

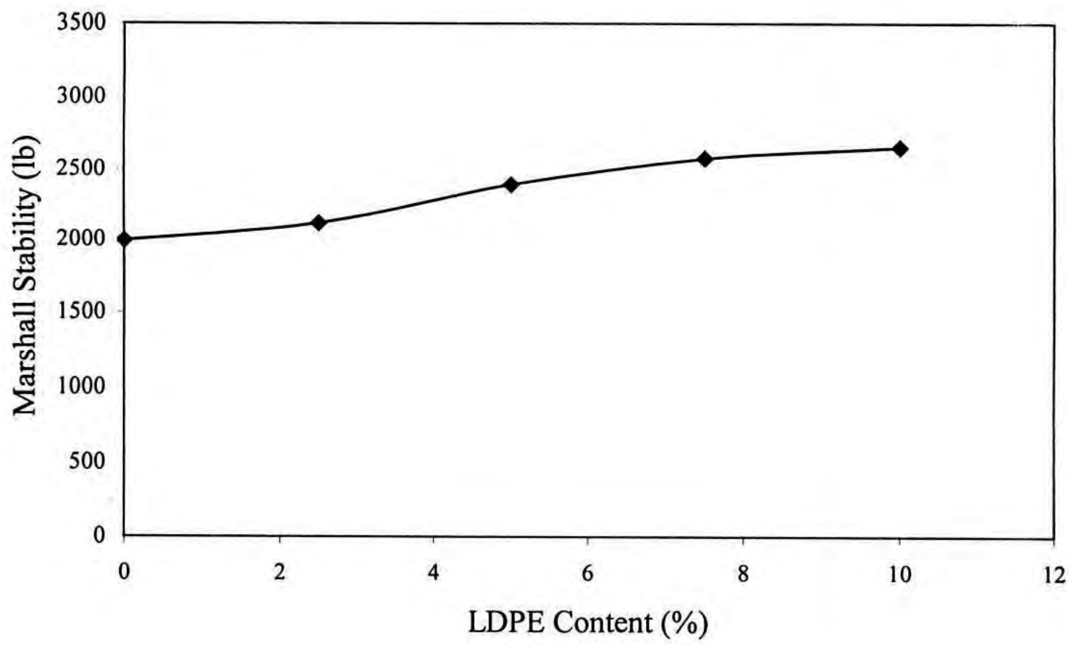

Figure 10A: Variation of Marshall Stability with LDPE Content for Mixes Prepared with 6.5 % Binder Content.

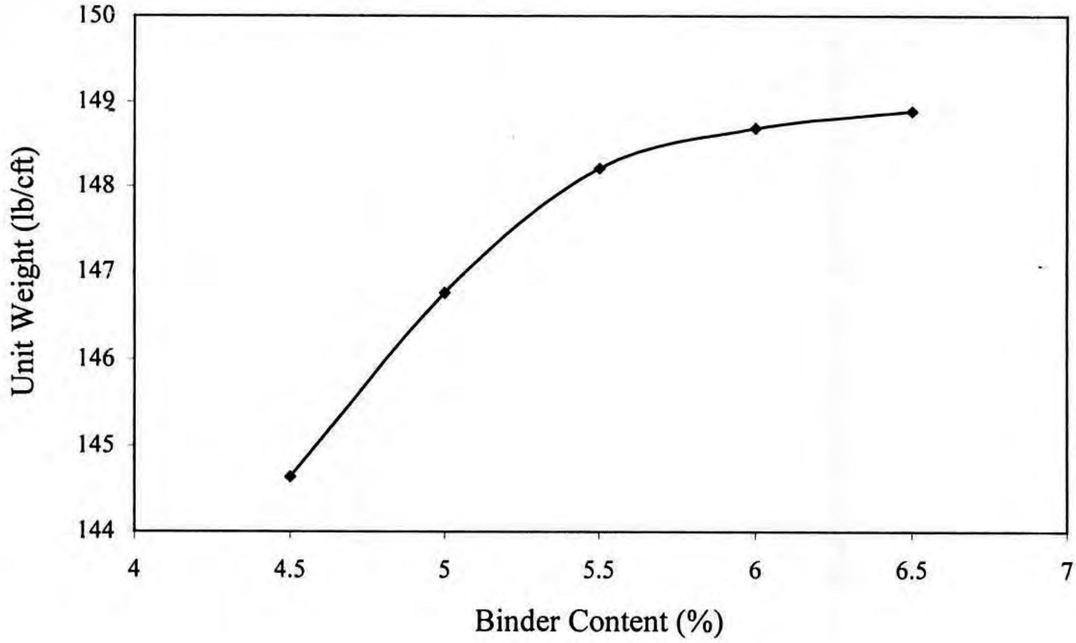

Figure 11A: Unit Weight Results for Mixes Prepared with Unmodified Bitumen.

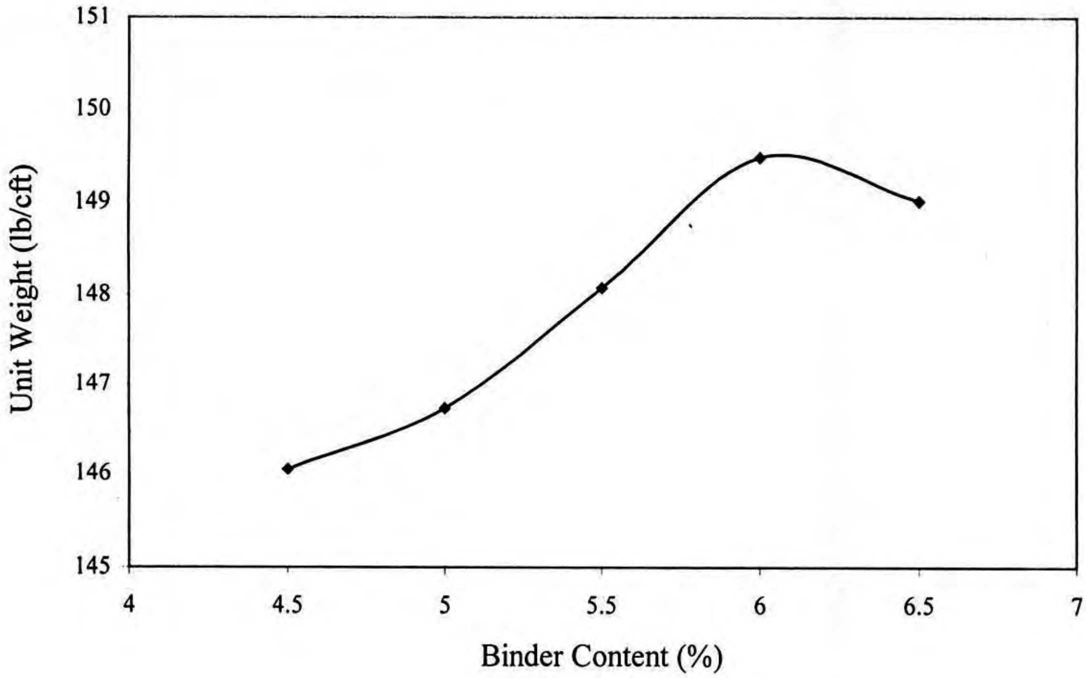

Figure 12A: Unit Weight Results for Mixes Prepared with 2.5 % LDPE Modified Bitumen.

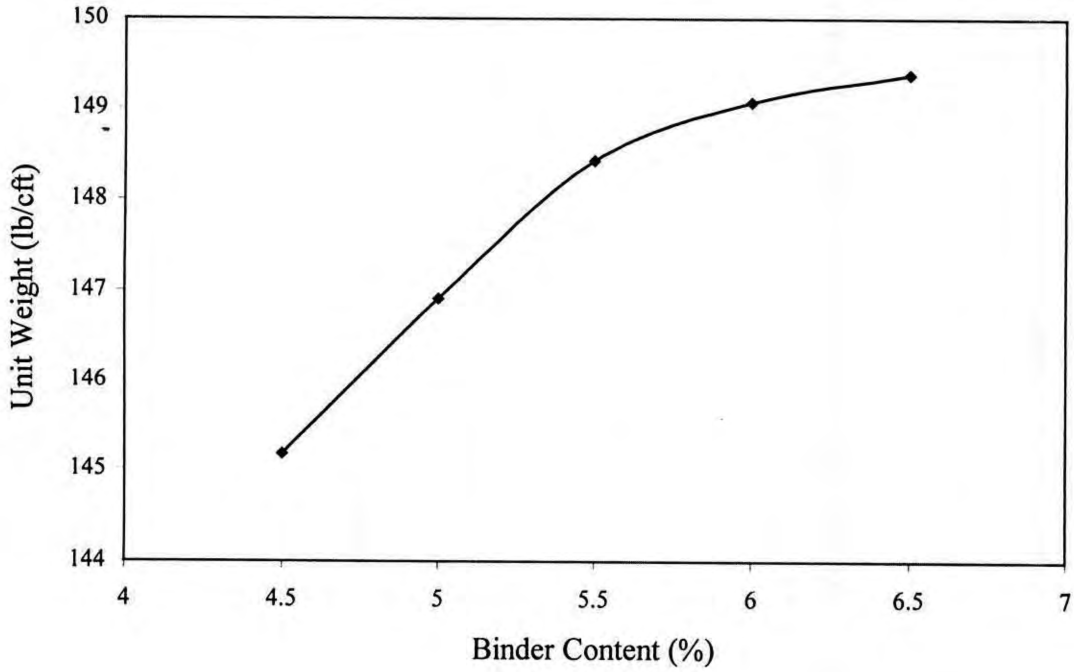

Figure 13A: Unit Weight Results for Mixes Prepared with 5 % LDPE Modified Bitumen.

