LABORATORY INVESTIGATIONS AND PERFORMANCE EVALUATION OF STONE MATRIX ASPHALT (SMA) AS A WEARING COURSE USING VARIOUS SYNTHETIC AND NATURAL FIBRES

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DECLARATION

I, Sambhav Jain, hereby declare that this thesis entitled **"Laboratory Investigations And Performance Evaluation Of Stone Matrix Asphalt As A Wearing Course Using Various Synthetic And Natural Fibres"** is an authentic record of my study carried out as requirements for the award of degree of **Master of Engineering** in **Civil Infrastructure Engineering** in the Civil Engineering Department, Thapar University, Patiala, under the supervision of **Mr. Tanuj Chopra, Assistant Professor,** Department of Civil Engineering, Thapar University, Patiala during July 2015 to July 2017. This matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

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CERTIFICATE

This is to certify that above statement made by the student concerned is correct and true to the best of my knowledge and belief.

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ABSTRACT

In today's world, road network of any country is of great importance for its economic growth. Bituminous mixtures are used as wearing and base course layers in a pavement structure and the performance of these mixes can be defined by its resistance against deformation, fatigue cracking, damage due to moisture and overall stiffness of the mixture. Rutting is one of the most important factors that lead to failure of flexible pavements.

The stone matrix asphalt (SMA) mixture is known to be highly rut resistant than other conventional wearing courses such as Bituminous Concrete. This paper describes the experimental examination conducted on Stone Matrix Asphalt (SMA) mixes assembled using VG 30 grade of bitumen and different types of fibres such as cellulose fibre, coconut fibre, glass fibre and jute fibre as their additives. Results were then collated with SMA mixes prepared with different types of fibres. Investigation work comprises SMA Mix design, Static Indirect Tensile Strength (ITS) and Drain down Test. The study include the design of the Stone Matrix Asphalt pavement using IITPAVE software

From the test results, it was perceived that SMA with cellulose fibre has higher Marshall Stability and lower drain down percentage as compared to all other fibres used. But Indirect Tensile Strength for SMA mix prepared with jute fibre is higher than all other mixes. SMA Mix with Jute fibre shows less vertical and horizontal strains when calculated using IITPAVE. SMA mixes having jute fibre as their additive also shows high fatigue and rutting life of the pavement when evaluated using IITPAVE software.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter-1
INTRODUCTION

1.1 General

Today, India is one of the fastest growing countries. There is no doubt that, over time, India has made great progress in many areas such as education, industrialization and so on, but there are still some areas that are of concerned. One such problem is the roadways and transportation in India. India's road network is huge and is considered the second largest road network in the world after the United States of America.

Although the Indian road construction industry has progressed remarkably, but there is a lot of room for the improvement of the quality and quantity of road infrastructure assets. With the promotion of technology in India, the new pavement design need to be used for the flexible pavement, which will not only increase the service life of the road, but also minimizes the cost of design and construction. These steps will provide a better pavement structure with minimal maintenance and recovery (M & R) requirements.

India has two kinds of pavement, one is a flexible pavement and the other one is a rigid pavement. In the case of elastic (flexible) pavements, it is known that they are well suited to national and state highways and are also suitable for other roads in India, but the only problem with such a pavement is short term durability when compared to the rigid pavement which is designed for 40 to 50 years life cycle. The only limitation of a rigid pavement is that the Rehabilitation and Up-gradation of the pavement is not easy. On the other hand, flexible pavements can be easily rehabilitated and can be open after 24 hours of laying for public use. In order to meet the above necessities, it is time to find the most efficient and more durable road type.

1.2 Stone Matrix Asphalt (SMA)

Stone Matrix Asphalt (SMA) was first developed in Germany in the 1960s. SMA as a pavement is also used in Europe, Australia, the United States, and Canada as a strong and durable asphalt surface option for heavy trafficked highways and residential streets. Since 1960s, Stone Matrix Asphalt (SMA) pavement surfaces have been used successfully in Germany on heavily trafficked roads. After the heavy use of Stone Matrix Asphalt (SMA) pavements because of its excellent performance, the national standards of Germany had set up the codes for SMA in 1984. Since then, due to its excellent performance and durable characteristics, the use of SMA has increased at a faster rate in the world of road authorities and Asphalt Industry.

Stone Matrix Asphalt (SMA) is a gap graded mixture contains high amount of coarse aggregate and less percentages of fine aggregate with high fraction of mineral filler and binder content. Normal stone matrix asphalt (SMA) mix comprises of about 70-80% of coarse aggregate whereas conventional mixes contain about 40-60% of coarse aggregate. In SMA mix, the normal binder content is more than 6%. Strength of these mixtures comes from the stone on stone contact impart from the coarse aggregate skeleton and durability comes from the high binder content. The strength and performance for stone matrix asphalt (SMA) is generally high as collate to other asphalt mixes.

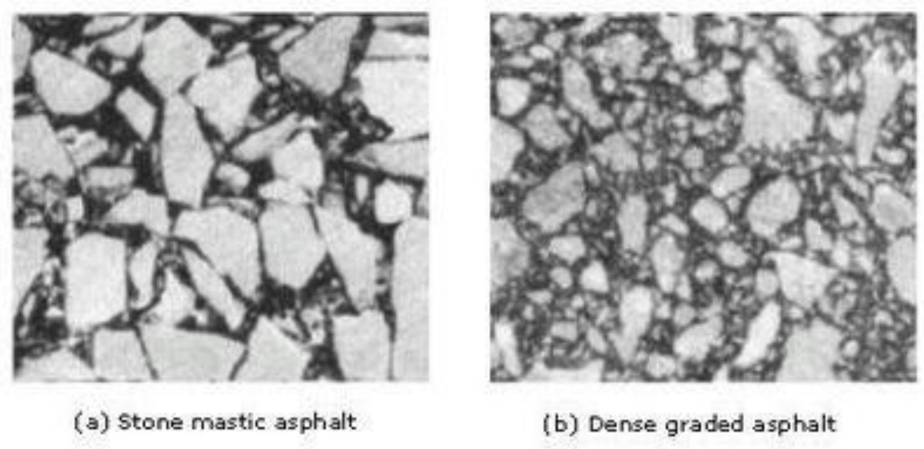

Figure 1.1 SMA Mix and Dense Graded Mix

Due to gap gradation, binder may drain out from the mix at the time of placing, production and storage. This can be overcome by the addition of a stabilizer.

SMA can be explained by two-component hot mix asphalt HMA system which consists of a coarse aggregate skeleton which is due to its gap-graded gradation and a high percentage of bitumen content. Stone Matrix Asphalt mixture has high resistance against rutting characteristics and high durability when compared to dense-graded asphalt mixture. This property of SMA mixture can be acquired because of the formation of a stone-to-stone aggregate skeleton in the mixture.

1.3 Composition

As per MoRTH Specification, this work shall be constructed in a single or multiple layer of Stone Matrix Asphalt which has fibre-additives and shall be constructed over bituminous surface which has been prepared already. Stone Matrix Asphalt (SMA) has unique structure which includes the skeleton of a coarse aggregate skeleton so as to obtain the stone-on-stone contact, which will provides the high resistant against the rutting of bituminous course for heavy traffic roads. The SMA having nominal maximum aggregate size of 13 mm should be intended for wearing course with nominal layer thickness of 40 to 50mm. The SMA having nominal maximum aggregate size of 19 mm should be intended for wearing course with nominal layer thickness of 45 to 75 mm. [16].

Table 1.1 Composition of Stone Matrix Asphalt (SMA)

SMA Designation	**13 mm SMA**	**19 mm SMA**
Course where Used	**Wearing Course**	**Binder (Intermediate) Course**
Nominal Aggregate Size	**13 mm**	**19 mm**
Nominal Layer Thickness	**40-50 mm**	**45-75**
IS Sieve (mm)	**Cumulative % by Weight of Total Aggregate passing**	**Cumulative % by Weight of Total Aggregate passing**
26.5	-	100
19	100	90-100
13.2	90-100	45-70
9.5	50-75	25-60
4.75	20-28	20-28
2.36	16-24	16-24
1.18	13-21	13-21
0.600	12-18	12-18
0.300	10-20	10-20
0.075	8-12	8-12

1.4 MATERIALS

1.4.1 Bitumen: The bitumen which can be used for Stone Matrix Asphalt layer which is fibre-stabilized shall be of viscosity grade VG-30 as per the Indian Standard Specification for paving bitumen IS: 73 [13] or Polymer Modified Bitumen (PMB) Grade 40 as per Indian Roads Congress Specification IRC: SP: 53 [12].

1.4.2 Coarse aggregates: The coarse aggregates should come from crushed rock which can be retained on 2.36 mm IS sieve. It should be hard, durable, clean, and should be free from dust and soft organic and other deleterious substances [9].

1.4.3 Fine aggregates : Fine aggregates should be fully crushed (100 %) and should manufactured sand from crushing operations. It should pass the 2.36 mm IS sieve and should be retained on 0.075 mm IS sieve. The fine aggregate shall be hard, durable, clean and free from soft pieces, organic or other deleterious substances. The fine aggregates which are used in the Stone Matrix Asphalt mixture should be non plastic [9].

Table 1.2 Physical Requirements for Coarse Aggregates for Stone Matrix Asphalt

Property	Test	Method	Specification
Particle Shape	Combined Flakiness and Elongation Index	IS:2386 (P-1)	< 30%
Water Absorption	Water Absorption	IS:2386 (P-3)	< 2%
Strength	Los Angeles Abrasion value	IS:2386 (P-4)	< 25%
	Aggregate Impact Value	IS:2386 (P-4)	< 24%
Polishing	Polished Stone Value	IS:2386 (P-114)	> 55%
Cleanliness	Grain Size Analysis	IS:2386 (P-1)	< 2% passing 0.075 mm sieve

1.4.4 Mineral filler: Mineral filler which is used in Stone Matrix Asphalt mixture should be finely divided mineral matter like dust, stone or hydrated lime. Fly ash shall not be used as a filler in Stone Matrix Asphalt mixtures [9].

Table 1.3 Grading Requirement of Mineral filler

IS Sieve (mm)	Cumulative % passing by Weight of Total Aggregate
0.6	100
0.3	95-100
0.075	85-100

1.4.5 Fibre Additives: The stabilizer additives should satisfy following requirements:-[9]

Table 1.4 Physical Requirement of Fibre for Stone Matrix Asphalt

S. No.	Description	Value specified
1.	Maximum Fibre Length	8 mm
2.	Moisture Content	< 5% by fibre weight
3.	Oil Absorption	>4 times fibre weight

1.5 Fibres Used

Since the Stone Matrix Asphalt is a gap graded mixture and contains generally high binder content, there is possibility that the binder may drain down from the mix during the production, transportation and storage. So to overcome this problem, the procedure of adding the stabilizer is required. In this study, three different fibres were added to the SMA Mix such as Coconut fibre, Glass fibre and Jute fibre, excluding the conventional mix of Stone Matrix Asphalt which contains cellulose fibre.

1.5.1 Cellulose Fibre

The manufactured cellulose fibre comes from plants that are managed into pulp and then extruded in the same way as synthetic fibres like nylon or polyester are made.

Figure 1.2 Cellulose Fibre

1.5.2 Coconut Fibre

Coconut fibre or Coir is a natural fibre extracted from the husk of coconut and can be found between the hard, internal shell and the outer sheel of the coconut. The length of the coconut fibre in this study kept in between 3 to 8 mm.

Figure 1.3 Coconut Fibre

1.5.3 Glass Fibre

Glass fibre is a material consists of extremely fine fibres of glass. Glass fibre has high mechanical properties as compared to other natural fibres. In this study,the length of these fibres is taken as 5 mm.

Figure 1.4 Glass Fibre

1.5.4 Jute Fibre

It is a long , soft and a vegetable fibre that can be made into coarse, strong threads. Jute fibre is much cheaper than cellulose fibre. In this study, the length of the fibre is taken as 5 mm.

Figure 1.5 Jute Fibre

1.6 Advantages of SMA

- Stone Matrix Asphalt (SMA) has high stability against permanent deformation (rutting) and high resistance against the wear as compared to dense graded asphalts.
- Pavements having Stone Matrix Asphalt as their wearing course has better friction because of high macro texture as compared to dense graded asphalt pavements.
- Stone Matrix Asphalt performs well at low temperature also.
- One of the main advantages is its longer life which increased durability and decreased rutting, even though it has higher cost than other hot mix asphalt (HMA) mixes.
- Stone Matrix Asphalt has longer service life as compared to other conventional mixes.
- Stone Matrix Asphalt has slow aging tendency and high resistance against premature cracking.

1.7 Disadvantages of SMA

- Stone Matrix Asphalt has high cost associated with higher binder content and filler contents, and fibre additive.
- SMA has high filler content which reduces productivity. This may be overcome by suitable plant modifications.

- Initially, skid resistance may be low on the pavement of Stone Matrix Asphalt until the thick binder film is worn off the top of the surface by traffic.
- Stone Matrix Asphalt mix should be cooled to 40 ^{o}C which results in the delay of opening to traffic as to prevent flushing of the binder surface.

Chapter 2

LITERATURE REVIEW

2.1 General

Stone Matrix Asphalt is a gap graded mixture which was developed in Germany in 1960s as a highly durable wearing course for heavy trafficked roads. Since then many highways has been constructed using Stone Matrix Asphalt (SMA) as their wearing course. Stone Matrix Asphalt is having very high rut resistance and high fatigue life. Since the traffic in the world is increasing at very high rate, Stone Matrix Asphalt is of great demand in the world. For the last 20 years many studies have been conducted over the laboratory investigations and performance evaluation of Stone Matrix Asphalt.

2.2 Effect of Gradation on Stone Matrix Asphalt

Muwaffaq Safiyanu Labbo et al. [2016] examined the performance of Stone Matrix Asphalt designed by the Bailey method of gradation and the conventional Trial and error method of gradation. Bailey method blend the aggregates in such a way that it gives the interlocking between the aggregates which helps in making strong aggregate skeleton for rutting resistance, durability and resistance to deformation. Stone Matrix Asphalt with a nominal maximum aggregate size 19 mm was used in this study. Marshall properties, Indirect Tensile Strength Test, Moisture Susceptibility and Drain Down Test of two gradation were conducted and the results were then compared and it was observed that the Marshall properties of SMA designed using the Bailey method were within the specified limits. The drain down results were also compared between the Bailey method of aggregate gradation and conventional Trial and Error method of gradation and it was observed that the Bailey mixture of SMA had less drain down than Trial and Error mixture of SMA.

Goutham Sarang et al. [2015] adopted two gradation one from Chinese specification and one from IRC specification with nominal size aggregate size of 16 mm and 13 mm respectively and compared their laboratory tests such as Marshall Mix Design, Indirect Tensile Strength Test, Drain down Test, Rutting test using Polymer Modified Bitumen (PMB70) with no additive used in the SMA mix because the value of drain down are well under the specified limits. 9 samples were made for each type of gradation for Marshall Mix design and cylindrical specimen for the tensile strength test. Two slabs were constructed for each type of gradation for the evaluation of rutting resistance of the SMA. The SMA mix having high nominal maximum aggregate size (NMAS) i.e. 16 mm shows better results than 13 mm SMA. Marshall stability for 16 mm SMA comes out to be 14.6-20.1 KN and for 13 mm SMA it is in the range of 14.5-19.4 KN. The Tensile Strength Ratio for 16 mm SMA is 91.26 % whereas for 13 mm SMA, it is 89.16 % i.e. 16 mm SMA is highly susceptible against moisture than 13 mm SMA. For rutting resistance, the wheel tracking device was run on the slab for 10,000 wheel passes and the deformation comes out for the 16 mm SMA was 4.1 mm which is slightly lower than 13 mm SMA which has the final deformation of about 4.8 mm. These results can be explained due to the presence of high proportion of coarse aggregates in the mixture.

Salam Ridha Oleiwi Al-Etba [2013] Trying to study the effect of aggregate gradation and filler type on SMA performance. Four different types of aggregate gradation with two types of fillers have been used i.e. hydrated lime and crushed stone dust for the preparation of SMA mixtures. Among the first three; upper, middle and lower curves, medium curve has good Marshall Properties. For the fourth level of the gradation that modified curve, the crushed stone has improved the Marshall properties such as Marshall Stability and the unit weight value over hydrated lime. It has been seen that the SMA mixture of hydrated lime improves air void and moisture sensitivity in the same gradation of sample with crushed stone.

2.3 Effect of Waste Plastic (PET) as Additive on Stone Matrix Asphalt

Umadevi Rongali et al. [2013] evaluates the performance of Stone Matrix Asphalt (SMA) by establishing the composition of fly ash and plastic waste in a composite based on various performance tests. The plastic waste was used in the shredded form which is in the range 2-8 mm and fly ash was obtained from NTPC Ltd. VG-30 grade of bitumen was used and aggregates (granite) was obtained from the nearby quarry. This study examines the performance of three different SMA mixes i.e. SMA with lime filler, SMA containing fly ash and SMA with fly ash-plastic waste composite and named as SMA1, SMA2 and SMA3 respectively. After conducting several tests the results shows that Tensile Strength Ratio (TSR) for SMA2 and SMA3 is significantly higher than the SMA1, which indicates higher resistance to moisture damage. KENPAVE software shows that SMA2 leads to increase in tensile strains at the bottom of the SMA layer but at the same time SMA3 leads in the decrement of tensile strains as compared to SMA1. The mix containing composite i.e. SMA3 reduces one third of the rutting as compared to the SMA1. Drain down test is also being conducted as it is an important parameter while transporting the Stone Matrix Asphalt and the results shows that fly ash and fly ash-plastic waste composite reduces the drain down as compared to the lime when added as a filler in the stone matrix asphalt mixture.