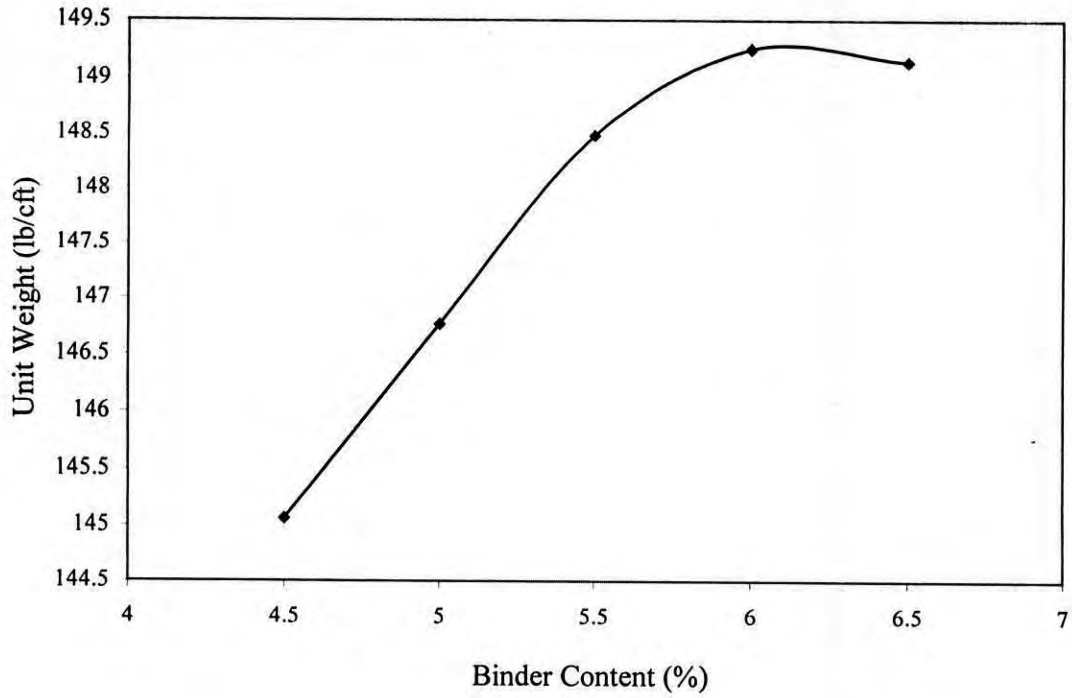

Figure 14A: Unit Weight Results for Mixes Prepared with 7.5 % LDPE Modified Bitumen.

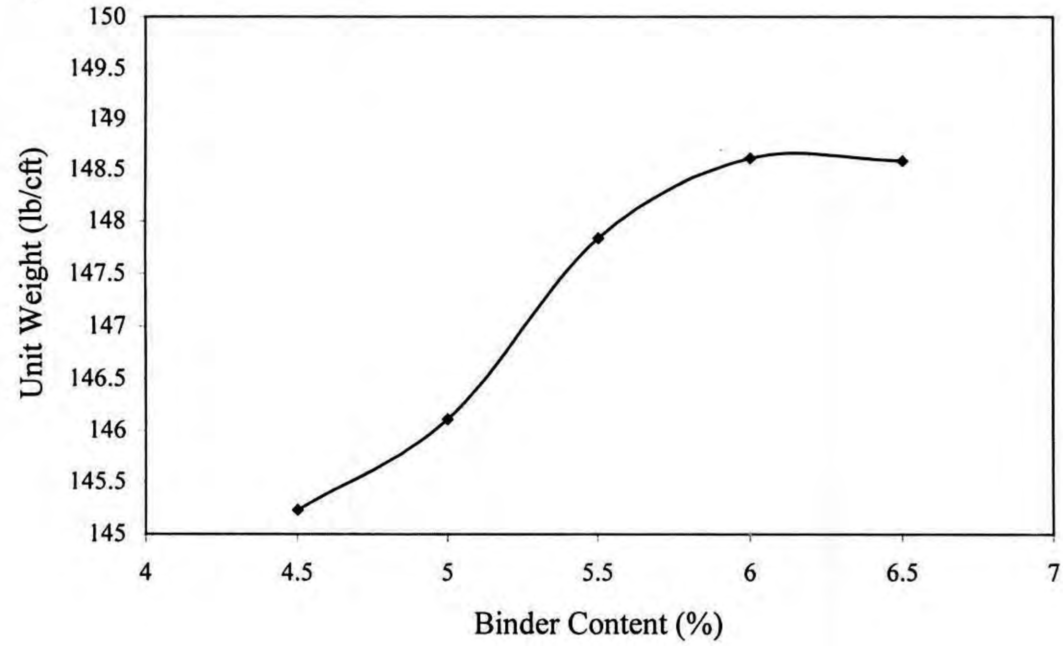

Figure 15A: Unit Weight Results for Mixes Prepared with 10 % LDPE Modified Bitumen.

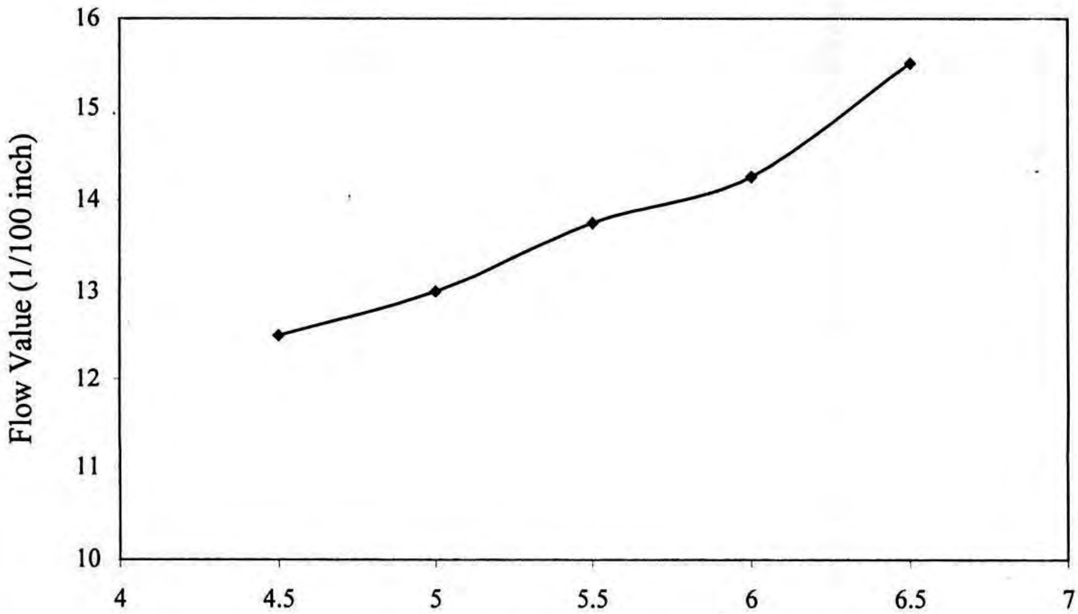

Figure 16A: Flow Value for Mixes Prepared with Unmodified Bitumen.

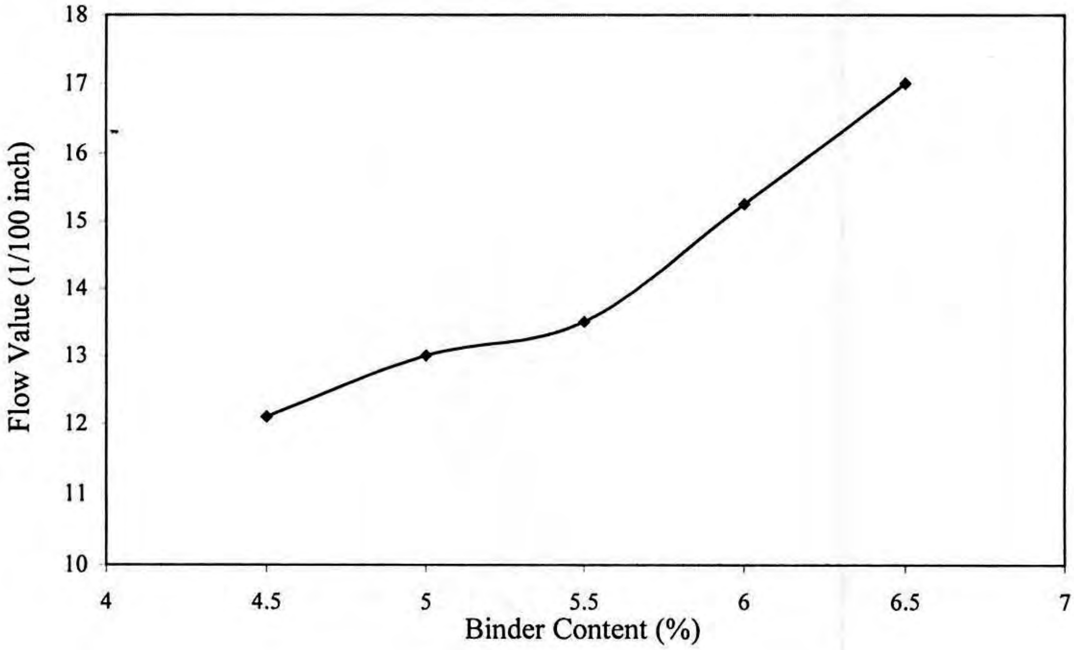

Figure 17A: Flow Value for Mixes Prepared with 2.5 % LDPE Modified Bitumen.