Taher Baghaee Moghaddam et al. [2012] investigates the consequences of adding polyethylene terephthalate (PET) on the fatigue and stiffness properties of Stone Matrix Asphalt mixtures at optimum binder contents. Waste PET was obtained from PET bottles and then crushed by the crushing machine and then sieved, the particles passing the 2.36 mm sieve were used for this study. The asphalt which was used in this study was of 80/100 penetration grade. The samples were prepared using Marshall Method at optimum asphalt content (OAC). Six different OACs were calculated for six different PET contents, 6.77%, 6.45%, 6.43%, 6.29%, 6.36% and 6.51% of OAC each for 0%, 0.2%, 0.4%, 0.6%, 0.8% and 1% (by weight of aggregates) of PET content, respectively. Indirect Tensile Stiffness Modulus Test was conducted to find out the stiffness of AC mixtures. The test was carried out on Universal Testing Machine (UTM) according to AASHTO TP31. Stiffness modulus was obtained for different percentages of PET at different stress levels (250, 350 and 450 kPa) at 20 ^{o}C. From the results it was seen that on increasing the applied stress stiffness modulus decreases but in the same stress levels, stiffness increases initially with the increment of PET and then decreases afterwards. In the last it was seen that 0.2% is the optimum PET content to attain maximum stiffness.

Esmaeil Ahmadinia et al. [2011] determines the effect of using waste plastic bottles (PET) in the engineering properties of Stone Matrix Asphalt (SMA). Different percentages of PET (0%, 2%, 4%, 6%, 8% and 10%) were added and evaluate the properties by conducting different laboratory tests. The study used crushed granite aggregates with SMA20 gradation and bitumen was of 80/100 penetration grade. Portland cement was used as filler in this study. When the Marshall method of Design was conducted, the stability values of different binder content increases initially when PET is added and reached to its maximum level which was around 6% of PET and then it started to decrease. Similarly due to high MQ, PET increased the stiffness modulus of the mixture enhancing the resistance level against permanent deformation. The suitable amount of the PET was found to be 6% by weight of bitumen.

Bindu C.S et al. [2010] examines the benefits of sustaining the Stone Matrix Asphalt (SMA) with shredded plastic waste. Conventional SMA i.e. without plastic and the Stabilized SMA i.e. with plastic were subjected to the performance tests such as Marshall Stability and Drain Down. 60/70 penetration grade of bitumen was used in this study. Different percentages (0-12%) by weight of bitumen of plastic were added with an increment of 2%. The size of the plastic waste was around 2-3 mm. No other additional fibre is added to this mixture. The results shows that as the plastic content increases, the stability increases up to 10% plastic content and the flow value decreases. After the 10% plastic content, the stability decreases and the flow value increases. From the Drain down test it was seen that for conventional and for 10% plastic modified SMA samples, the drain down values was found to be 0.303% and 0.09% respectively. No fibre was needed to prevent the drain down when this waste plastic was used.

2.4 Effect of Replacing Cellulose Fibre with Different Fibre on Stone Matrix Asphalt

Pawan Kumar et al. [2004] presents the details of laboratory investigations which are carried out to determine possibility of use of natural fibre in place of synthetic fibre in Stone Matrix Asphalt (SMA) mixture. Since the synthetic fibres are used in the construction of Stone Matrix Asphalt (SMA) in flexible pavements but they are not manufactured in India which makes them very costly. So to reduce the cost, coated jute fibres were used in this study. The tests which are conducted in this study to evaluate the performance of the two mixes i.e. using the synthetic fibre and natural fibre are Moisture Susceptibility Test, Rutting Test, Stiffness modulus, Drain Down Test and Indirect Tensile Strength (ITS) Test. The test results indicated that natural jute fibre can replace the synthetic fibre in the SMA mixture. The Drain down test results shows that the drain down percent for SMA with synthetic fibre is 0.034 and for SMA with natural fibre is 0.078 which are both within the specified limits of 0.3% by weight of mixture. Rutting test shows that that the permanent deformation is same in both fibres. The Marshall stability of the SMA with natural jute fibre (7.4 kN) is marginally greater than SMA with synthetic fibre (7.1 kN). At 25 ^{o}C and 35 ^{o}C, the stiffness modulus of the SMA with jute fibre is somewhat lower as compared to SMA with synthetic fibre. The study shows that natural jute fibre can be used in the construction of the Stone Matrix Asphalt (SMA) in place of synthetic fibre which reduced the cost since the construction cost for the SMA with natural fibre per metric ton is relatively lower.

S.S. Avanti [2013] examines the experimental investigation conducted on three types of Stone Matrix Asphalt mixes, the first prepared using polymer modified bitumen PMB 70 with SBS and coconut fibre, the other one is prepared using VG-30 grade of bitumen and coconut fibre and the last one is the conventional mix of stone matrix asphalt i.e. Vg-30 grade of bitumen and cellulose fibre. The test conducted were the Marshall Mix Design, Drain Down Test, Tensile Strength Ratio Test and Static Indirect Tensile Strength Test on all three types of SMA mixes and the results were then compared. The result shows that the Static Indirect Tensile strength for SMA mix with PMB 70 at room temperature is 0.43 MPa which is slightly higher than that of SMA mix with VG-30 grade of bitumen which is 0.40 MPa. The drain down for SMA mix with PMB 70 is around 36 % lower than the SMA mix with VG-30 grade of bitumen. The optimum binder content for SMA mix prepared with PMB 70 is 0.3 % higher than SMA mix prepared with VG-30 grade of bitumen.

A. Behnood et al. [2012] investigates the possibility of using steel slag as aggregates in Stone Matrix Asphalt (SMA) mixtures. The study uses the steel slag as the coarse portion of aggregates as well as fine portion of aggregates. The steel slag was obtained from the steel industries in Iran. When tests were conducted on the SMA mixture prepared using steel slag the results indicates that steel slag can enhance the Marshall properties of mixtures. The average value of stability of the mixture containing only limestone was 8.84 kN while on the other hand, the SMA mix containing steel slag shows 11.08 kN as its maximum stability. The Indirect Tensile Strength (ITS) test shows the mixture containing only limestone had 690 kN tensile strength, whereas the SMA mix contained steel slag as their coarse portion have an indirect tensile strength up to 834 kN. Resilient Modulus were also calculated for different mixtures and it shows that mixture containing steel slag shows high resilient modulus than the mixtures which are only having limestone in their preparation. The test for moisture susceptibility is also conducted in which indirect tensile values are calculated for both conditioned and unconditioned samples. The Tensile Strength Ratio (TSR) for the mixture having steel slag as the portion of aggregates is 0.84 which is much higher than the mix having only limestone as their portion of aggregates.

Brian d. Prowell et al. [2010] evaluated SMA for use on airfield pavements. Performance of SMA was compared to dense-graded P401 mixes designed using the same aggregates. This study examines the susceptibility to rutting, reflective cracking, fuel resistance, moisture damage and deicer resistance. And at last the performance of SMA compared to P401 is summarized and was based on the literature review, laboratory testing and performance of in-service airfields. The results shows that SMA is having same properties as compared to P401 in terms of rutting susceptibility and deicer resistance. But in all other areas, especially in resistance to reflective cracking, SMA mixture is superior to dense-graded P401 mixes.

2.5 Gap in the Literature Review

In the previous literature it shows that work had been conducted on Stone Matrix Asphalt (SMA) using the replacement of fibre with another single fibre or some changes in the grade of binder. But in case of research work, I have replaced three different variants of fibres with conventional mix of Stone Matrix Asphalt i.e. using cellulose fibre and grade of the binder remains the same. Then with the four mixes of Stone Matrix Asphalt (SMA), some laboratory investigations has been conducted such as Marshall Method of Mix Design, Indirect Tensile Strength (ITS) Test, Drain Down Test and to design and compare the rutting and fatigue life of SMA mixes to find out the comparison of different properties of four mixes using different fibres.

2.6 Objective of the Study

The objective of this study is to carry out the laboratory investigations and to evaluate the performance of Stone Matrix Asphalt (SMA) using different fibre additives such as cellulose fibre, coconut fibre, glass fibre and jute fibre by conducting different laboratory tests such Marshall Method of Mix Design, Indirect Tensile Strength (ITS) Test, Drain Down Test and to design the Stone Matrix Asphalt pavement using IITPAVE software. The study also shows the comparison of strains, fatigue life and rutting life of Stone Matrix Asphalt (SMA) pavement using different fibres as their additives. The outcome of the results shows that SMA mix with jute fibre has high Indirect Tensile Strength as comparison to all other mixes using different fibres. SMA mix with Jute fibre shows less vertical and horizontal strains when calculated using IITPAVE. SMA mixes having jute fibre as their additive also shows high fatigue and rutting life of the pavement when evaluated using IITPAVE software.

2.7 Outline of the Thesis

The thesis has been categorized into five chapters

- Chapter-1 is about the general introduction to the Stone Matrix Asphalt, its composition, its advantages and disadvantages, types of fibres used in the study.

- Chapter-2 highlights the studies (Literature Review) which have been conducted on the performance of Stone Matrix Asphalt since the last two decades.
- Chapter-3 comprises of the materials used in the study and tests performed on these materials and the experimental program conducted on Stone Matrix Asphalt.
- Chapter-4 focuses on the results obtained from the experimental investigation conducted and followed by discussion of these results.
- Chapter-5 describes the design of rut and the fatigue life for the Stone Matrix Asphalt (SMA) pavement using different fibres.
- Chapter-6 highlights the conclusions of the research study and some research recommendations for future work.

2.8 Study Methodology

The flowchart shown in **Figure 2.1** illustrates the step-wise methodology followed in this research study in flowchart format.

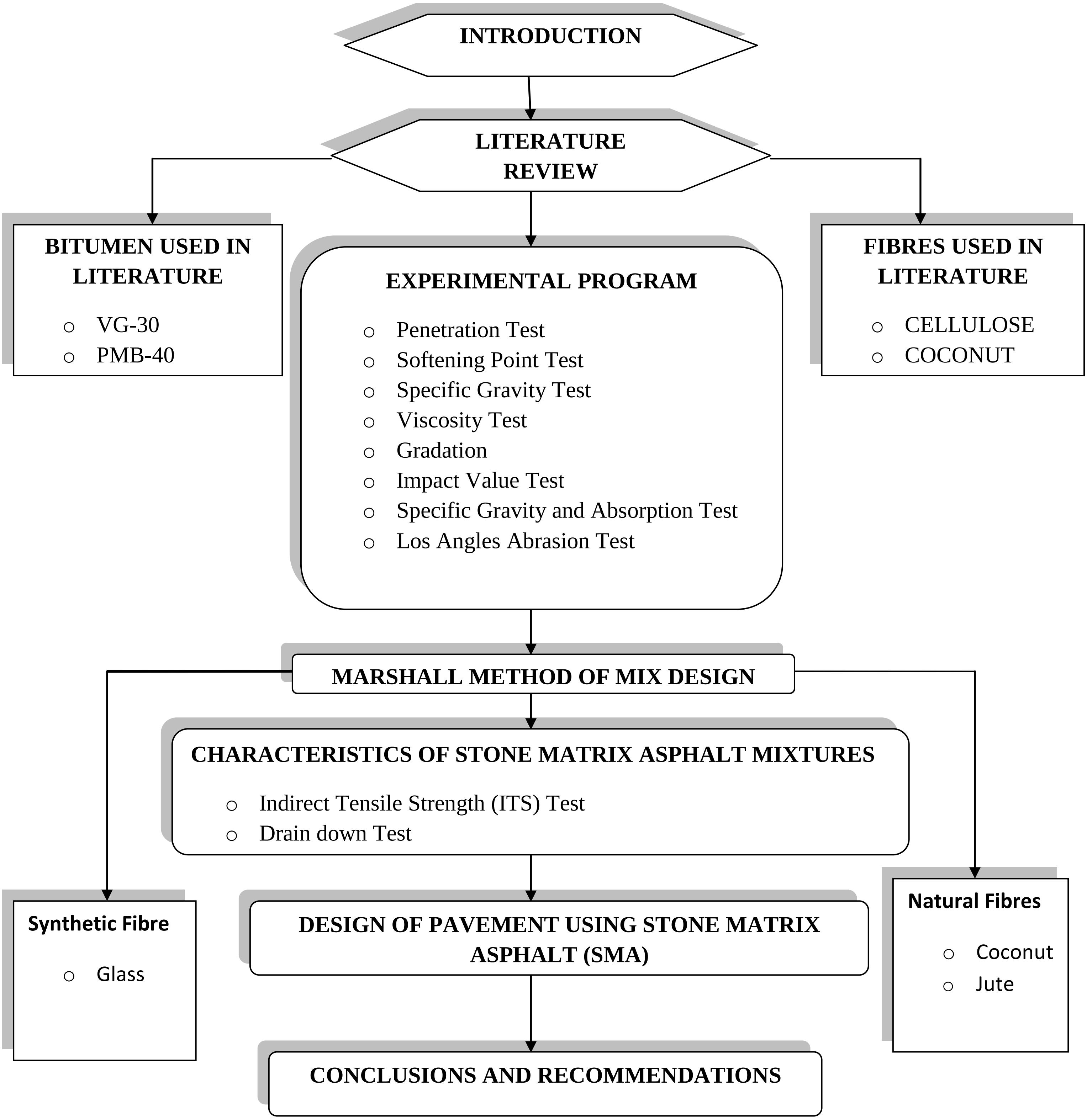

Figure 2.1 Research Study Methodology

Chapter 3

EXPERIMENTAL PROGRAM

3.1 Materials and Testing

The testing of materials to be used must be performed in order to evaluate its performance and to ensure whether the material used will be suitable for experimental work or not. All the basic tests such as softening point test, penetration test and specific gravity tests were performed.

In the project, the materials used were bitumen, aggregate, cellulose fibre, coconut fibre, glass fibre and jute fibre. The aggregate used is procured from a stone quarry in Anandpur Sahib. The bitumen used is of Grade VG 30. Additionally, three types of fibres are used in the project namely coconut fibre, glass fibre and jute fibre.

3.2 Tests on Bitumen

There are various tests to calculate the properties of asphalt binders. The following tests were conducted during the study to evaluate the different properties of asphalt binder which is to be used.

3.2.1 Penetration Test

Penetration test is one of the indirect methods to determine the consistency of an asphalt binder, since the calculation of absolute viscosity of bituminous materials is not too easy. The main purpose of this test is to grade the bituminous materials by measuring the depth (in units of one tenth of a millimeter) in which a standard needle will penetrate vertically under controlled conditions of standard load, temperature and duration. Therefore, the basic principle of penetration test is to measure the penetration of a standard needle in a bitumen sample maintained at 25 ^{o}C during five seconds. The bitumen is softened so that it can be stirred easily and poured into containers. A grade of 60/70 bitumen means the penetration value is in the range of 60 to 70 mm at standard conditions.

3.2.2 Specific Gravity test

The specific gravity of an asphalt binder is the fundamental property, generally used to classify the binders for the use in construction jobs. For most of the time, the bitumen is weighed, but during final use with aggregate system, the bitumen content is determined in volume basis. Thus, specific gravity plays an important role for the conversion of weight to volume. Chemical composition of binder can affect the specific gravity of a binder.

The specific gravity is defined as the ratio of the mass of a given volume of the bituminous materials to the mass of an equal volume of water at an standard temperature of 27 ^{o}C $\pm$ 0.1 ^{o}C. The specific gravity of the binder can be measured using Pycnometer and varies from 0.97 to 1.02.

3.2.3 Softening point Test

All the bitumen grades need sufficient fluidity before they can practically be used with the aggregate mix. The common procedure is to dissolve the bitumen by heating. The softening point is the temperature at which the material gains a particular degree of softening under standard conditions of test. The test is conducted using the Ring and Ball method. The equipment in this method comprises of a brass ring which contains the bitumen sample which is to be tested and is suspended in water or glycerin at a specified temperature. A steel ball is then placed on the bitumen sample and liquid medium is heated at a specified rate. The temperature at which the softened bitumen touches the metal plate placed at a specified distance below the ring is noted as the softening point of that bitumen sample.

3.2.4 Viscosity Test

It is defined as the degree of fluidity of the bitumen at different temperatures for its application to Spread, Penetrate and to fill the voids. The viscosity test is performed with the help of MCR 52 Dynamic Shear Rheometer (DSR) as shown in **Figure 3.** The spindle of 25 mm diameter is used to check the viscosity of the bitumen grade VG 30 at temperature of 60°C. The shear rate given to the spindle is 4 revolutions per seconds for the duration of 120 seconds.