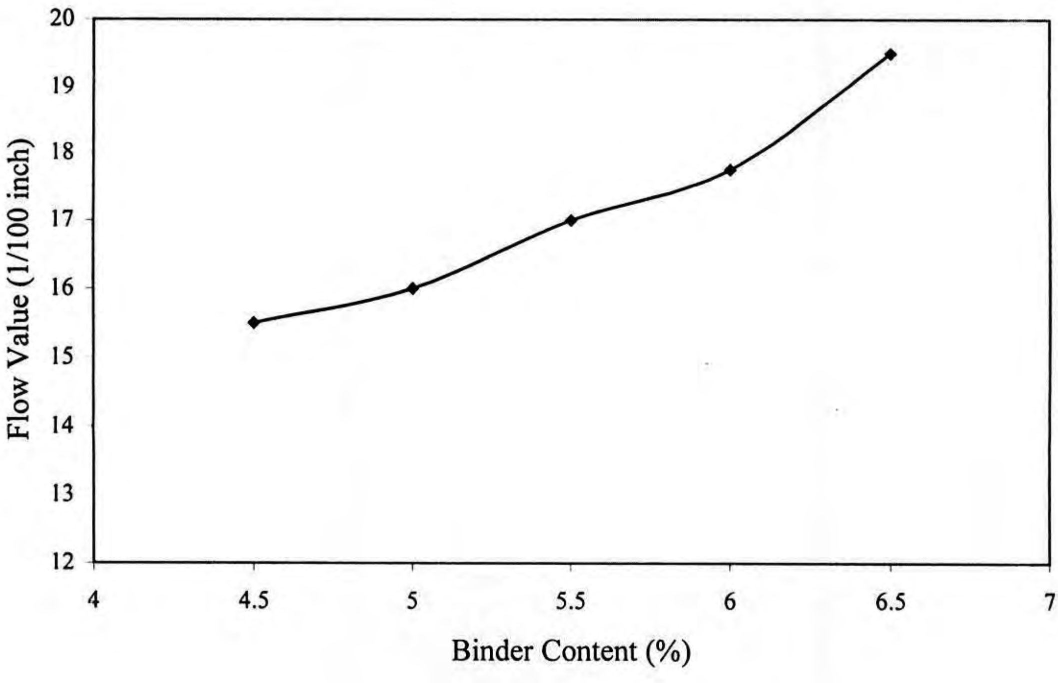

Figure 18A: Flow Value for Mixes Prepared with 5 % LDPE Modified Bitumen.

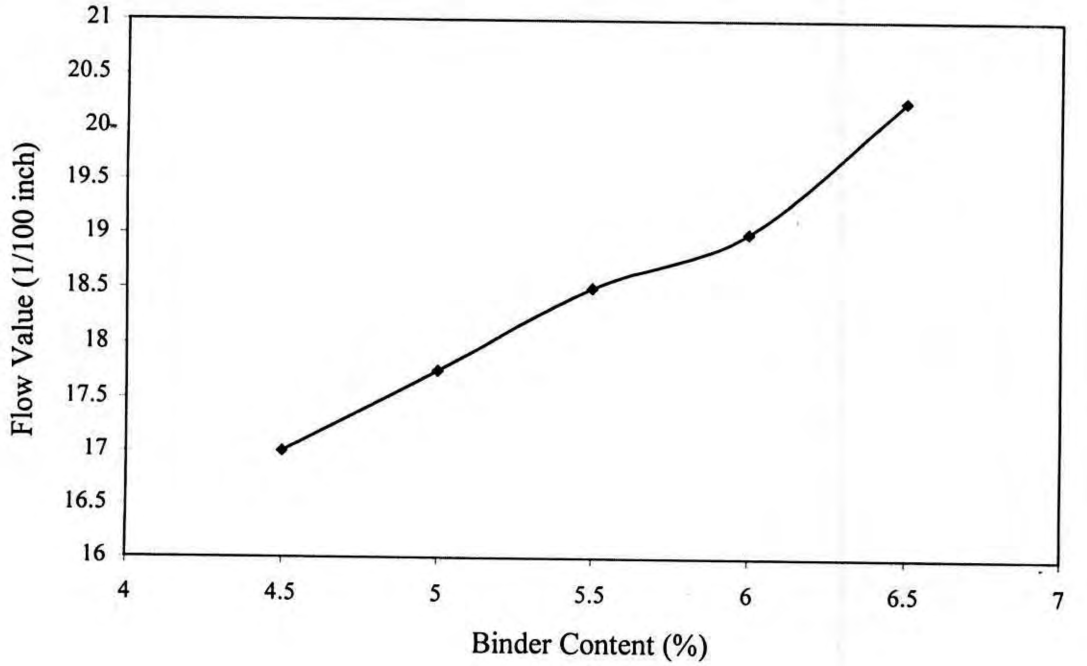

Figure 19A: Flow Value for Mixes Prepared with 7.5 % LDPE Modified Bitumen.

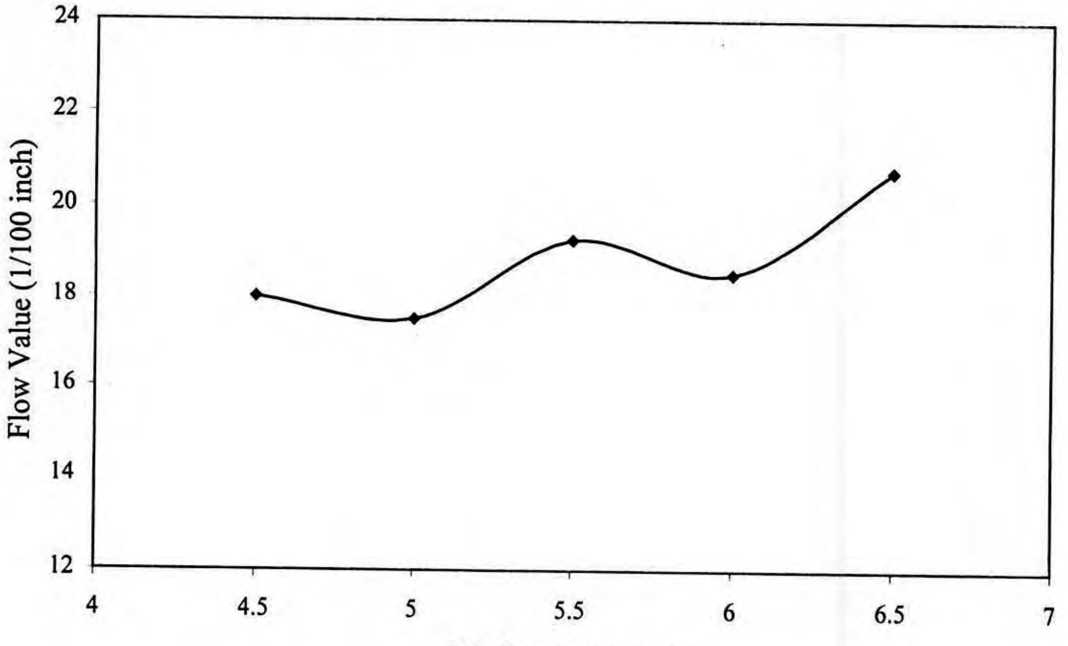

Figure 20A: Flow Value for Mixes Prepared with 10 % LDPE Modified Bitumen.