Figure 3.1 Dynamic Shear Rheometer

Table 3.1 Results of Tests Conducted on Bitumen

S. No.	Description	Test Results	Value specified in IS:73-2013
1.	Penetration Test (mm) at 25^0C	50	45 (min.)
2.	Specific gravity Test	1.01	0.97 - 1.02
3.	Softening Point Test, ^{0}C, minimum	52	47 (min.)
4.	Viscosity Test at 60 ^{0}C, (Poise)	3050	2400-3600

3.3 Tests on Aggregates

Aggregates are principle constituents of pavement. They are also used in each layer of the pavements as either stabilized or as an unstabilized base or sub-base courses. Therefore, knowledge of aggregate properties is essential to design good quality pavement. The aggregate for this project is taken from a stone quarry situated at Anandpur Sahib, Punjab. The aggregates were tested for its basic properties and it was ensured that the aggregate must satisfy all the guidelines stated as per relevant IS codes, IRC codes and MoRTH specifications.

The following tests were conducted to evaluate the properties of the aggregates used in this study.

3.3.1 Aggregate Impact Value (AIV) Test

This test measures strength property of aggregates under sudden loading. The ability of the material to resist impact is known as toughness. When vehicles move on the roads, the aggregates starts experiencing impact force which may result in the breaking of aggregates into smaller pieces. Therefore the aggregates should have sufficient toughness to resist their breaking due to impact. This property can be measured using impact value test. The testing method followed is as per IS: 2386 Part IV. The maximum Impact value allowed is 18% for SMA [9]. Two trials were done for finding the AIV and the average of the 2 trials was taken as the impact value of the aggregates. The results of AIV experiment are presented in **Table 3.2**.

Table 3.2 Results of Aggregate Impact value Test

Description/Trial No:	**Trial-1**	**Trial-2**
(a) Weight of Aggregates before testing (gm)	330	330
(b) Weight of Aggregates retained on 2.36mm sieve (gm)	272	274
(c) Weight of Aggregates passing on 2.36mm sieve (gm)	58	56
Aggregate Impact Value (%) **c/a * 100**	17.57	16.97
Average AIV (%) (Max 18%)	**17.27**	

3.3.2 Specific Gravity and Water Absorption Test

The specific gravity of an aggregate is known to be a sign of quality or strength of the material. Aggregates which have low specific gravity are generally seen to be weaker than those with higher specific gravity values. It is the ratio of the mass of a unit volume of aggregate to the mass of an equal volume of gas free distilled water at the stated temperature. It is also expressed as the ratio of the density of the aggregate particles to the density of water. The results of the Specific gravity test are given in **Table 3.3** as per IS: 2389.

Table 3.3 Results of specific Gravity Test for Aggregates

S. No.	Aggregate Size	Bulk Specific Gravity
1	Coarse Aggregate	2.638
2	Fine Aggregate	2.612
3	Filler	2.581

Water absorption is also one of the properties which give an idea of porosity and strength of the rock. Aggregates which have higher water absorption value are considered to be more porous and are not suitable for the construction of highways unless they are found to be acceptable based on strength, impact and hardness tests. The test method followed is as per IS: 2386 Part III [11]. Maximum limit allowed is 2% [11]. The results of the water absorption test are presented in **Table 3.4**.

Table 3.4 Results of water Absorption Test for Aggregate

Description/Trial No.	Trial 1	Trial 2
(a) Weight of saturated surface dry weight, g	2028	2030
(b) Weight of oven dry sample, g	2000	2000
(c) Water Absorption **100*(a-b)/b**	1.4	1.5
Average Absorption %	**1.45**	

Since the water absorption of the aggregates was less than 2%, Soundness test is not performed [11].

3.3.3 Los Angles Abrasion Test

Due to the movement of traffic, the aggregates used in the surface course of pavements are subjected to wearing action at the top surface. Hardness is the defined as the resistance to this wear and hence is an essential property for the road aggregates, especially when used in wearing course. The road aggregates should be hard enough to resist this abrasion due to the traffic movement. The Los Angles Abrasion Test is performed to evaluate the resistance to wear. The results of the abrasion are shown in **Table 3.5**.

Table 3.5 Results of Los Angles Abrasion Test

Description/Trial No.	Trial 1	Trial 2
Weight of Specimen, g (W_1)	5000	5000
Weight of Specimen after Abrasion test, retained on 1.70 mm sieve, g (W_2)	4078	4072
Los Angles Abrasion value (%) = **100*(W_1- W_2)/ W_1**	18.44	18.56
Average (%)	**18.5**	

3.4 GRADATION FOR STONE MATRIX ASPHALT

The gradation for the mix has been adopted as per guidelines of IRC: SP-79. Two different gradations are given in the specification, one for intermediate course and other for wearing course. We have adopted gradation for wearing course [16] and the gradation is given in **Table 3.6** while the gradation loop is shown in **Figure 3.2**. Midpoint gradation has been adopted as this gradation seems to exhibit better properties as compared with upper and lower point gradations.

As per MoRTH Specification, this work shall be constructed in a single or multiple layer of Stone Matrix Asphalt which has fibre-additives and shall be constructed over bituminous surface which has been prepared already. Stone Matrix Asphalt (SMA) has unique structure which includes the skeleton of a coarse aggregate skeleton so as to obtain the stone-on-stone contact, which will provides the high resistant against the rutting of bituminous course for heavy traffic roads. The SMA having nominal maximum aggregate size of 13 mm should be intended for use as wearing course with nominal layer thickness of 40 to 50mm. The SMA having nominal maximum aggregate size of 19 mm should be intended for use as intermediate course with nominal layer thickness of 45 to 75 mm. [16].

Table 3.6 Mid-Point Gradation for Stone Matrix Asphalt

Sieve Size (mm)	Limits as per IRC SP-79		Mid-value (Percentage Passing)	Cumulative percentage retained	Percentage retained
	Lower	Upper			
19	100	100	100	0	0
13.2	90	100	95	5	5
9.5	50	75	62.5	37.5	32.5

4.75	20	28	24	76	38.5
2.36	16	24	20	80	4
1.18	13	21	17	83	3
0.6	12	18	15	85	2
0.3	10	20	15	85	0
0.075	8	12	10	90	5
Pan	-	-	-	100	10

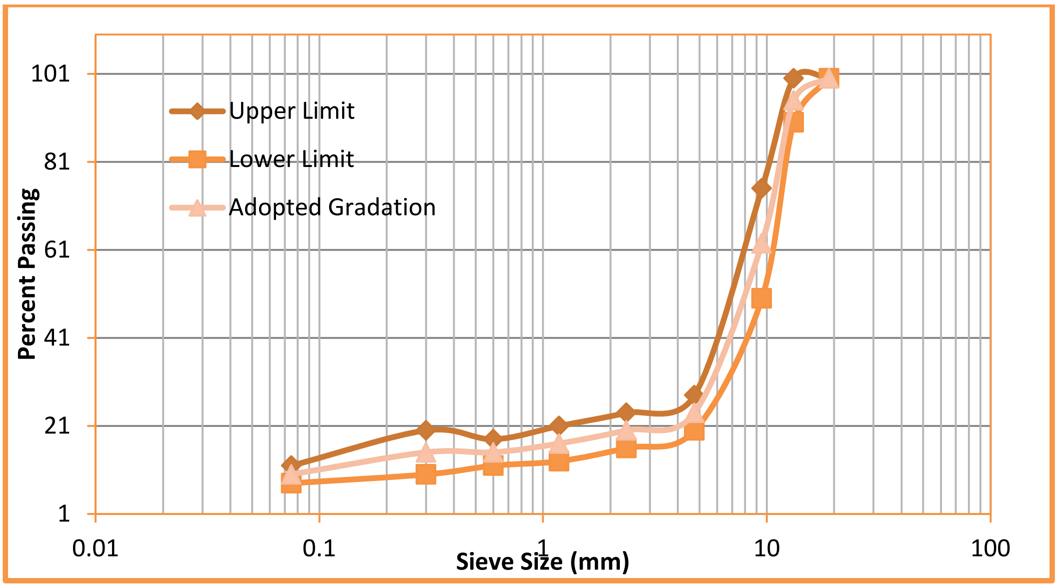

Figure 3.2 Gradation Loop for Stone Matrix asphalt

3.5 MARSHALL METHOD OF MIX DESIGN

3.5.1 General

The concepts of the Marshall method of designing bituminous mixtures were first introduced by Bruce Marshall, a former Bituminous Engineer in the Mississippi State Highway Department. It is a design methodology which is adopted worldwide for determining the strength and flow characteristics of the bituminous paving mixes. It is generally used for the design of bituminous mixes which can carry heavy traffic loads by fulfilling the requirements of the pavement surface characteristics. In India, this method is usually preferred to characterize the bituminous mixes and used to calculate the Optimum Binder Content (OBC) for different mixes.

3.5.2 Objective

The main objective of the Marshall Mix Design is to determine the Optimum Binder Content of a Stone Matrix Asphalt (SMA) mix by Marshall Method of Mix Design using various fibres as their additives such as coconut fibre, glass fibre and jute fibre. Further, the Marshall characteristics such as Marshall Stability, Flow value, Voids in Mineral Aggregates (VMA), Voids Filled with Bitumen (VFB), Unit Weight in mixture etc., of all these mixes were also studied and compared.

3.5.3 Outline of Method

The procedure for the Marshall method starts with the preparation of test specimens. The steps which are preliminary to specimen preparation are as follows:-

- All the materials which are used should meet the requirements of the project and the relevant codal specifications.
- The combinations of aggregate blending should meet the gradation requirements of the project.
- For performing the Volumetric Analysis, the bulk specific gravity of all types of aggregates used in the blend and the specific gravity of the bitumen which is used in the study should be determined.

3.5.4 Preparation of Test Specimen

The Marshall method, like other mix design methods, uses several trial aggregate-asphalt binder blends, each with different asphalt binder content. The aggregates and filler are mixed together in the desired proportion to fulfill the design requirements and the specified gradation. For casting the Marshall Sample, 1200 grams of aggregate are taken and mixed with corresponding bitumen content by weight of mix and 0.3% fibre by weight of mix at a mixing temperature of about 160 ^{0}C. The mixing of aggregates and bitumen should be done properly so that all aggregates are uniformly coated with bitumen. The Marshall mould, collar and the hammer are preheated in the oven.

The binder should be heated to a temperature of 120 ^{0}C - 165 ^{0}C. The weighed quantity of heated bitumen is added to the heated aggregate and the mixture is thoroughly mixed at the specified mixing temperature. The recommended mixing temperature for VG-30 grade of bitumen is about 160 ^{0}C.

Figure 3.3 Mixing of Aggregates and Binder

Samples are typically prepared at 0.5 percent by weight of mix increments, with at least two samples above the estimated asphalt binder content and two below.

Each sample is then heated to the anticipated compaction temperature and compacted with a Marshall hammer. The prepared sample should ideally be of 101.6 mm diameter and 63.5 mm thickness for bituminous concrete layer but in case of Stone Matrix Asphalt (SMA), diameter comes out to be 101.6 mm and thickness of 70 mm. However correction factors can be applied if the dimensions are not in the specified ranges. The specimen is compacted by giving 50 blows on each face of the sample (for SMA) by a hammer of weight 4.5 kg and a drop of 457 mm. Load is applied perpendicular to the axis of the specimen at a constant deformation rate of 51 mm per minute. In this research, total 36 samples were made for the Marshall Mix Design, 9 for each type of fibre mix for the calculation of Optimum Binder Content.

3.5.5 Testing of Specimen

The procedure which is used to test the Marshall specimen is as follows:-

1. Measure the height of the specimen by taking and averaging measurements at three or four locations of the specimen. The excess material should be brushed out from the edges of the specimen.

2. Each specimen is weighed in the air and its apparent weight is calculated by suspending it in water which will used to determine the specific gravity of each bituminous mixes (SMA).

3. Calculate the bulk density of the specimen.

4. The specimen which are to be tested are kept immersed under water in a thermostatically controlled water bath maintained at $60 \pm 1\ {}^{0}C$ for 30 to 40 minutes.

5. Remove the specimen from the water bath, then quickly dry the specimen and place it in the lower segment of the breaking head. Place the upper head on the specimen and place the whole assembly in position on the testing machine.

6. Apply deformation load at the rate of 51 mm per minute. Note the failure load on the proving ring and similarly analyze the deformation also.

Figure 3.4 Calculation of Apparent weight Suspending in water

Figure 3.5 Marshall Specimen of SMA mix with Cellulose Fibre

7.

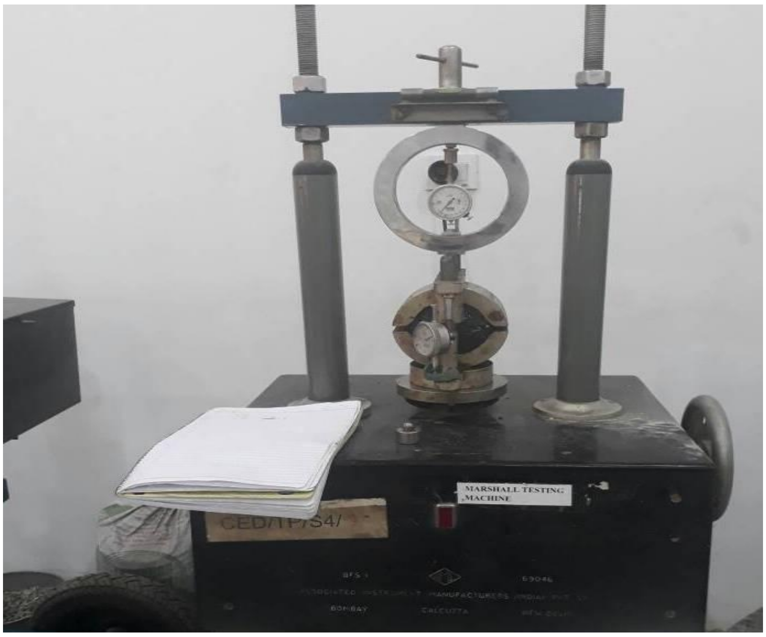

Figure 3.6 Marshall Apparatus

3.5.6 Volumetric Analysis

Marshall Method of Mix Design is used to determine the volume of asphalt binder and aggregates which is necessary to make a mixture Stone Matrix Asphalt with the desired properties. In Marshall Method of Mix Design, each compacted specimen undergoes the following analysis:

- Bulk Specific Gravity of the mix
- Theoretical Specific Gravity of the mix
- Percent Air Voids
- Percent Voids in Mineral Aggregate
- Percent Voids filled with Bitumen

3.5.6.1 Bulk specific gravity (G_{mb})

This can be determined by taking the weight of Marshall Sample in air and then in water. Saturated Surface Dry weight (SSD) is also taken by taking sample weight in air after taking weight in water so that the voids only on the surface of sample are filled. G_{mb} is then calculated as:

$$G_{mb} = \frac{Weight\ in\ air}{SSD\ weight - Weight\ in\ water}$$

3.5.6.2 Theoretical maximum specific gravity (G_{mm})

The theoretical maximum specific gravity is the specific gravity excluding air voids. Thus, theoretically, if all the air voids were eliminated from an SMA sample, the combined specific gravity of the remaining aggregate and asphalt binder would be the theoretical maximum specific gravity. This can be determined either by using following formula or by determining density of un-compacted mix using pycnometer method. The formula does not account for the bitumen absorbed by the aggregates but it can be used with negligible error:

$$G_{mm} = \frac{100 + c}{\frac{a}{X} + \frac{b}{Y} + \frac{c}{Z}}$$

Where

a, b = fraction of different aggregate blends in %,

c = Bitumen content in %

X, Y = Specific Gravity of a and b aggregates

Z = specific gravity of bitumen.

3.5.6.3 Air Voids Percent (V_v)

Air Voids V_v is the percentage of air voids by volume in the specimen and is calculated by

$$V_v = \frac{G_{mm} - G_{mb}}{G_{mm}}$$

Where,

G_{mm} is the Theoretical specific gravity of the mix.

G_{mb} is the bulk specific gravity of the mix.

3.5.6.4 Voids in Mineral Aggregate (VMA)

Voids in mineral aggregate is the volume of the voids in the aggregates and is sum of the air voids and the volume of bitumen and is given by

$$\mathrm{VMA} = \mathrm{V_v} + \mathrm{V_b}$$

3.5.6.5 Voids filled with Bitumen (VFB)

VFB are the voids in the mineral aggregates filled with the bitumen and is given by

$$VFB = \frac{V_b}{VMA} \times 100$$

3.6 Drain down Test

This test is done specially for the mixture such as Stone Matrix Asphalt and Open Graded Asphalt in which we require to calculate the binder drain down of an uncompacted mix. Drain Down is defined as the portion of mix which leaves itself from the sample and flows downwards when it is held at high temperatures. This problem can be faced during the transport, placement and production storage of the mixture and is significant for the mixtures having high coarse aggregate content i.e. Stone Matrix Asphalt in which voids are much larger as compared to uncompacted mix which results in high drain down as comparison to other conventional mixes [4]. Total 8 samples were made for the drain down test, 2 for each type of fibre mix after calculating their respective optimum binder content.

Drain Down test is conducted as per AAHTO T305 on the mixture prepared at optimum binder content and is poured into the wire basket having a sieve cloth of size 6.3 mm [4].

A catch plate is then taken and weighed and the wire basket above with the mixture poured in it is also weighed. The basket is then placed over the catch plate and kept in an oven for 1 hour ± 5 min. at 120 °C to 175 °C with ± 2°C of the set temperature.

Figure 3.7 Empty Bucket and Bucket with SMA mix in the Oven

After 1 hour, the binder from the mixture is drained into the catch plate and is again weighed. The drain down is calculated as a percentage of the mass retained to the total mass of the mixture.

Drain Down (%) = {(Z-Y)/(X-W)}×100

Where,

W = Mass of empty wire basket, g

X = Mass of wire basket with sample, g

Y= Mass of empty plate, g

Z = Mass of catch plate with drained sample, g

3.7 Indirect Tensile Strength (ITS) Test

The Indirect Tensile Strength value is a significant parameter since the resistance to fatigue cracking in the pavement is directly dependant on the tensile properties of the mixture. Therefore, ITS is an indicator of the tensile strength of the mix which provides resistance against the failure by fatigue, rutting and temperature cracking.

Just like cement concrete mix, there is no direct method to determine the tensile strength of bituminous mix. Hence the tensile strength is measure indirectly by splitting tensile test. In this test, a compressive load is applied on a cylindrical Marshall Mix specimen by loading the cylindrical specimen in a direction across its vertical diametrical plane at a specified rate of deformation i.e. 50 mm/minute. Total 8 samples were made for the ITS test, 2 for each type of fibre mix after calculating their respective optimum binder content.

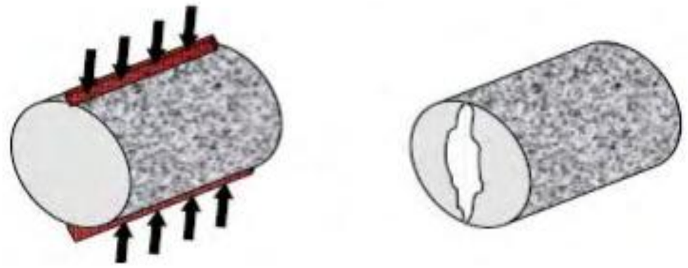

Figure 3.8 loading Configuration of Indirect Tensile Strength (ITS) Test

The test is conducted as per ASTM D 6931. Samples casted are kept for conditioning for about 3-4 hours at 25^{o}C and then tested for Dry ITS [5].

The loading strip is 12.7 mm wide and 70 mm long. ITS can be calculated using the following equation:-

$$\text{ITS (KPa)} = \frac{2000 \times P}{\pi \times d \times h}$$

Where,

P= maximum load in Newton,

d= diameter of sample in mm,

h= height of sample in mm

Chapter 4

RESULTS AND DISCUSSIONS

4.1 General

This chapter discusses the results obtained from the laboratory investigations of the Stone Matrix Asphalt (SMA) mixes designed using Marshall method of Mix Design with different addition of various additives such as coconut fibre, glass fibre and jute fibre. All achieved prepared Marshall Mix specimen were subjected to compaction of 50 blows on each face to achieve the required density. Stability-Flow analysis and Volumetric analysis were performed for all prepared specimens to determine the Optimum Binder Content (OBC) for all types of fibres used in the study. In addition to Marshall Mix method, other tests such as Drain down Test and Indirect Tensile Strength (ITS) Test were also conducted and the results were compared for the different fibres used. The Indirect Tensile Strength results were used to calculate Resilient Modulus for each type of fibre using an empirical equation from the previous literature. The resilient modulus were then compared for different fibres additions.

4.2 Bitumen Testing

Various tests were conducted on the asphalt binder sample like penetration test, specific gravity test and softening point test etc. The penetration test was conducted to obtain the consistency of asphalt binder at specified temperature and assign the grade of asphalt while softening point test is used to obtain temperature for the bitumen melt. The test results for these different properties of bitumen are shown in Table

Table 4.1 Tests results of Bitumen Used

S. No.	Description	Test Results	Value specified in IS:73-2013
1.	Penetration Test (mm) at 25^{0}C	50	45 (min.)
2.	Specific gravity Test	1.01	0.97 - 1.02
3.	Softening Point Test, ^{0}C, minimum	52	47 (min.)
4.	Viscosity Test at 60 ^{0}C, (Poise)	3050	2400-3600

4.3 Aggregate Testing

Aggregate testing was conducted to check the various specified properties of the mineral aggregates and the test results were compared with MoRTH's and IRC:SP:79-2008 specifications. The test results are presented and compared with allowable values in **Table 4.2**.

Table 4.2 Tests Results conducted on Aggregates Used

Property	Results	IRC:SP: 79-2008 requirements
Aggregate Impact Value	17.27 %	24 % max.
Los Angles Abrasion Value	18.5 %	25 % max.
Water Absorption	1.45 %	2 % max.
Specific Gravity Test	2.638	-

4.4 Results of Stone Matrix Asphalt (SMA) Mix Design for Wearing Course Using Cellulose Fibre

To decide the optimum binder content (OBC), Marshall Mix samples were prepared by varying the percentage of VG-30 grade of bitumen as a conventional mix i.e. using cellulose fibre. Stability-Flow laboratory analysis and Volumetric analysis were performed for the Marshall Mix samples with binder content varying from 6% to 7% by weight of mix. The test values were obtained and plotted graphically. The output results of stability and flow values are shown in **Table 4.3** and **Figure 4.1 to 4.5.** From the graphs plotted in **Figure 4.1 to 4.5**, the optimum binder content comes out to be 7.1% by weight of aggregates using stability-flow values.

Table 4.3 Marshall Tests Results for SMA Mix with Cellulose Fibre

S. No.	Binder content by Wt. of Mix (%)	Bulk Density (gm/cc)	Air Voids (%) Vv	VMA (%)	VFB (%)	Corrected Stability (kg)	Flow Value (mm)
1	6	2.24	5.6	20.04	67.16	688	3.2
2	6.5	2.28	4.2	20.41	78.89	1003	3.53
3	6.75	2.3	3.7	20.64	88.51	988.9	4.25

4	7	2.28	3.52	20.89	90.12	795.5	5.65

The above table signifies that the maximum stability comes out to be 997.36 kg at bitumen content 7.1% by wt. of aggregates using cellulose fibre. With addition of more binder, the stability value starts getting decreasing.

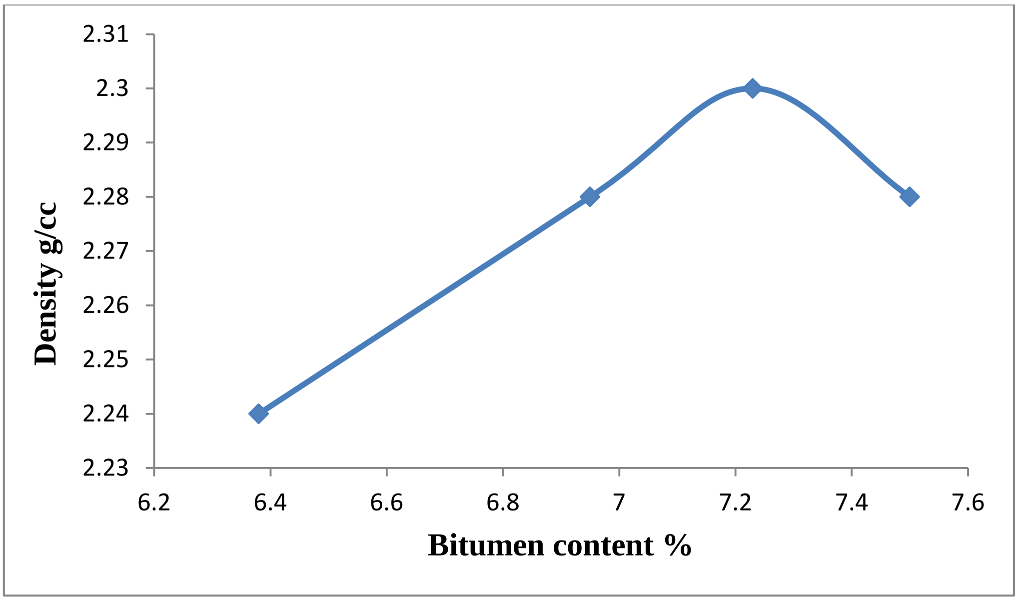

Figure 4.1 Variation of Bulk Density with Binder Content

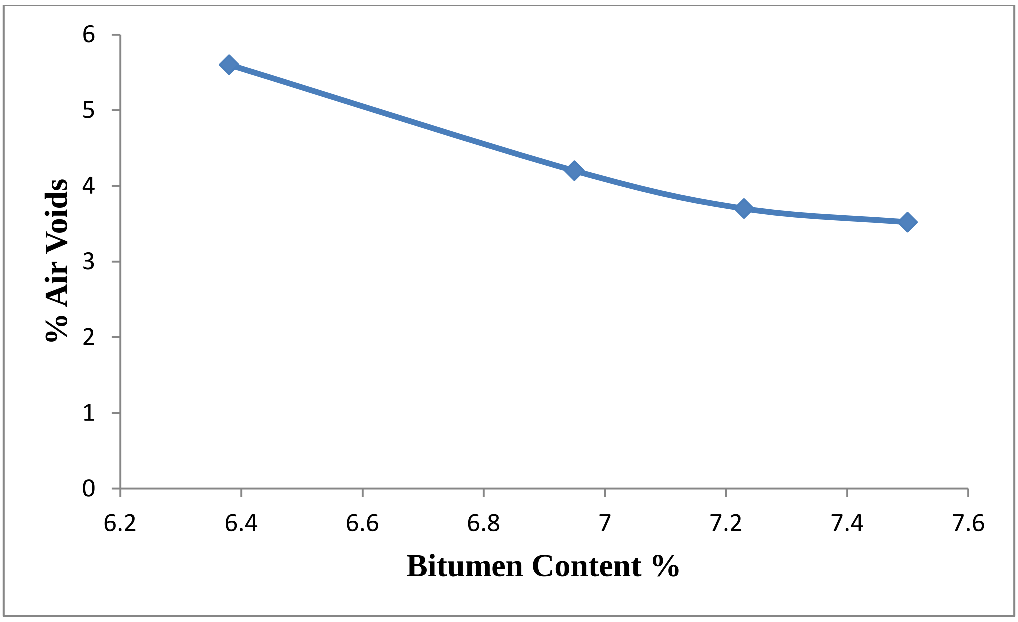

Figure 4.2 Variation of Air Voids with Binder Content

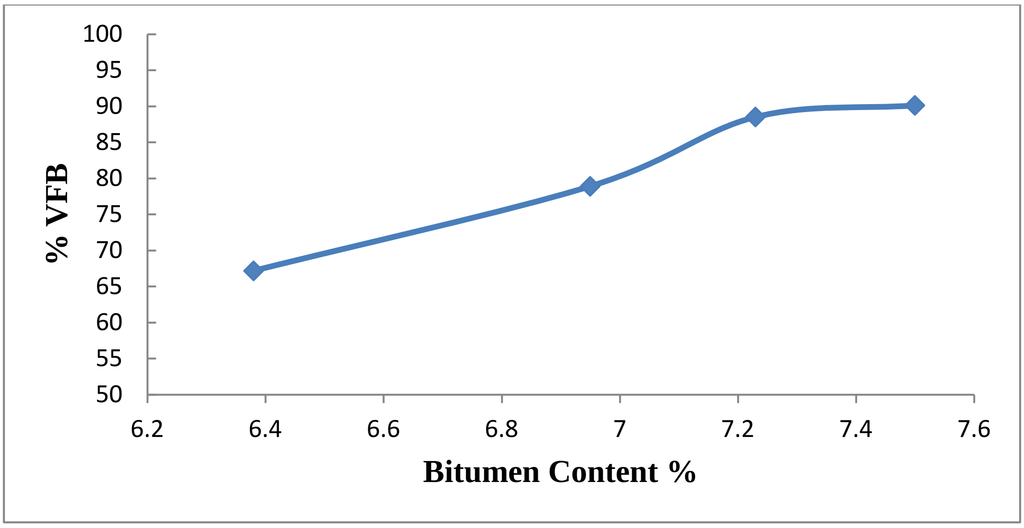

Figure 4.3 Variation of VFB with Binder Content

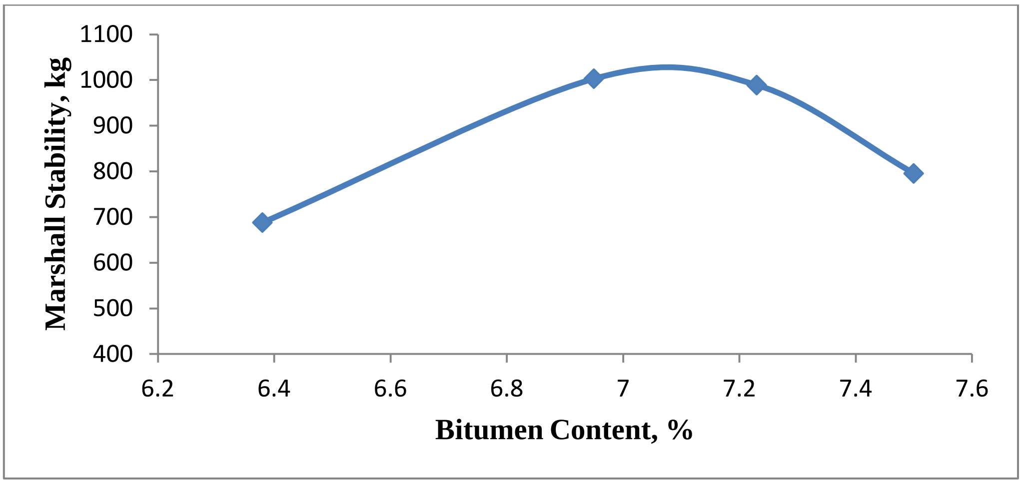

Figure 4.4 Variation of Marshall Stability with Binder Content

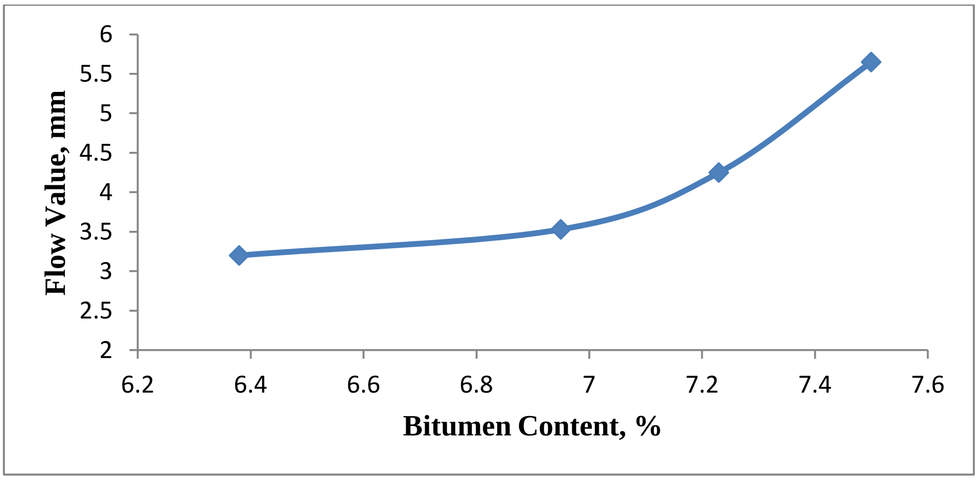

Figure 4.5 Variation of Flow Value with Binder Content

From the above graphs obtained, the Optimum Binder Content (OBC) is calculated as follows:

- Max Stability = 7.1 percent bitumen content
- Max Bulk Density = 7.27 percent bitumen content
- 4% Air Voids = 6.95 percent bitumen content

The Optimum Bitumen Content at is the average of three values above = 7.1 % by wt. of aggregates.

The result shows the optimum binder content at 6.6% by wt. of mix.

4.5 Results of Stone Matrix Asphalt (SMA) Mix Design for Wearing Course Using Coconut Fibre

To calculate the optimum binder content (OBC), Marshall Mix samples were prepared by varying the percentage of VG-30 grade of bitumen using coconut fibre. Stability-Flow laboratory analysis and Volumetric analysis were performed for the Marshal Mix samples with binder content varying from 6% to 7% by weight of mix. The test values were obtained and plotted graphically. The output results of stability and flow values are shown in **Table 4.4** and **Figure 4.6 to 4.10**. From the graphs plotted in **Figure 4.6 to 4.10**, the optimum binder content comes out to be 6.92% by weight of aggregates using stability-flow values.