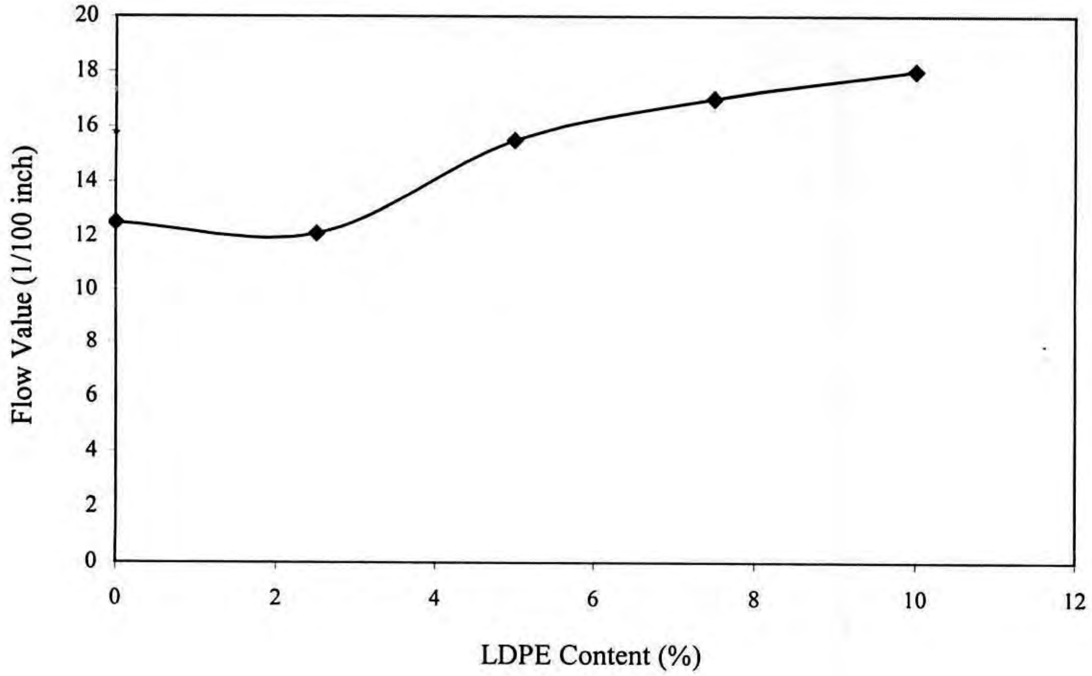

Figure 21A: Variation of Flow Value with LDPE Content for Mixes Prepared with 4.5 % Binder Content.

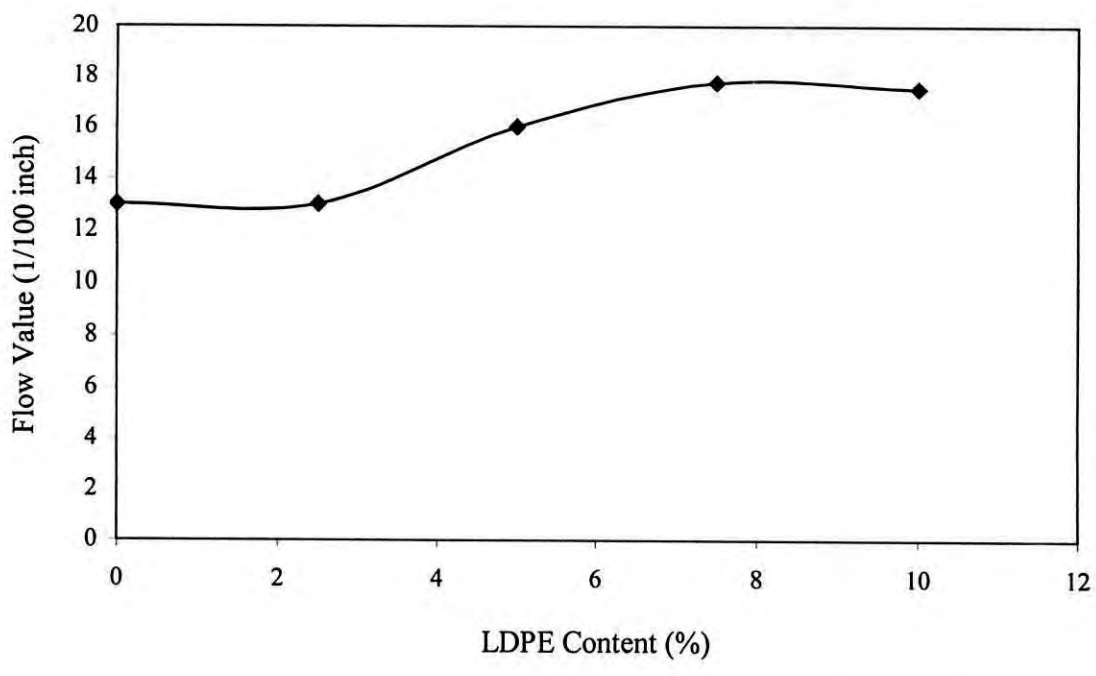

Figure 22A: Variation of Flow Value with LDPE Content for Mixes Prepared with 5 % Binder Content.

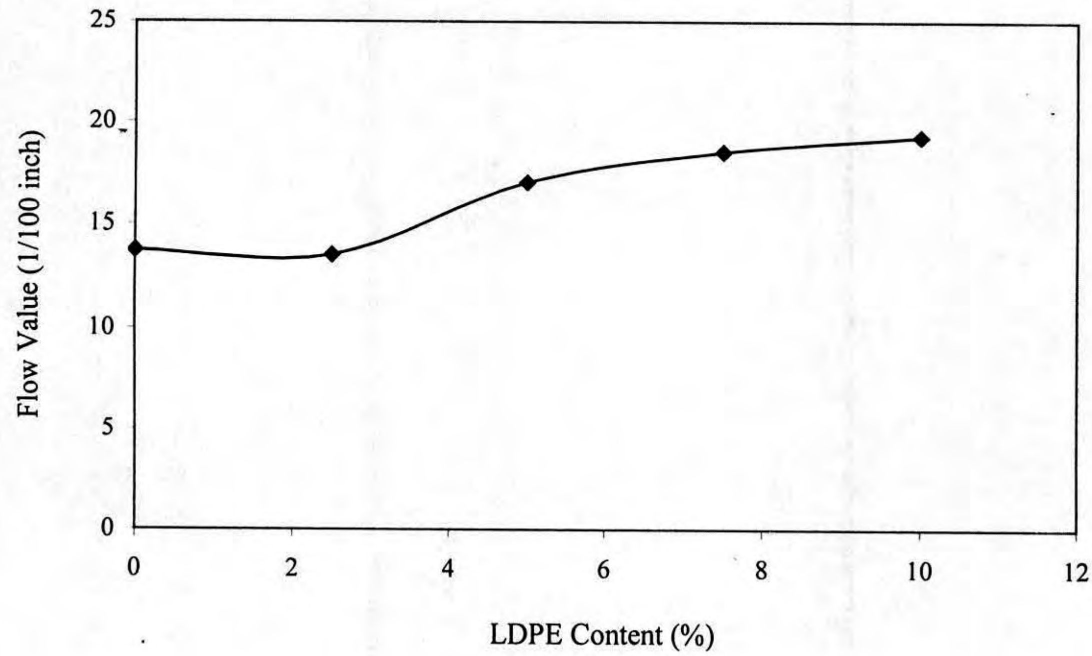

Figure 23A: Variation of Flow Value with LDPE Content for Mixes Prepared with 5.5 % Binder Content.

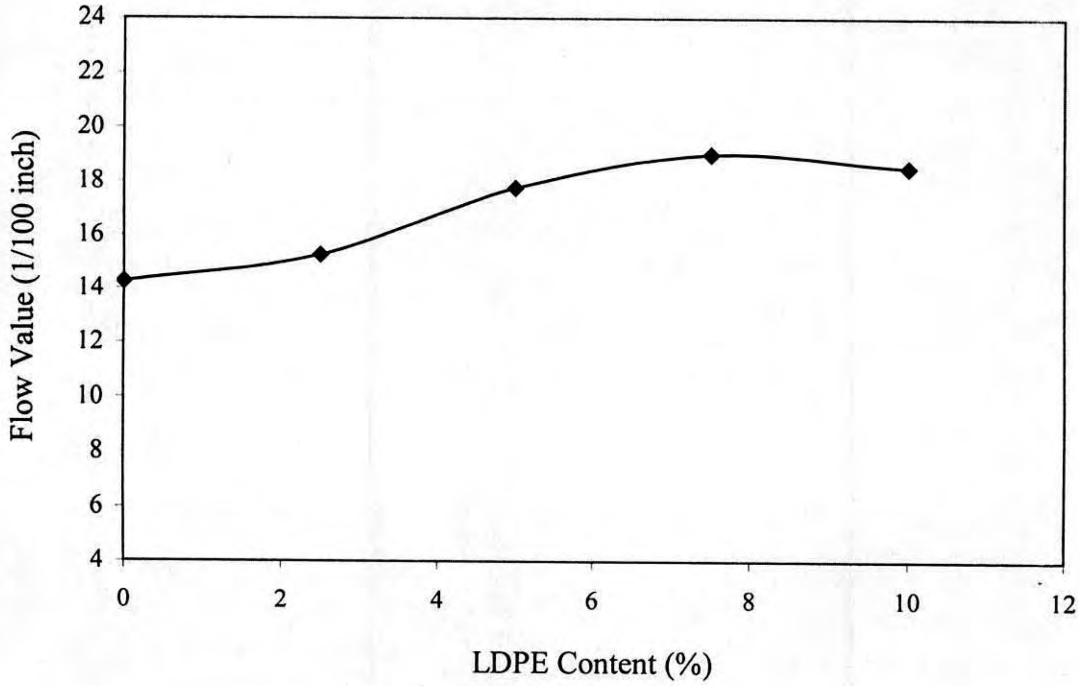

Figure 24A: Variation of Flow Value with LDPE Content for Mixes Prepared with 6 % Binder Content.

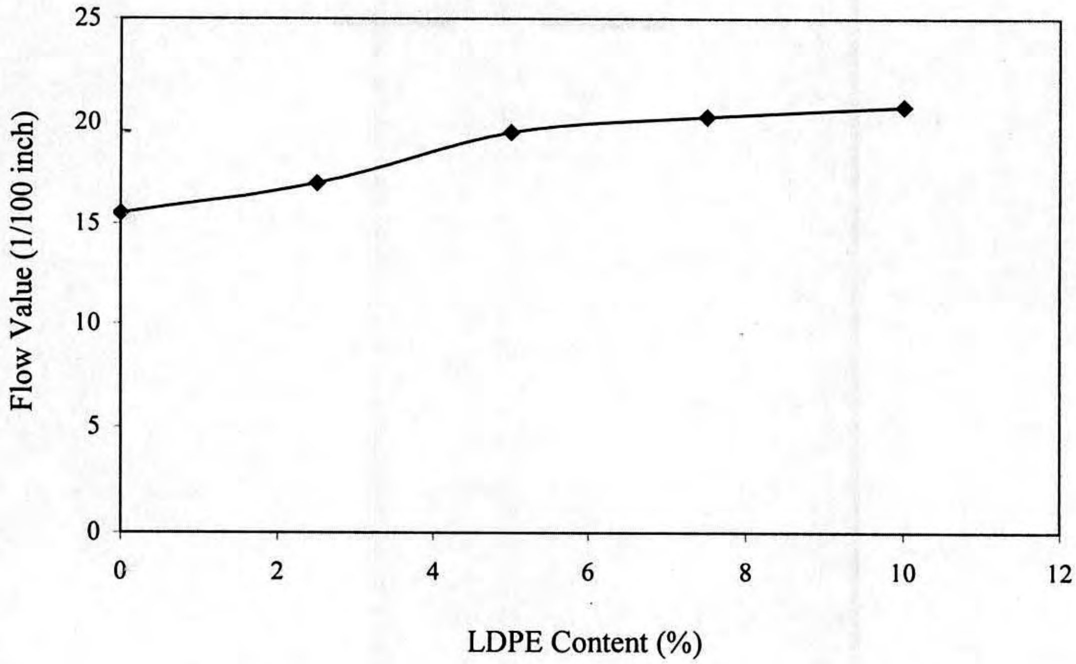

Figure 25A: Variation of Flow Value with LDPE Content for Mixes Prepared with 6.5 % Binder Content.

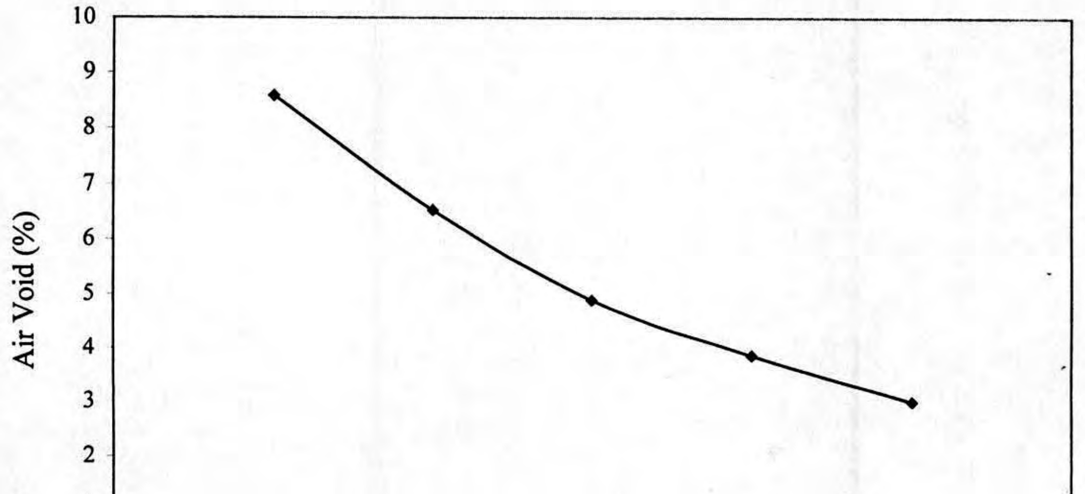

Figure 26A: Air Void Results for Mixes Prepared with Unmodified Bitumen.

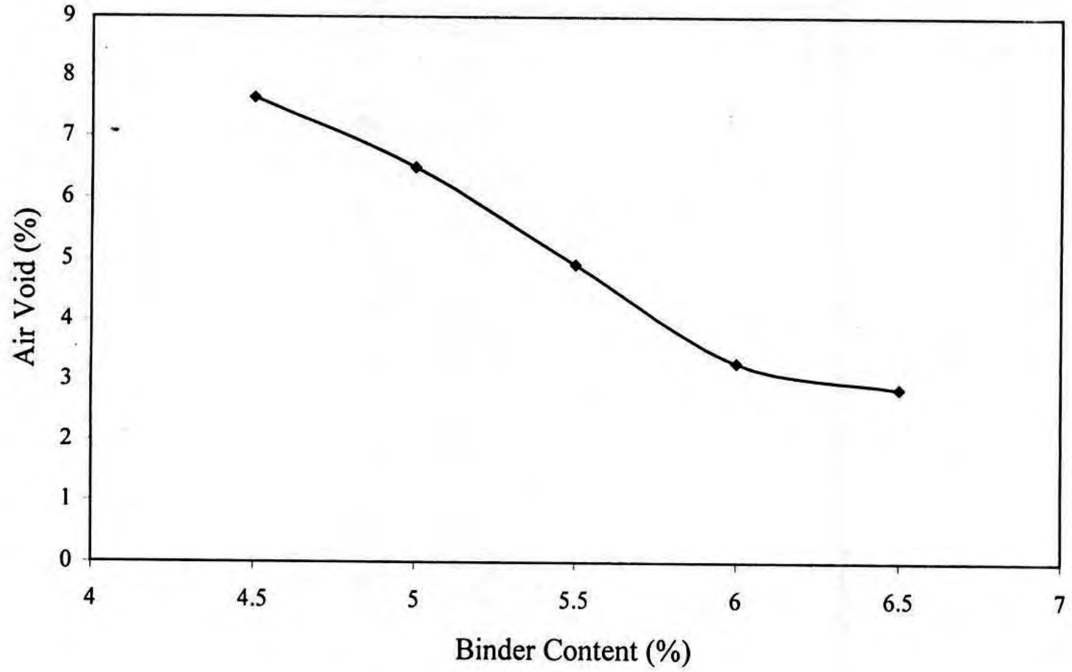

Figure 27A: Air Void Results for Mixes Prepared with 2.5 % LDPE Modified Bitumen.

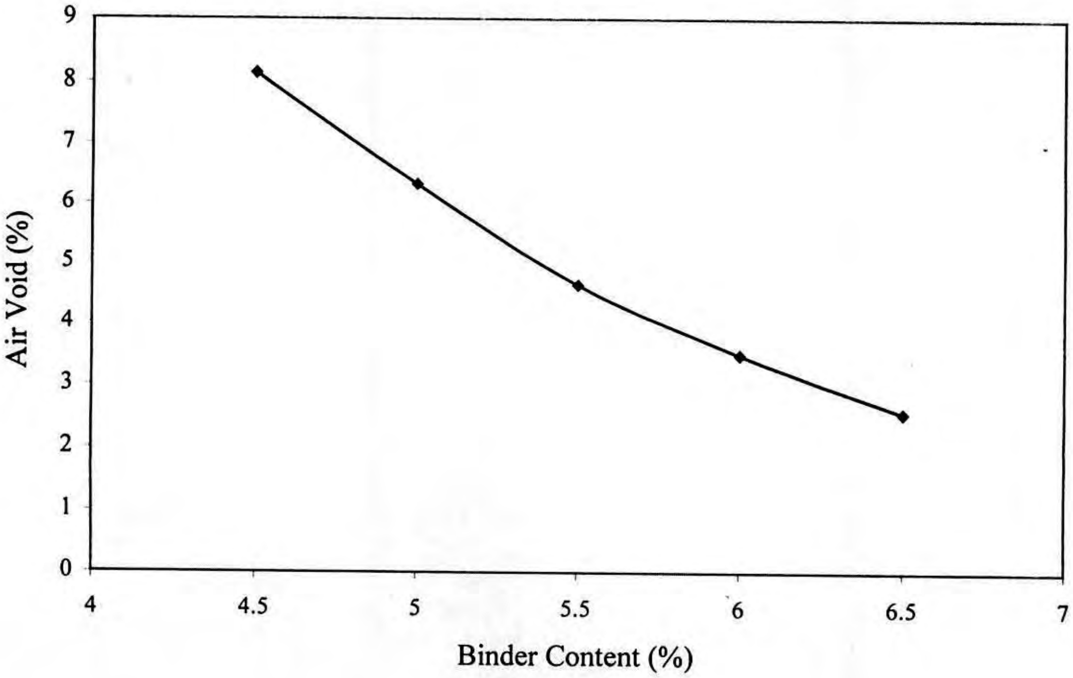

Figure 28A: Air Void Results for Mixes Prepared with 5 % LDPE Modified Bitumen.