Table 4.4 Marshall Tests Results for SMA Mix with Coconut Fibre

S. No.	Binder content by Wt. of Mix (%)	Bulk Density (gm/cc)	Air Voids (%) Vv	VMA (%)	VFB (%)	Corrected Stability (kg)	Flow Value (mm)
1	6	2.251	5.23	20.34	69.93	649.93	4.47
2	6.5	2.288	3.94	20.9	80.24	742.47	4.6
3	7	2.242	3.90	21.1	83	584.8	5.1

The above table signifies that the maximum stability comes out to be 742.47 kg at bitumen content 6.92% by wt. of aggregates using coconut fibre. With addition of more binder, the stability value starts getting decreasing.

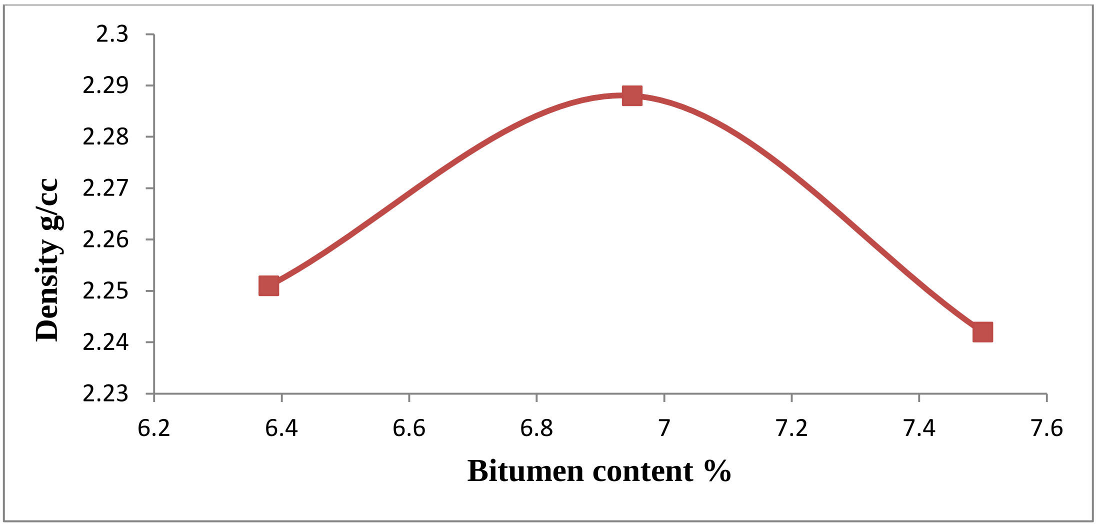

Figure 4.6 Variation of Bulk Density with Binder Content

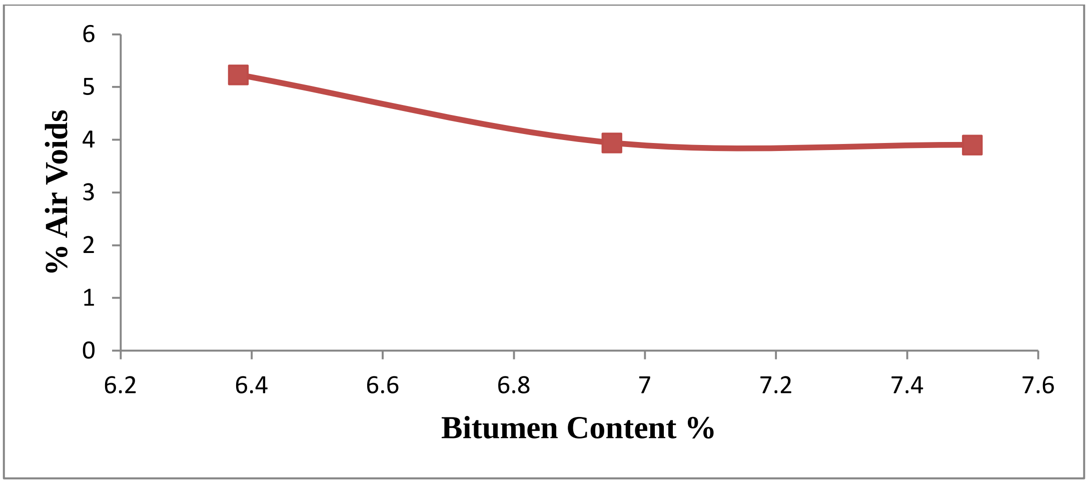

Figure 4.7 Variation of Air Voids with Binder Content

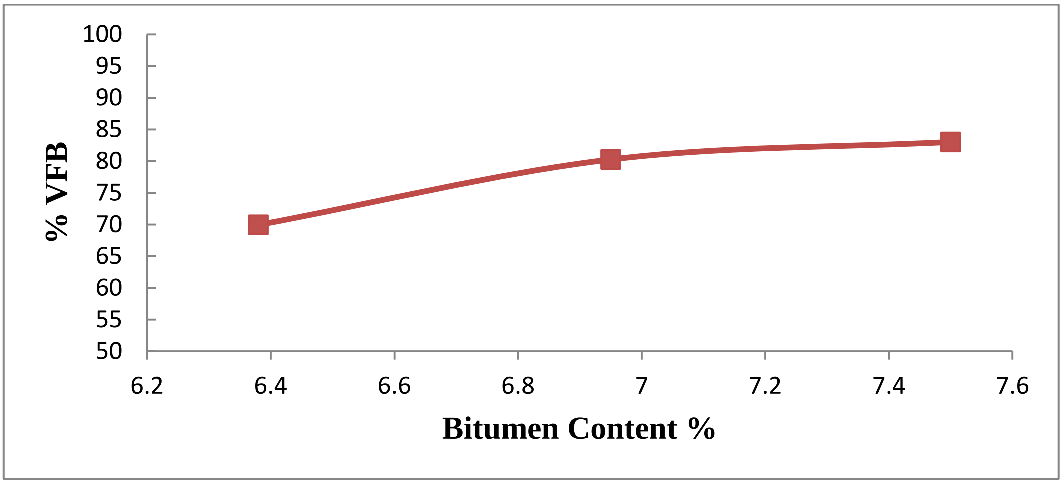

Figure 4.8 Variation of VFB with Binder Content

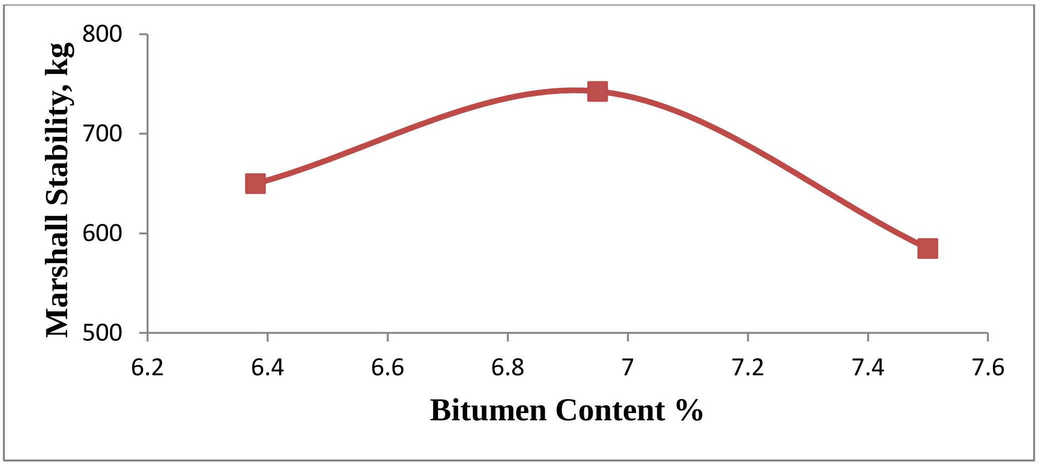

Figure 4.9 Variation of Marshall Stability with Binder Content

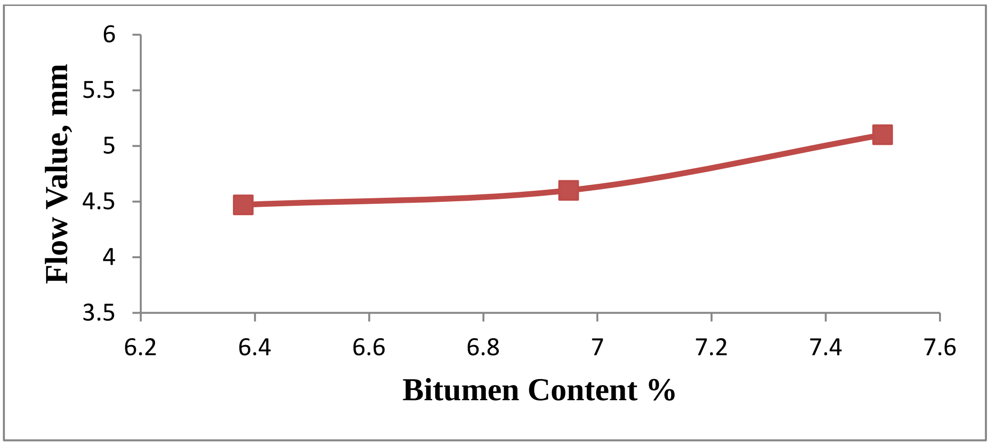

Figure 4.10 Variation of Flow Value with Binder Content

From the above graphs obtained, the Optimum Binder Content (OBC) is calculated as follows:

- Max Stability = 6.95 percent bitumen content
- Max Bulk Density = 6.95 percent bitumen content
- 4% Air Voids = 6.87 percent bitumen content

The Optimum Bitumen Content at is the average of three values above = 6.92 % by wt. of aggregates.

The result shows the optimum binder content at 6.47% by wt. of mix.

4.6 Results of Stone Matrix Asphalt (SMA) Mix Design for Wearing Course Using Glass Fibre

To decide the optimum binder content (OBC), Marshall Mix samples were prepared by varying the percentage of VG-30 grade of bitumen using glass fibre. Stability-Flow laboratory analysis and Volumetric analysis were performed for the Marshal Mix samples with binder content varying from 6% to 7% by weight of mix. The test values were obtained and plotted graphically. The output results of stability and flow values are shown in **Table 4.5** and **Figure 4.11 to 4.15**. From the graphs plotted in **Figure 4.11 to 4.15**, the optimum binder comes content out to be 6.95% by weight of aggregates using stability-flow values.

Table 4.5 Marshall Tests Results for SMA Mix with Glass Fibre

S. No.	Binder content by Wt. of Mix (%)	Bulk Density (gm/cc)	Air Voids (%) Vv	VMA (%)	VFB (%)	Corrected Stability (kg)	Flow Value (mm)
1	6	2.245	5.11	20.08	69.03	607.73	4.33
2	6.5	2.248	3.99	20.49	77.23	751.07	4.57
3	7	2.215	3.89	20.93	85.6	662.2	4.87

The above table signifies that the maximum stability comes out to be 751.07 kg at bitumen content 6.95% by wt. of aggregates using glass fibre. With addition of more binder, the stability value starts getting decreasing.

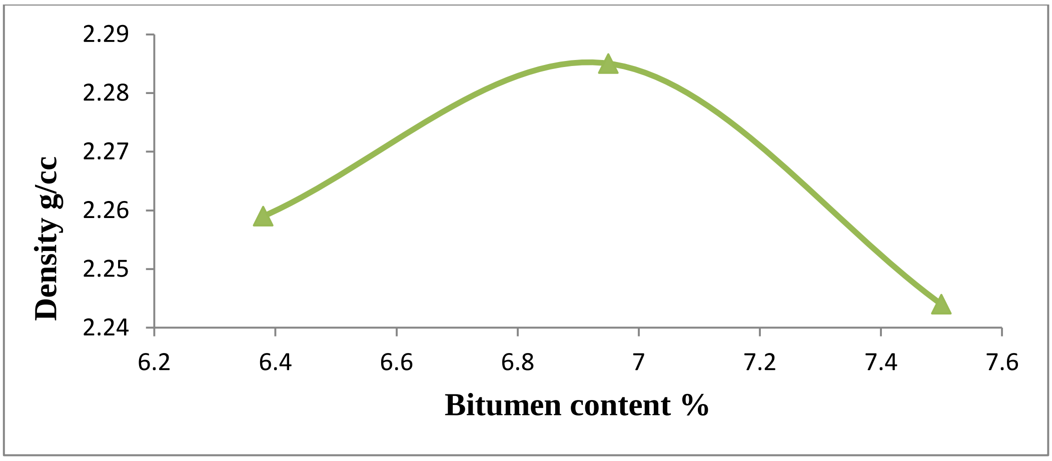

Figure 4.11 Variation of Bulk Density with Binder Content

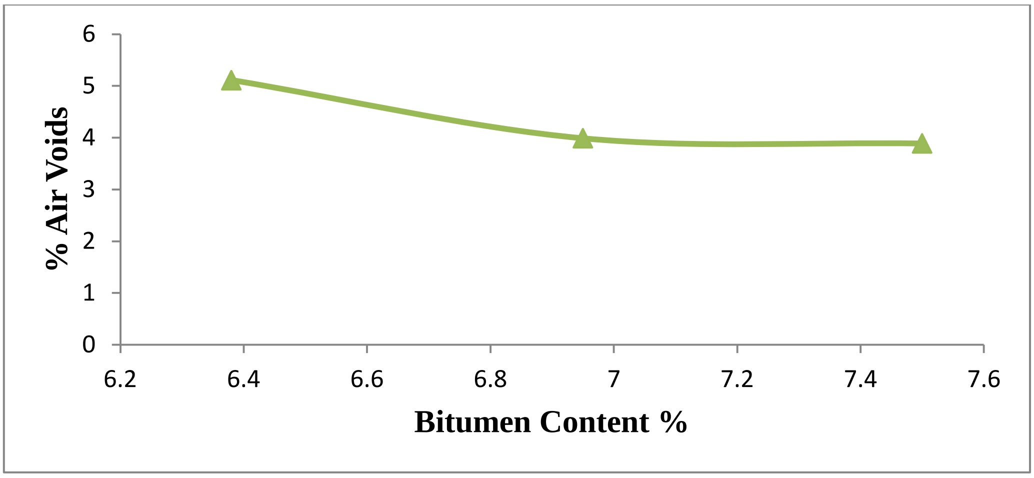

Figure 4.12 Variation of Air Voids with Binder Content

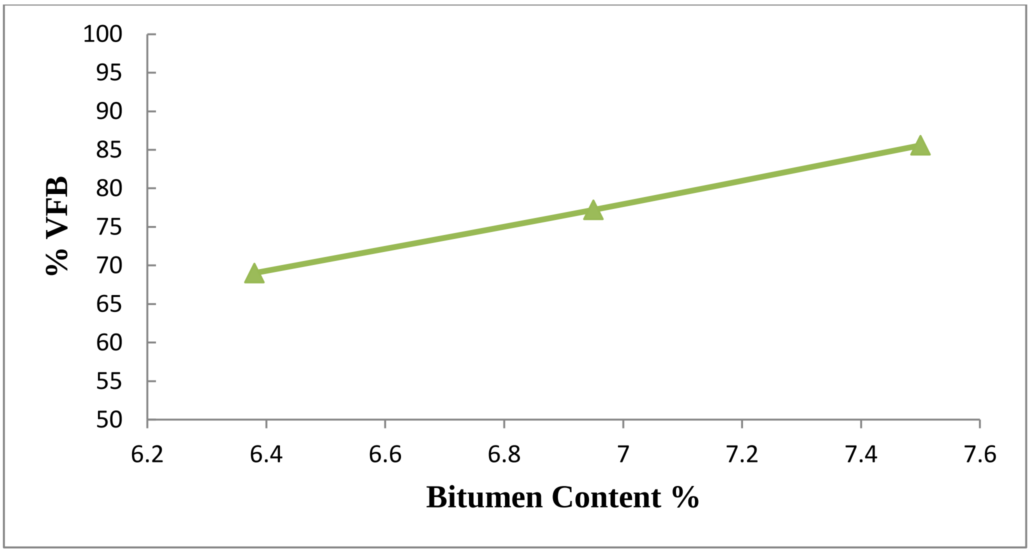

Figure 4.13 Variation of VFB with Binder Content

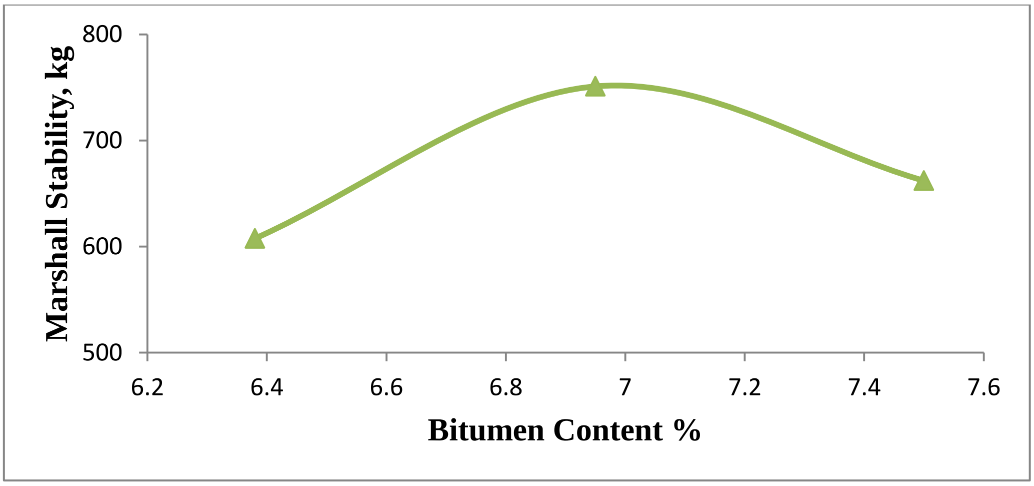

Figure 4.14 Variation of Marshall Stability with Binder Content

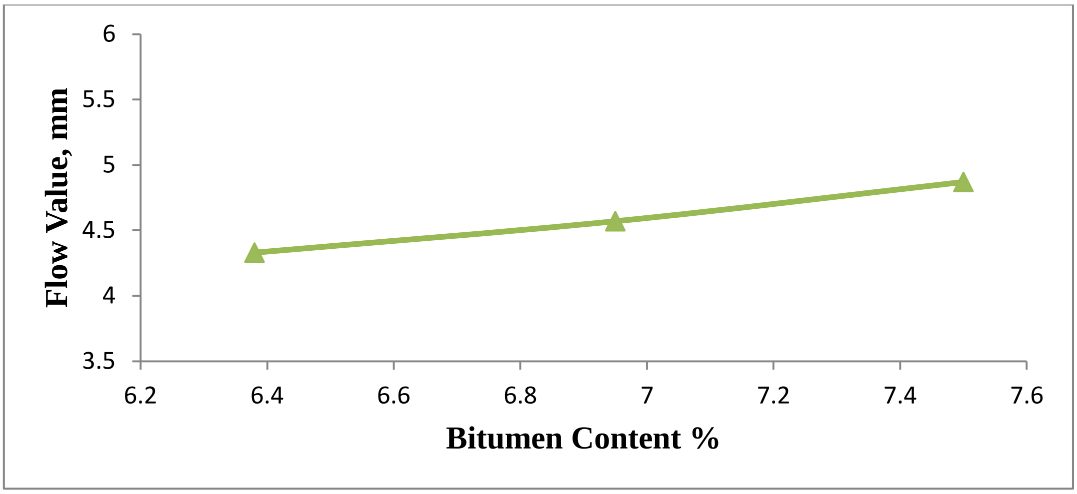

Figure 4.15 Variation of Flow Value with Binder Content

From the above graphs obtained, the Optimum Binder Content (OBC) is calculated as follows:

- Max Stability = 6.95 percent bitumen content
- Max Bulk Density = 6.95 percent bitumen content
- 4% Air Voids = 6.95 percent bitumen content

The Optimum Bitumen Content at is the average of three values above = 6.95 % by wt. of aggregates.

The result shows the optimum binder content at 6.5% by wt. of mix.

4.7 Results of Stone Matrix Asphalt (SMA) Mix Design for Wearing Course Using Jute Fibre Fibre

To decide the optimum binder content (OBC), Marshall Mix samples were prepared by varying the percentage of VG-30 grade of bitumen using jute fibre. Stability-Flow laboratory analysis and Volumetric analysis were performed for the Marshal Mix samples with binder content varying from 6% to 7% by weight of mix. The test values were obtained and plotted graphically. The output results of stability and flow values are shown in **Table 4.6** and **Figure 4.16 to 4.20**. From the graphs plotted in **Figure 4.16 to 4.20**, the optimum binder content comes out to be 6.95% by weight of aggregates using stability-flow values.

Table 4.6 Marshall Tests Results for SMA Mix with Jute Fibre

S. No.	Binder content by Wt. of Mix (%)	Bulk Density (gm/cc)	Air Voids (%) Vv	VMA (%)	VFB (%)	Corrected Stability (kg)	Flow Value (mm)
1	6	2.263	5.647	19.94	71.68	774	4.27
2	6.5	2.296	3.547	20.51	81.67	957.47	4.4
3	7	2.267	3.2	20.8	87.25	731	5.27

The above table signifies that the maximum stability comes out to be 957.47 kg at bitumen content 6.95% by wt. of aggregates mix using jute fibre. With addition of more binder, the stability value starts getting decreasing.

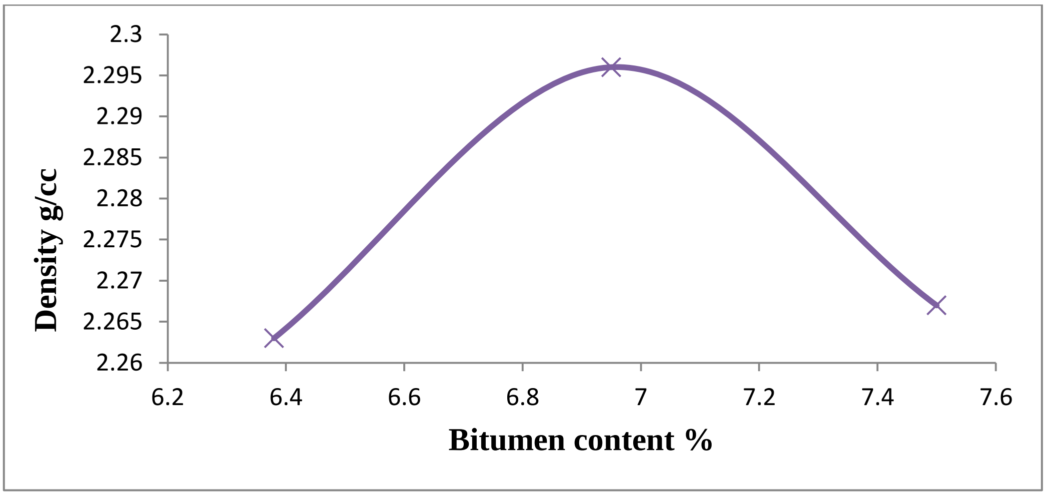

Figure 4.16 Variation of Bulk Density with Binder Content

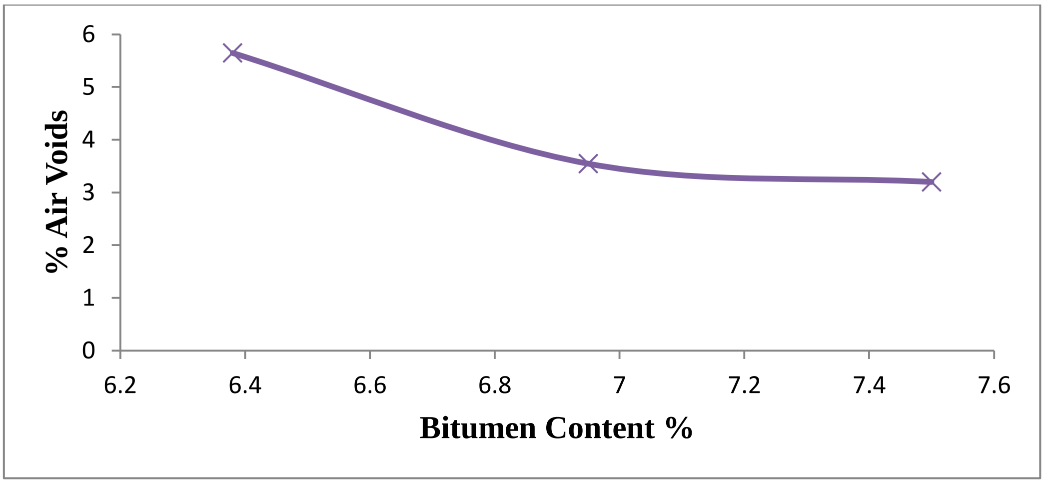

Figure 4.17 Variation of Air Voids with Binder Content

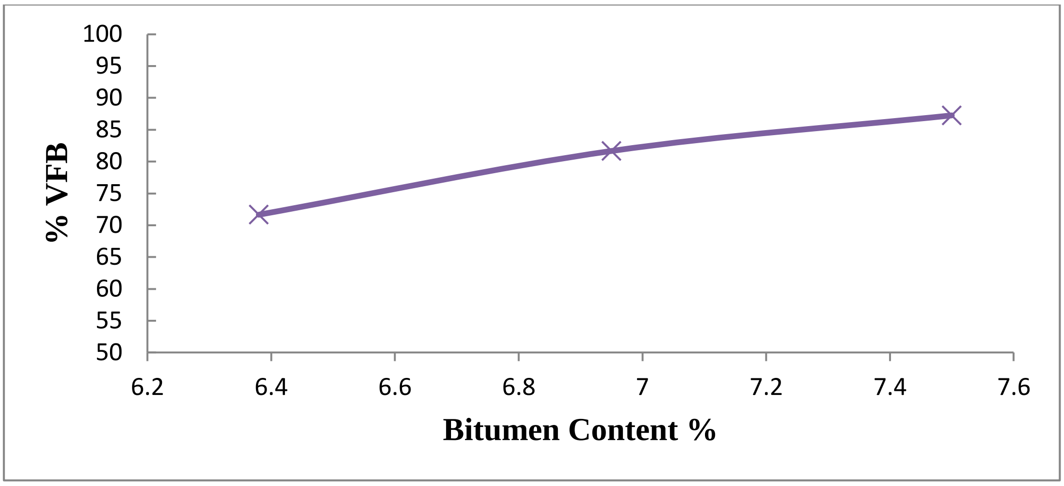

Figure 4.18 Variation of VFB with Binder Content

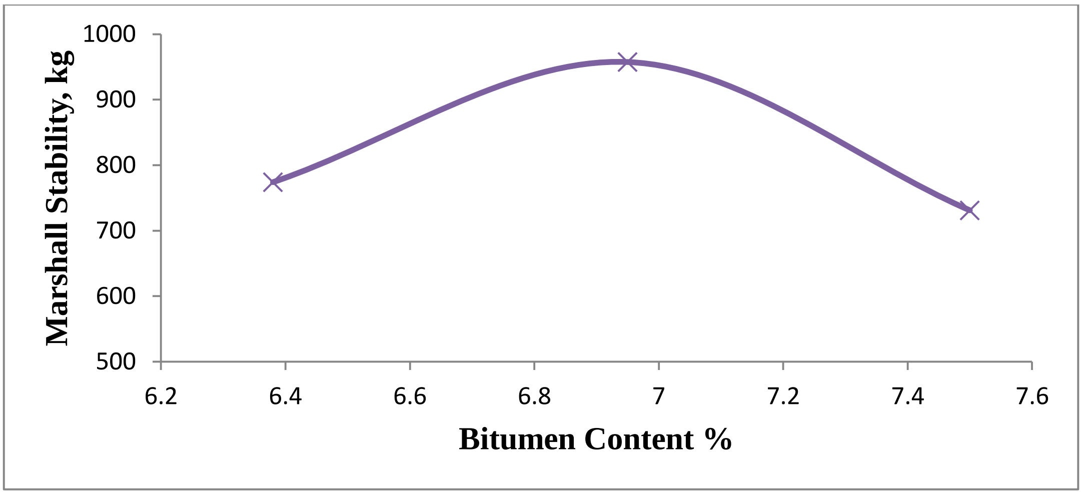

Figure 4.19 Variation of Marshall Stability with Binder Content

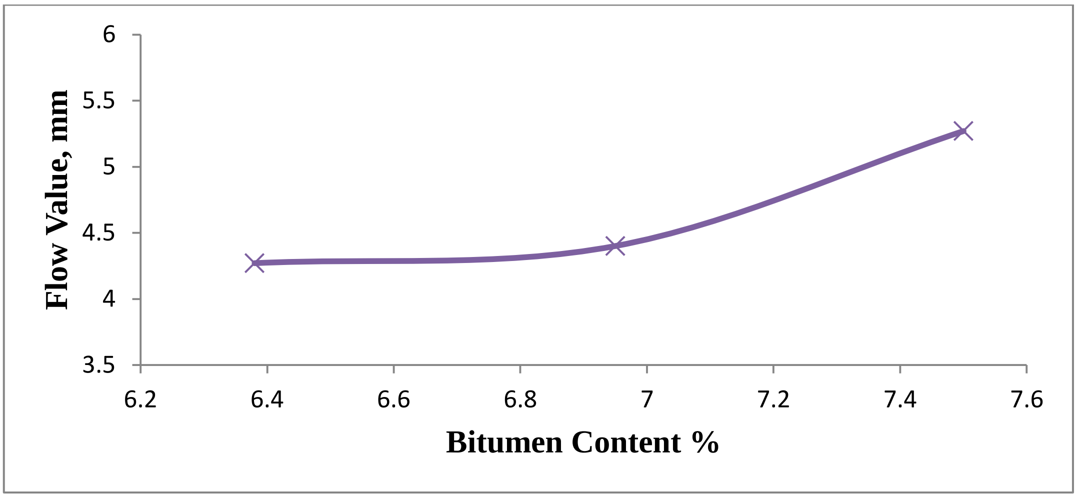

Figure 4.20 Variation of Flow Value with Binder Content

From the above graphs obtained, the Optimum Binder Content (OBC) is calculated as follows:

- Max Stability = 6.95 percent bitumen content
- Max Bulk Density = 6.95 percent bitumen content
- 4% Air Voids = 6.93 percent bitumen content

The Optimum Bitumen Content is the average of three values above = 6.95 % by wt. of aggregates.

The result shows the optimum binder content at 6.5% by wt. of mix.

4.8 Calculation of Indirect Tensile Strength (ITS)

The Indirect Tensile Strength Test was conducted on various Stone Matrix Asphalt mixtures like mixtures using cellulose fibre, coconut fibre, glass fibre and jute fibre using their respective optimum binder content. ITS was conducted on all the specimen at room temperature. The Indirect Tensile Strength of the test specimen was calculated in accordance with ASTM D 6931-12 using the following equation:

$$\text{ITS (KPa)} = \frac{2000 \times P}{\pi \times d \times h}$$

Where,

P= maximum load in Newton. It is the failure load as recorded from the proving ring.

d= diameter of sample in mm,

h= height of sample in mm

Figure 4.21 shows one of the tested specimens which have a crack along the diameter as in Split Tensile Strength Test.

Figure 4.21 Failed Specimen due to ITS Test

Table 4.7 shows the results of Indirect Tensile Strength Test for different types of Stone Matrix Asphalt (SMA) mixes using different fibres as their additives. ITS value was calculated for different fibres using their respective optimum binder content (OBC).

Table 4.7 Results of ITS Test for Different Fibres

Sample	Failure Load (N)	Sample Diameter (mm)	Sample Thickness (mm)	ITS (kPa)
SMA 1 with cellulose fibre	3200	101	70	288.3
SMA 2 with cellulose fibre	3300	101	70	297.3
Average				**292.8**
SMA 1 with coconut fibre	3000	101	69.5	272.22
SMA 2 with coconut fibre	3100	101	69	283.33
Average				**277.775**
SMA 1 with Glass fibre	3600	101	71	319.76
SMA 2 with Glass fibre	3650	101	71	324.2
Average				**321.98**
SMA 1 with Jute fibre	4200	101	71	373.05
SMA 2 with Jute fibre	4400	101	71	390.81
Average				**381.93**

4.9 Calculation of Drain down

Drain Down test is conducted as per AASHTO T305 on the mixture prepared using different fibres at their respective optimum binder content (OBC). Drain down is a very important factor for the gap graded or open graded mixture such as Stone Matrix Asphalt (SMA) during their production, placing and storage. **Table 4.8** shows the result of drain down percentages obtained from the test for different fibres.

Table 4.8 Results of Drain down Test for Different Fibres

Type of additive	Drain down (%)
Cellulose Fibre	0.156
Coconut Fibre	0.158
Glass Fibre	0.235
Jute Fibre	0.158

Results from the drain down test shows that the all four mixtures prepared using different fibres exhibit drain down percentage well within the specified limit (i.e. 0.3% max.) according to the IRC:SP:79-2008.

4.10 Calculation of Resilient Modulus

The Resilient Modulus (M_R) is a measure of material stiffness. A material's resilient modulus is actually an estimate of its modulus of elasticity (E). An empirical relation has been taken [9] based on ITS and corresponding Resilient Modulus values from past literature [15-20]. Following relation between ITS and Resilient Modulus has been used:

$$M_r = 0.1423 * ITS^6 - 4.7707 * ITS^5 + 54.255 * ITS^4 - 218.3 * ITS^3 - 11.614 * ITS^2 + 1362.6 * ITS + 1785.1 \quad (4.1)$$

Where,

M_r = Resilient Modulus value in MPa

ITS= Indirect Tensile Strength value in MPa

The above equation has been developed using polynomial regression and has an R squared value of 0.8809. Based on **Equation 4.1** the Resilient Modulus is calculated for all SMA mixes and is shown in **Table 4.9**:

Table 4.9 Results of Resilient Modulus for Different Fibres

Sample	ITS (MPa)	Resilient Modulus (MPa)
Cellulose Fibre	0.2928	2177.982
Coconut Fibre	0.27776	2158.317
Glass Fibre	0.32198	2215.906
Jute Fibre	0.38193	2292.778

4.11 Comparison of Mix Design Using Different Fibres

Stone Matrix Asphalt (SMA) mixes were designed using different fibres such as cellulose fibre, coconut fibre, glass fibre and jute fibre. Marshall Stability and other Volumetric properties were also obtained for mixes with different fibres. These values were then compared with each other. **Table 4.10** shows the comparison between the volumetric properties for different fibres.