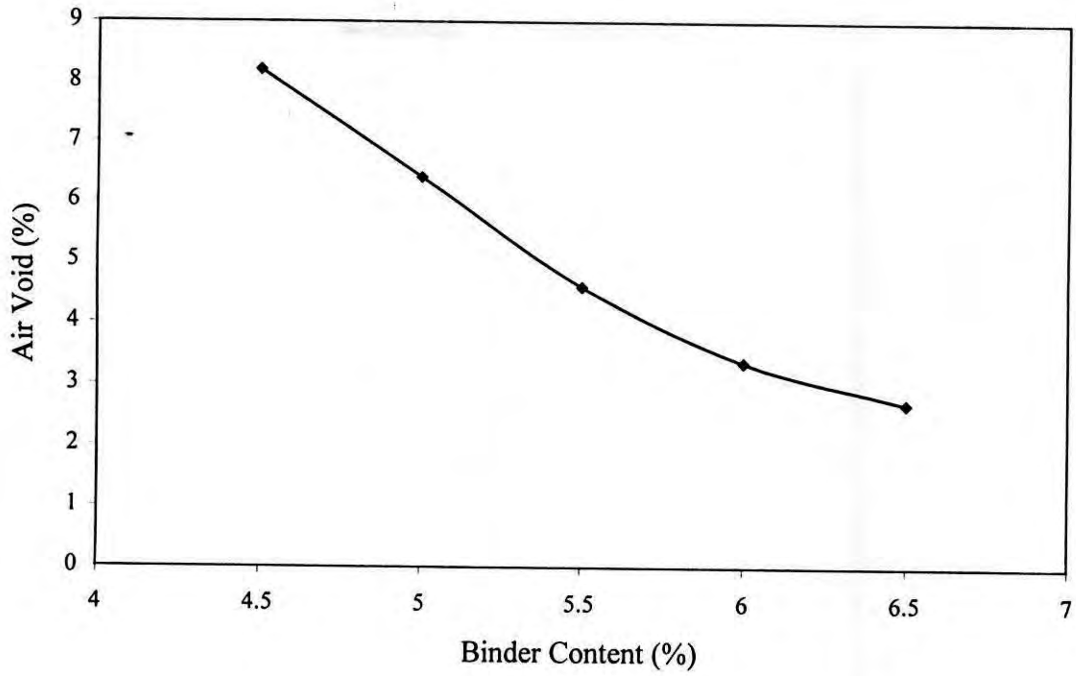

Figure 29A: Air Void Results for Mixes Prepared with 7.5 % LDPE Modified Bitumen.

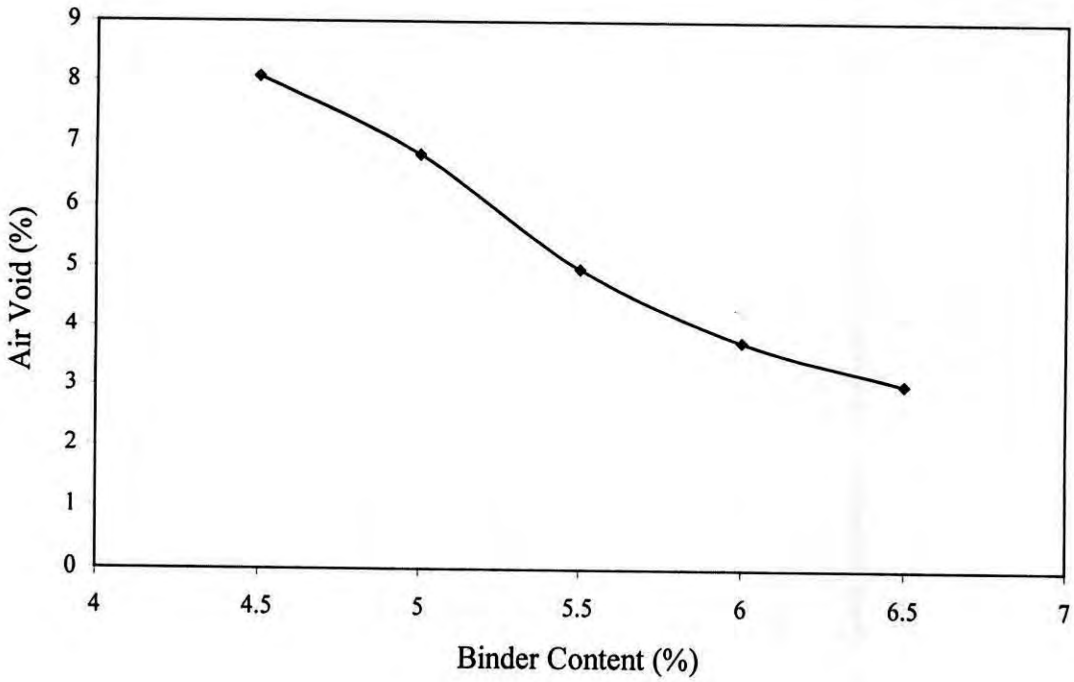

Figure 30A: Air Void Results for Mixes Prepared with 10 % LDPE Modified Bitumen.

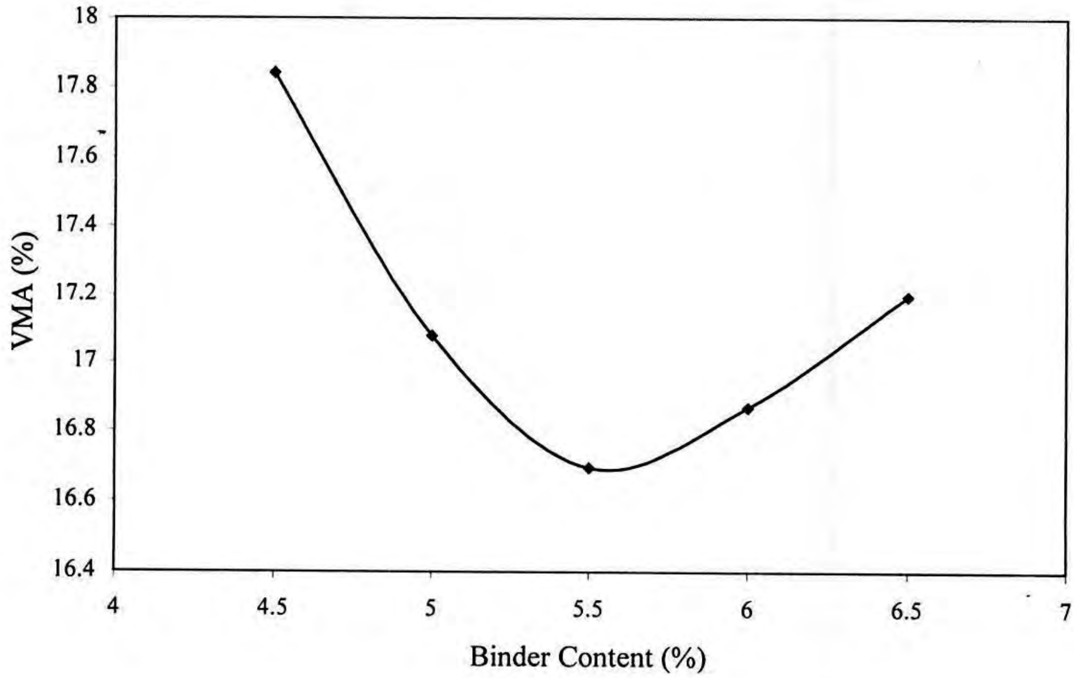

Figure 31A: Void in Mineral Aggregate Results for Mixes Prepared with Unmodified Bitumen.

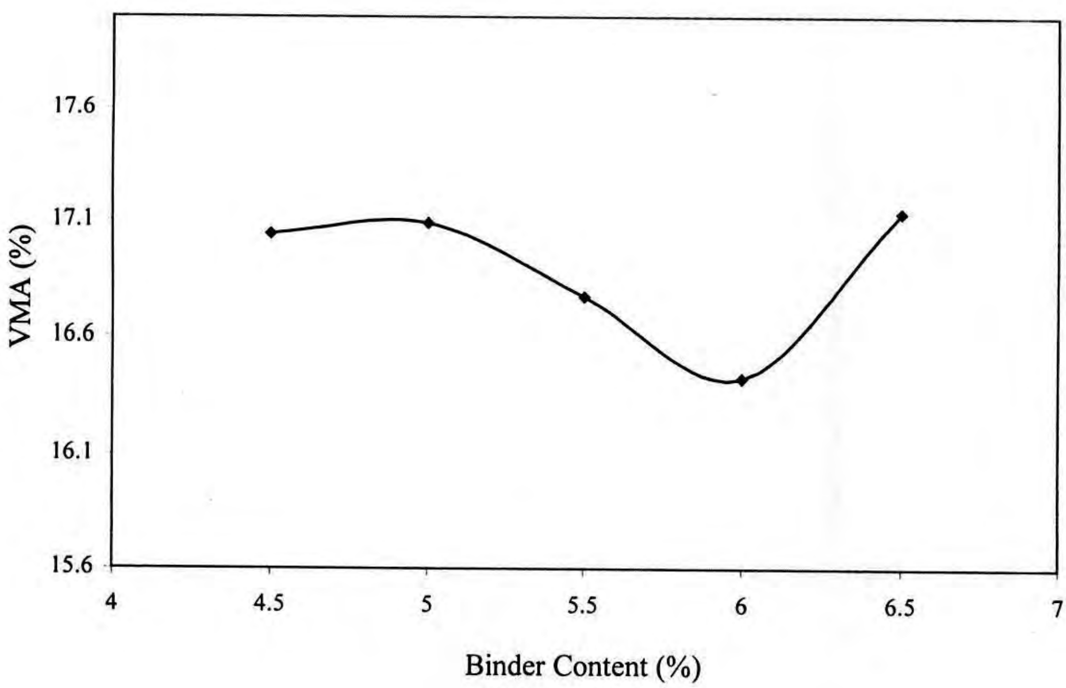

Figure 32A: Void in Mineral Aggregate Results for Mixes Prepared with 2.5 % LDPE Modified Bitumen.

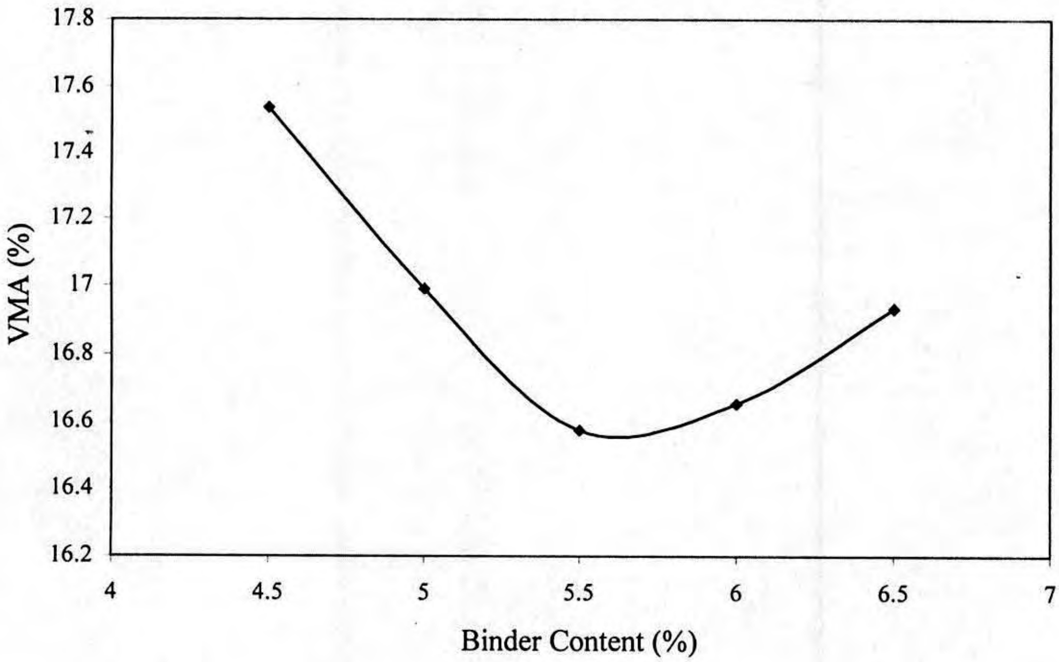

Figure 33A: Void in Mineral Aggregate Results for Mixes Prepared with 5 % LDPE Modified Bitumen.

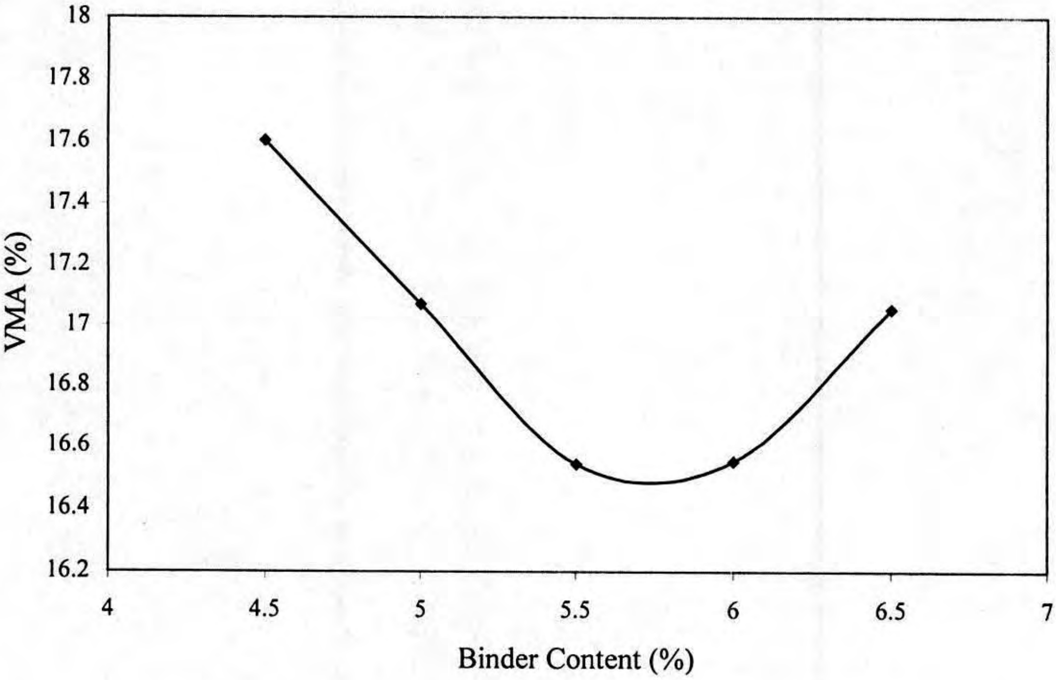

Figure 34A: Void in Mineral Aggregate Results for Mixes Prepared with 7.5 % LDPE Modified Bitumen.

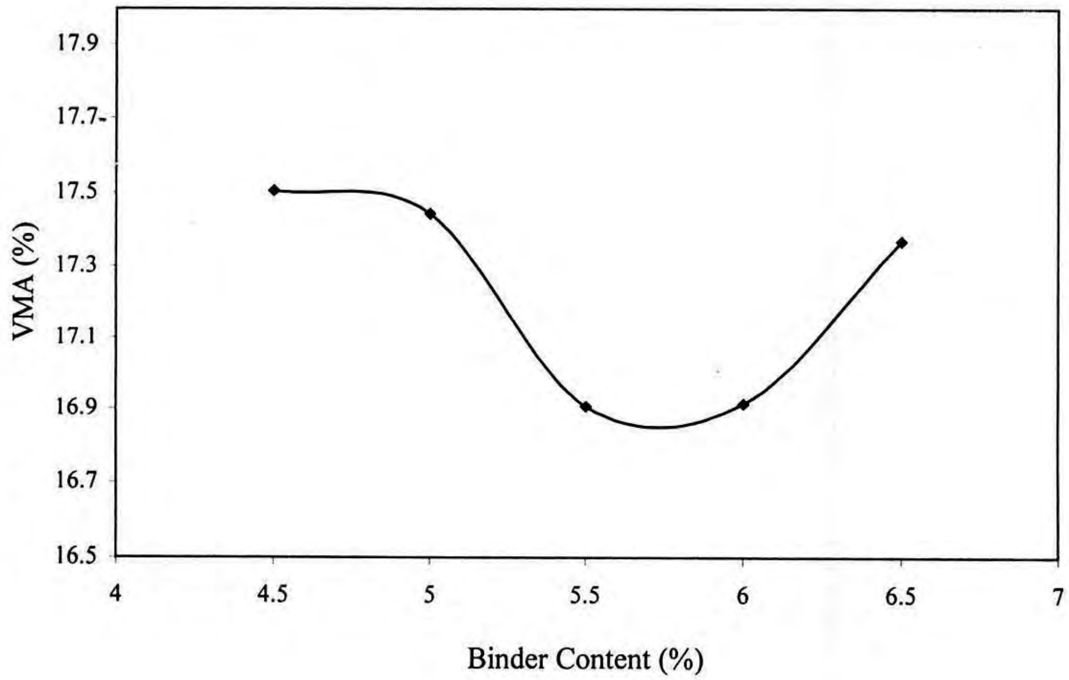

Figure 35A: Void in Mineral Aggregate Results for Mixes Prepared with 10 % LDPE Modified Bitumen.

Figure 36A: Void Filled with Binder Results for Mixes Prepared with Unmodified Bitumen.