Table 4.10 Effect of different Fibres on Marshall Properties of SMA

Volumetric Properties	Results of SMA Mix			
	Cellulose Fibre	**Coconut Fibre**	**Glass Fibre**	**Jute Fibre**
OBC, (% by wt. of mix)	6.64	6.47	6.5	6.5
Density, g/cc	2.3	2.288	2.285	2.296
Air Voids, %	3.92	4.064	3.99	3.547
VMA, %	20.5	20.81	20.49	20.51
VFB, %	84.5	79.84	77.23	81.67
Stability, kg	997.36	742.47	751.07	957.47
Flow Value, mm	3.8	4.52	4.57	4.4

It can be clearly seen from the above table, that the reference SMA mix with cellulose fibre has higher stability as compared to the other mixes. Further, it can also be concluded that there is no such difference in Optimum Binder Content (OBC) of SMA mixes modified with different types of fibres.

Figure 4.22 to 4.26 shows the graphs having the difference in the Marshall properties of Stone Matrix Asphalt (SMA) mixes using different fibres as their stabilizer additives.

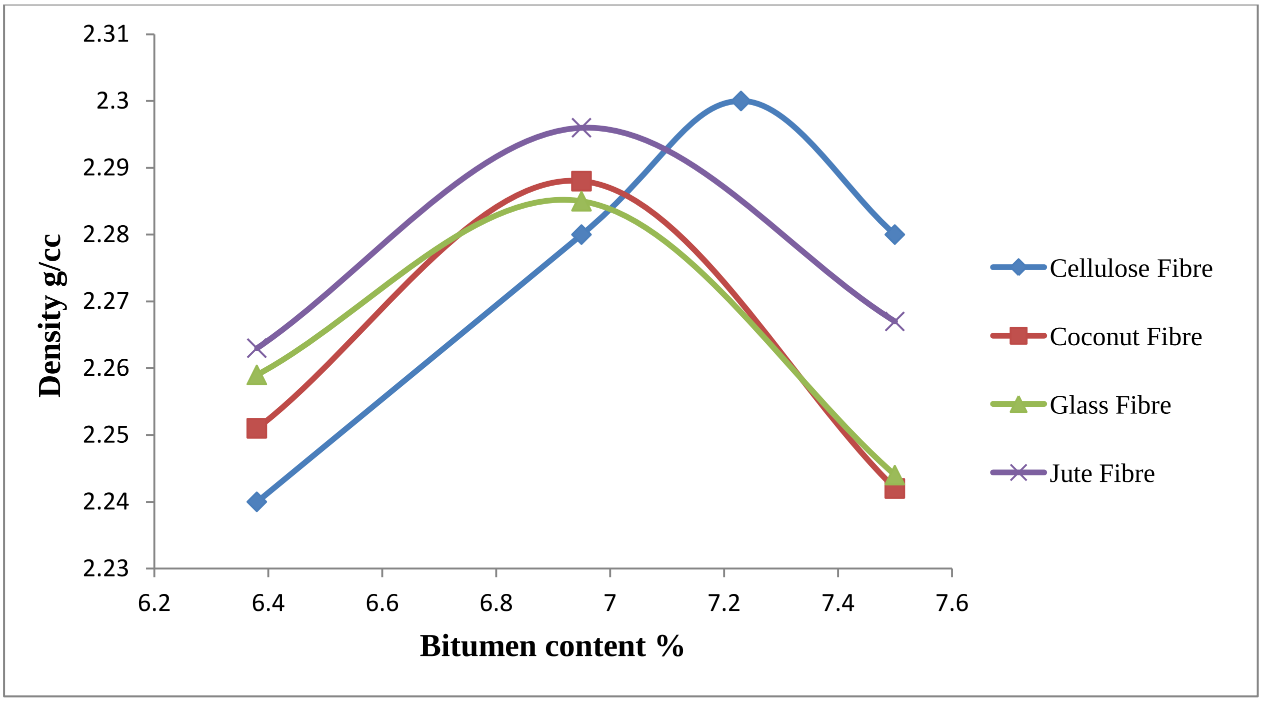

Figure 4.22 Variation of Density with Binder Content for Different Fibres

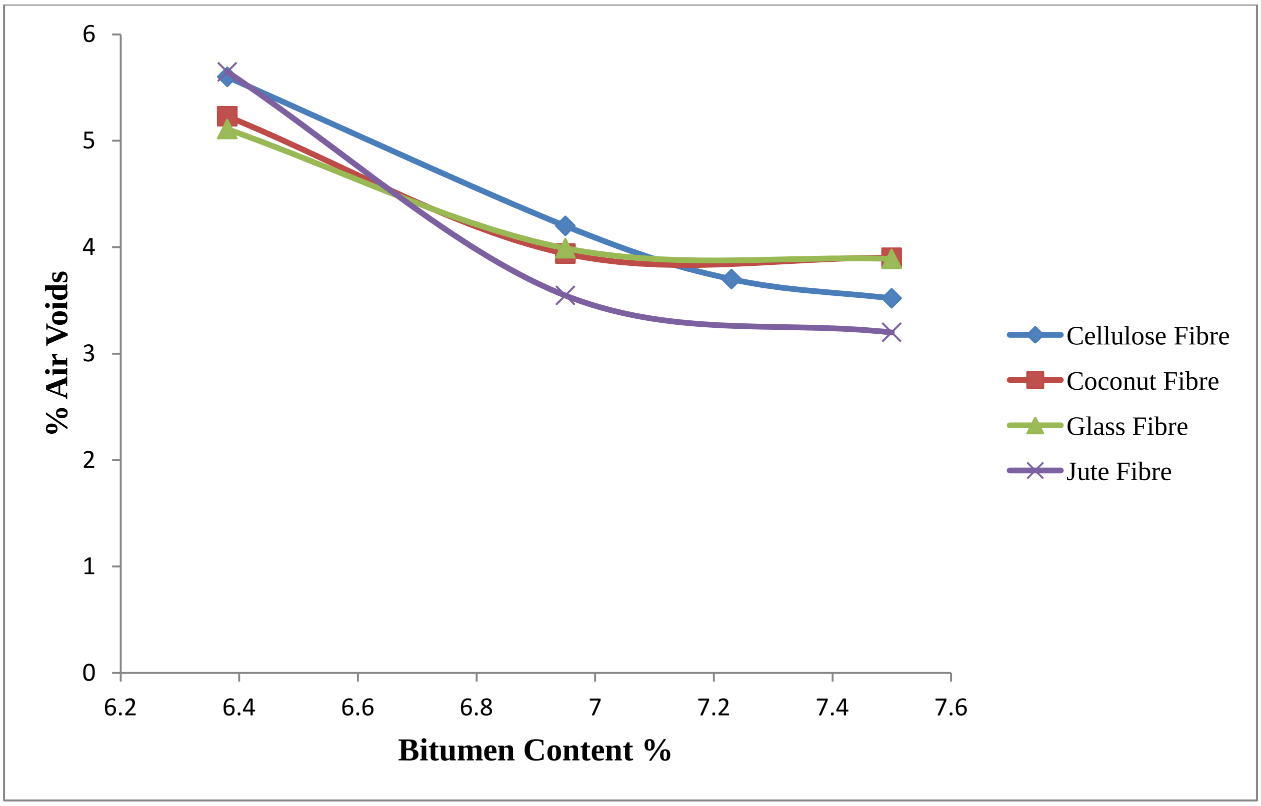

Figure 4.23 Variation of Air Voids with Binder Content for Different Fibres

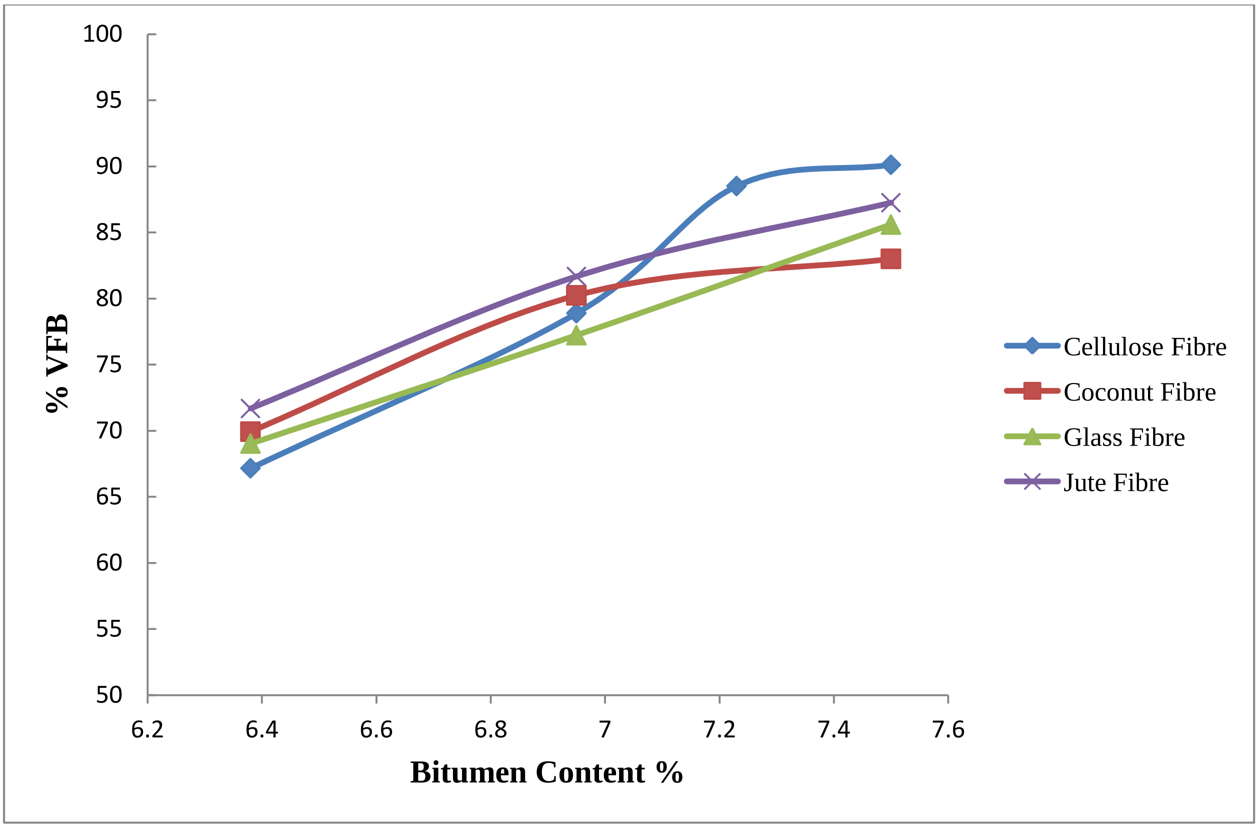

Figure 4.24 Variation of VFB with Binder Content for Different Fibres

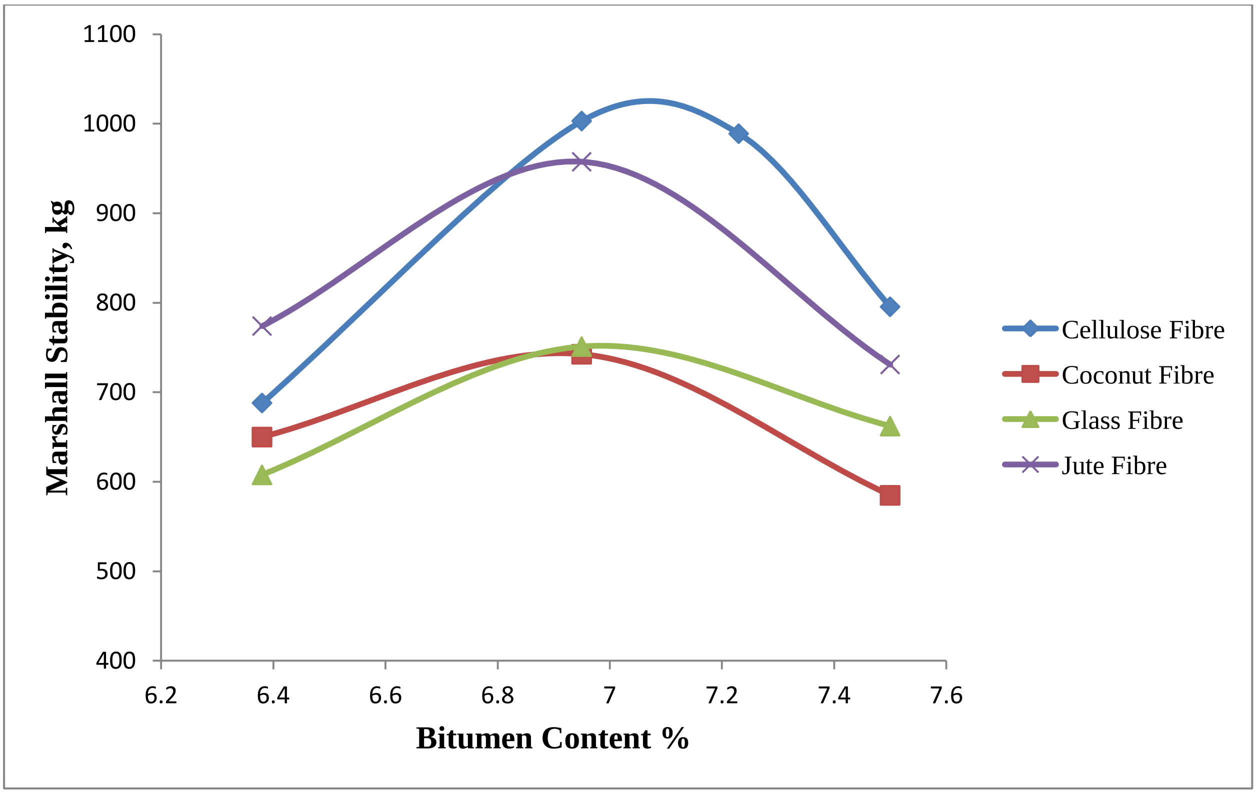

Figure 4.25 Variation of Marshall Stability with Binder Content for Different Fibres

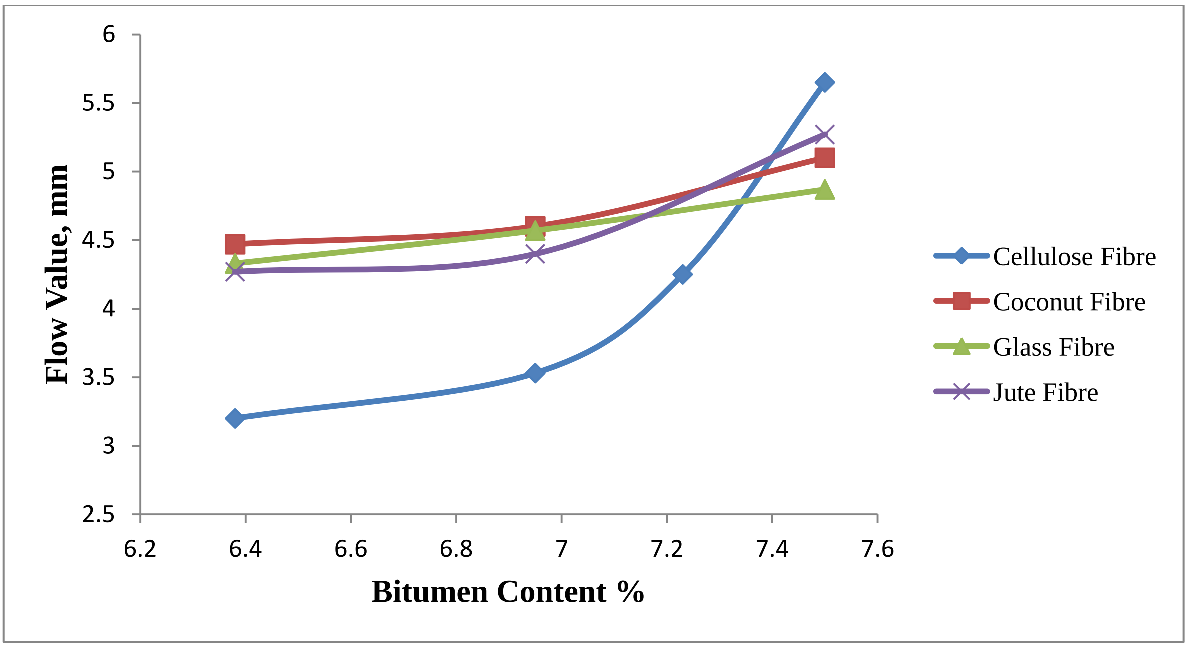

Figure 4.26 Variation of Flow Value with Binder Content for Different Fibres

4.12 Comparison of Indirect Tensile Strength Using Different Fibres

Indirect Tensile Strength (ITS) Test was conducted on Stone Matrix Asphalt (SMA) mixes using different fibres such as cellulose fibre, coconut fibre, glass fibre and jute fibre and the results were then compared which is shown in the **Figure 4.27**