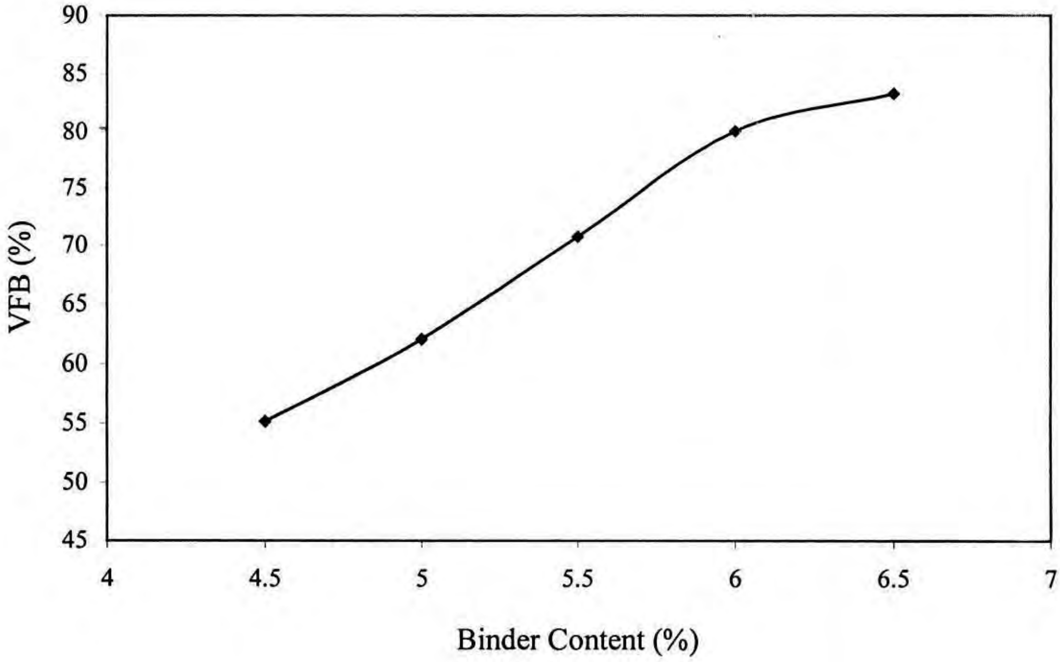

Figure 37A: Void Filled with Binder Results for Mixes Prepared with 2.5 % LDPE Modified Bitumen.

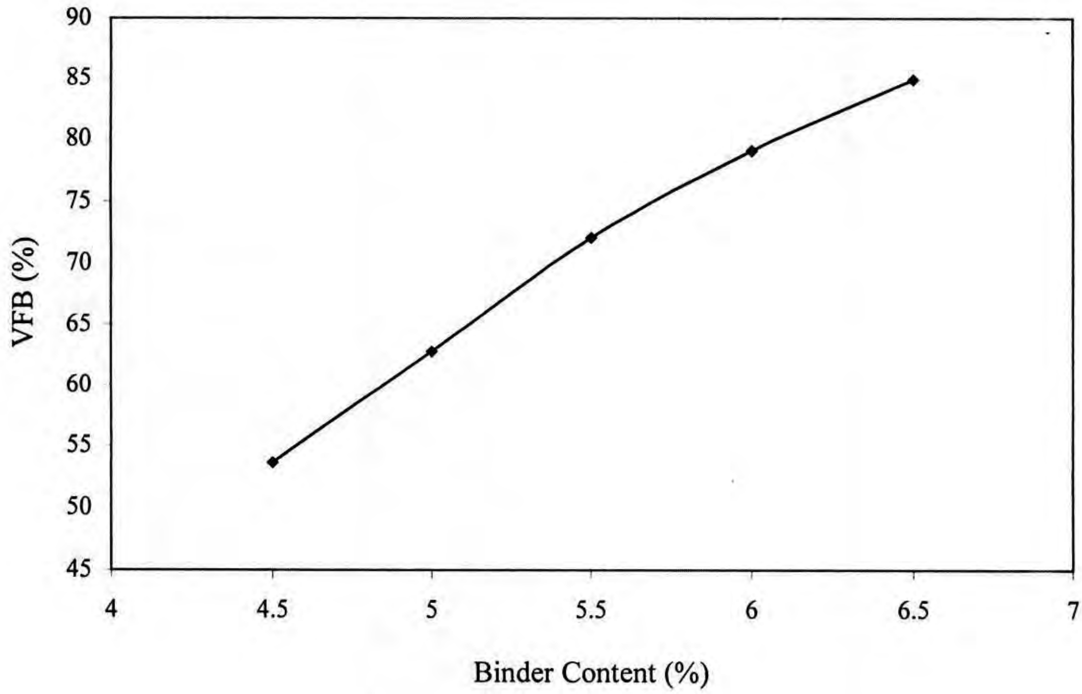

Figure 38A: Void Filled with Binder Results for Mixes Prepared with 5 % LDPE Modified Bitumen.

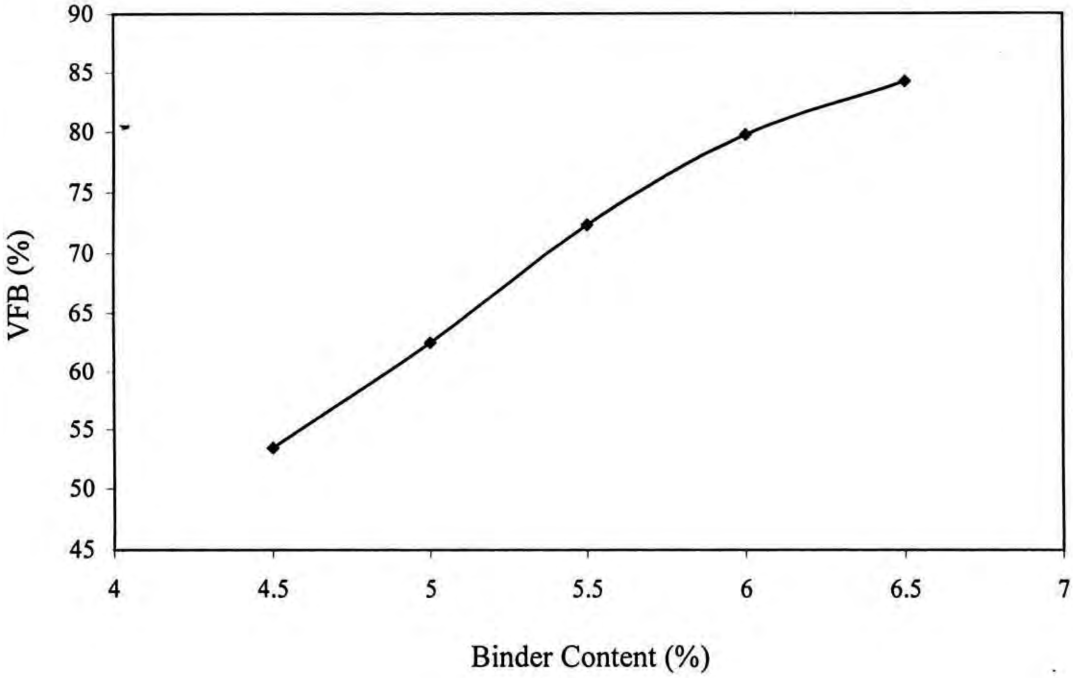

Figure 39A: Void Filled with Binder Results for Mixes Prepared with 7.5 % LDPE Modified Bitumen.

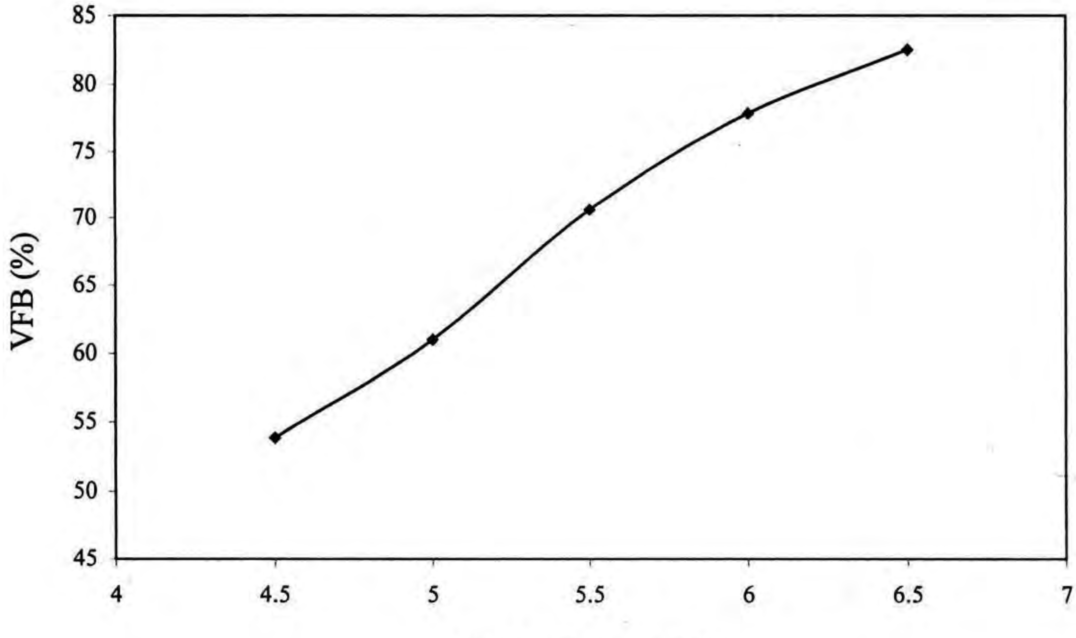

Figure 40A: Void Filled with Binder Results for Mixes Prepared with 10 % LDPE Modified Bitumen.