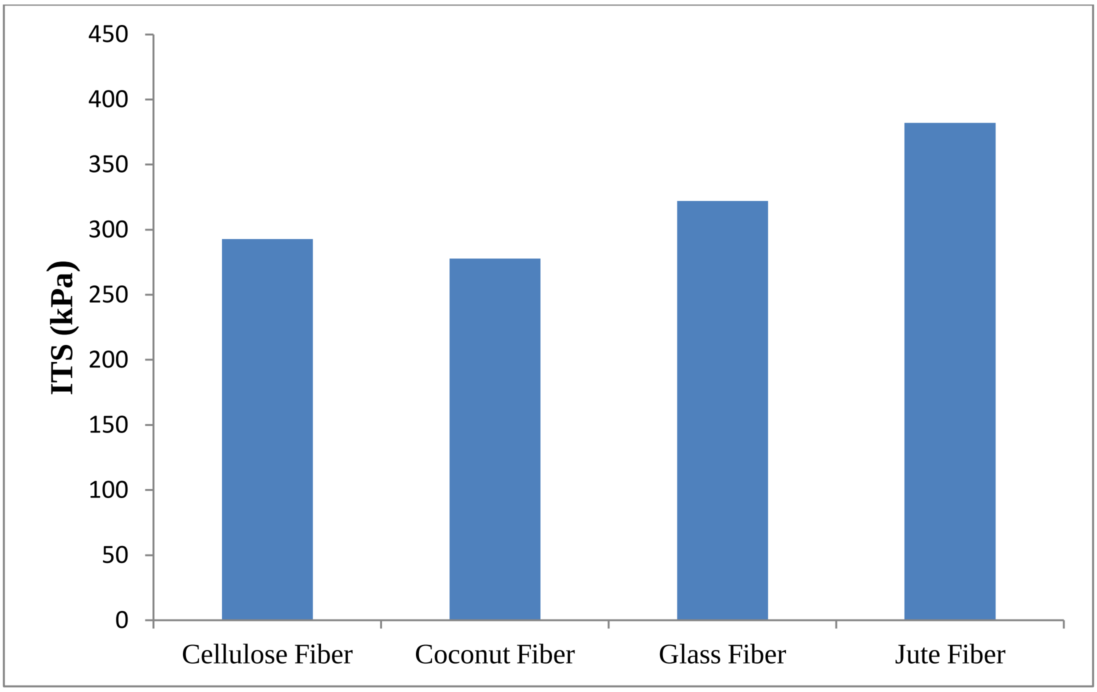

Figure 4.27 Comparison of ITS value for Different Fibres

The test result shows that the SMA mix with Jute fibre shows higher tensile strength i.e. 381.93 kPa as compared to all the other SMA mixes with different fibres.

4.13 Comparison of Resilient Modulus Using different Fibres

The value of Resilient Modulus has been calculated using the empirical equation (see equation 4.1, section 4.10) using the value of Indirect Tensile Strength for all the SMA mixes using different fibres. The results were compared as shown in **Figure 4.28**

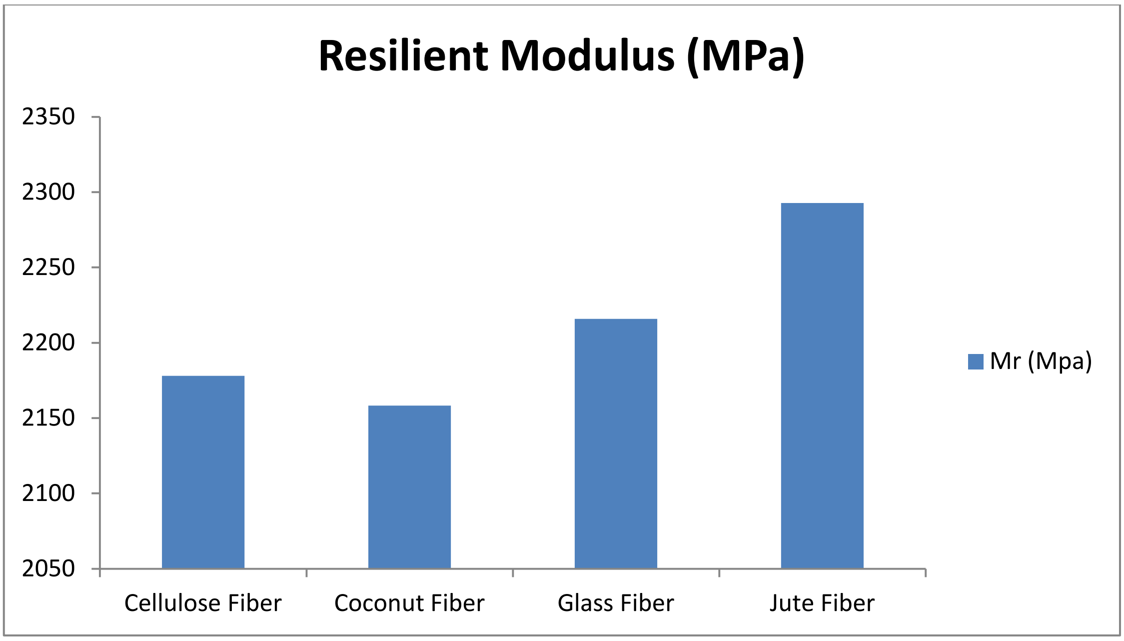

Figure 4.28 Comparison of Resilient modulus values for Different Fibres

The test result shows that the SMA mix with Jute fibre has high resilient modulus value i.e. 2292.78 MPa as compared to all other Stone Matrix Asphalt (SMA) mixes with different fibres.

4.14 Comparison of Drain Down using Different Fibres

Drain down test is very important factor for the design of gap graded asphalt or open graded asphalt just like Stone Matrix Asphalt (SMA). It was performed as per ASTM D 6390 for the SMA mixes with different fibres. The results were compared as shown in **Figure 4.29**

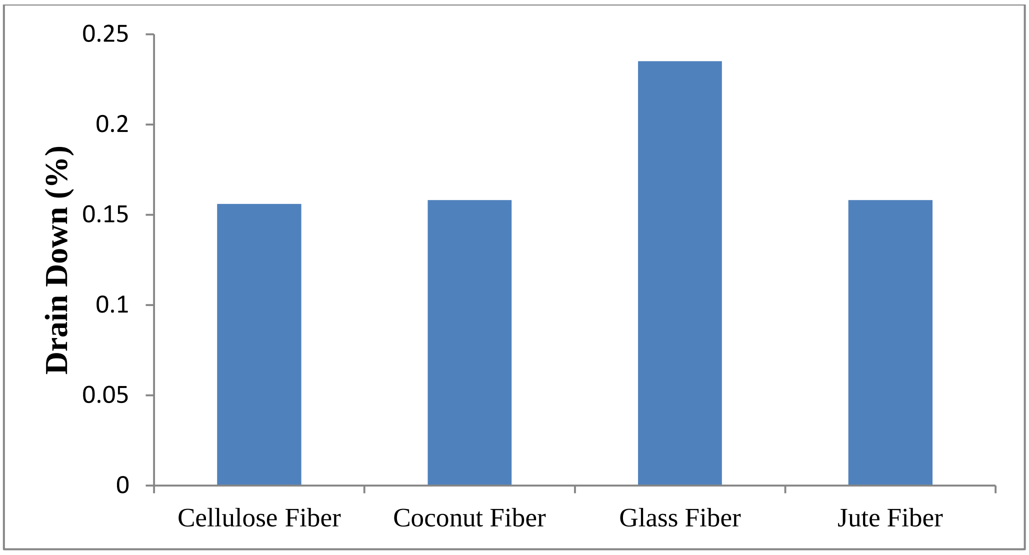

Figure 4.29 Comparison of Drain down results for different fibres

The test result shows the drain down percent for all the SMA mixes using different fibres are well within specified limits as per IRC:SP:79-2008. From the above graph it is seen that SMA mix with glass fibre has higher drain down percent than other SMA mixes with different fibres.

Chapter 5

DESIGN OF FLEXIBLE PAVEMENT (SMA) USING DIFFERENT FIBRES

5.1 General

In this chapter, the design of a typical 2-Lane Dual Carriageway has been performed by using stone matrix asphalt by prepared with different additives. The additives used are cellulose fibre, coconut fibre, glass fibre and jute fibre. The values of Resilient Modulus of different SMA mixes are as shown in **Table 5.1** below:-

Table 5.1 Values of Resilient Modulus

Different Additives	Value of Resilient Modulus(MPa)
SMA with cellulose fibre	2177.98
SMA with coconut fibre	2158.32
SMA with glass fibre	2215.91
SMA with jute fibre	2292.78

For design purpose, the actual strains will be calculated using IITPAVE software and will be compared with Limiting Strains as per IRC: 37-2012.

5.2 Vehicle Damage Factor

Axle Load survey has been conducted for different vehicles and named as vehicle 1, 2, 3, 4, 5, 6 and 7. Vehicle Damage Factor has been calculated using this axle load survey and is mentioned in **annexure** and is shown in **Table 5.2**.

Table 5.2 Calculated Avg. VDF for Different Vehicles

Vehicle Type	No. of Vehicles	Avg. VDF
1 (2-Axle)	87	3.355
2 (2-Axle Tandem)	102	6.61
3 (2-Axle Tridem)	12	5.194

4 (3-Axle Tandem)	21	8.711
5 (3-Axle Tridem)	3	16.046
6 (2-Axle)	94	5.448
7 (2-Axle)	58	5.413

Therefore,

Weighted average VDF = **5.2**

5.3 Computation of Design Traffic

The design traffic in terms of the cumulative number of standard axles which is to be carried should be calculated using the following equation [10]:

$$N = \frac{365 \times [(1 + r)^n - 1] \times A \times D \times F}{R}$$

Where,

N = Cumulative number of standard axles in terms of msa.

A - Initial traffic in the year of completion of construction in terms of the number of Commercial Vehicles Per Day (CVPD).

D = Lane distribution factor [10] (0.75 for Dual 2-Lane Carriageway)

F = Vehicle Damage Factor (VDF).

n = Design life in years.

r = Annual growth rate of commercial vehicles in decimal

The traffic in the year of completion is estimated using the following formula [10]:

$$A=P(1+r)^x$$

Where,

P = Number of commercial vehicles as per last count.

x = Number of years between the last count and the year of completion of construction.

Total traffic = 2500 CVPD

Lane Distribution factor for Dual 2-Lane Carriageway = 0.75

Vehicle Damage factor = 5.2

Design life = 15 years

Annual Growth Rate = 6 %

Therefore,

$$N = \frac{365 \times [(1+0.06)^{15} - 1] \times 2500 \times 0.75 \times 5.2}{0.06}$$

N = 83 msa

5.4 Determination of Allowable Strains

Pavement section has two types of strains produced under the application of wheel load on the top surface. They are, horizontal tensile strain (ε_t) and vertical compressive strain (ε_z). Tensile strain (ε_t) is located at the bottom of bituminous layer/layers, whereas, vertical strain (ε_z) is located at the top of subgrade. If horizontal tensile strain (ε_t) exceeds the limiting strain value, there will be cracking on the top surface of bituminous layer and the pavement may distress due to fatigue. If vertical compressive strain (ε_z) exceeds the limiting strain value, there will be permanent deformation (rutting) on the pavement surface.

Two equations specified in IRC 37:2012 for computing horizontal tensile strain (ε_t) are shown below:

$$N_f = 2.21 \times 10^{-4} \times [\frac{1}{\varepsilon_t}]^{3.89} \times [1/M_R]^{0.854}$$ ………. (5.1)

$$N_f = 0.711 \times 10^{-4} \times [\frac{1}{\varepsilon_t}]^{3.89} \times [1/M_R]^{0.854}$$ ………. (5.2)

Where,

N_f = fatigue life in number of standard axles

ε_t = maximum tensile strain at the bottom of bituminous layers

M_R = resilient modulus of the bituminous layers

Equation 5.1 is to be used for traffic lesser than 30 msa whereas, **equation 5.2** is recommended for traffic greater than 30 msa.

Also, equations specified in IRC 37:2012 for computing vertical compressive strain (ε_z) are shown below:

$$N = 4.1656 \times 10^{-8} \times [\frac{1}{\varepsilon_v}]^{4.5337} \qquad \text{……………. (5.3)}$$

$$N = 1.41 \times 10^{-8} \times [\frac{1}{\varepsilon_v}]^{4.5337} \qquad \text{……………. (5.4)}$$

Where,

N = number of cumulative standard axles

ε_{v} = maximum vertical strain at the top of subgrade

Equations 5.2 and **5.4** are used for determining the fatigue and rutting values, for cumulative standard axles of 83 × 10^6. Temperature of 35ºC and VG 30 grade of bitumen is taken for determining resilient modulus of dense bituminous macadam layer. The value of resilient modulus is taken as 1700 MPa from Table 7.1 of IRC 37:2012.

The values of maximum horizontal tensile strain (ε_t) and maximum vertical strain (ε_v) calculated using **equations 5.2** and **5.4** are given in **Table 5.3**

Table 5.3 Allowable Strains Calculated for Different Fibres

Sample	Horizontal Tensile Strain (Microns)	Vertical Compressive Strain (Microns)
Cellulose Fibre	146.24	332.38
Coconut Fibre	146.53	332.38
Glass Fibre	145.7	332.38
Jute Fibre	144.6	332.38

5.5 Calculation of Resilient Modulus for Subgrade and Sub base Layers

- The resilient modulus for subgrade can be calculated using the following equation [10]:

  M_R subgrade = 17.6 * $(CBR)^{0.64}$ ……………………..(5.5)

  = 17.6 * $7^{0.64}$

$= 61.2$ MPa

- The resilient modulus for sub base layer can be calculated using the following equation [10]:

$M_{R\ subbase} = 0.2 * M_R\ subgrade * h^{0.45}$ ……………………..(5.6)

$= 0.2 * 61.2 * 520^{0.45}$

$= 204.16$ MPa

5.6 Design of flexible pavement using IITPAVE

A flexible pavement is considered as multi-layer layer elastic structure. IITPAVE is used for determining stress and strain values at critical locations of pavement section. Design of flexible pavement is to be done for all the type of fibres additives used in the SMA mixtures. Resilient modulus (M_R) calculated using the empirical equation, as shown in **Table 5.1**, is used for determining pavement thickness.

5.7 Actual Strains Calculations

Calculation of actual strain for different additives is done using IITPAVE Software. The parameters that are entered for the calculation are as follows:

- No. of Layers = 4
- Resilient Modulus (Different for different additives)
- Poison Ratio = 0.35
- Thickness of Different Layers
- Single wheel Load = 20000 N
- Tyre Pressure = 0.56 MPa
- Points for Stress Computation = 2

5.8 Changes in the Fatigue Life and Rutting Life with Change in DBM Layer Thickness

In this section, the thickness of Dense Bituminous Macadam (DBM) layer has been varied and its effect on fatigue life and rutting life is observed. Also, design DBM layer thickness i.e. thickness at which actual strain values are less than limiting/allowable strain values, is to be determined for all type of fibres additives used in the Stone Matrix Asphalt mixes. The values of horizontal tensile strain and vertical compressive strain are obtained using IITPAVE. Design is to be done using following considerations:

- Design is to be done for the traffic of 83 msa.
- Thickness of Stone Matrix Asphalt (SMA) layer is fixed and taken as 40 mm
- Thickness of bituminous layers is varied and taken as 180 mm, 190 mm, 200mm, 210 mm and 220 mm.
- The value of resilient modulus is taken as 1700 MPa for Dense Bituminous Macadam layer (as per **Table 7.1** of IRC: 37-2012).
- Thickness of granular layer is taken as 520 mm.
- Resilient modulus of subgrade used for the analysis was calculated from **equation 5.5**.
- Computation of fatigue life and rutting life is to be done using **equation 5.2** and **equation 5.4** respectively.

Results obtained for different fibres additives used in SMA mixes, are shown in **Table 5.4**.

Table 5.4 Variation in fatigue and rutting life with change in DBM layer thickness

DBM Layer Thickness (mm)	Design Parameters	Cellulose fibre	Coconut fibre	Glass fibre	Jute fibre
180	ε_t ($\mu\varepsilon_t$)	163.7	163.8	163.6	163.2
	ε_z ($\mu\varepsilon$)	212.9	213	212.5	211.8
	Fatigue Life (msa)	53.52	53.4	53.65	54.2
	Rutting Life (msa)	625.42	624.1	630.77	640.3
190	ε_t ($\mu\varepsilon$)	155.7	155.8	155.5	155.2
	ε_z ($\mu\varepsilon$)	205.3	205.5	204.9	204.3
	Fatigue Life (msa)	65.04	64.88	65.36	65.9
	Rutting Life	737.46	734.22	744.01	754

	(msa)				
200	ε_t (με)	148.2	148.3	148.1	147.8
	ε_z (με)	198.1	198.2	197.8	197.1
	Fatigue Life (msa)	78.81	78.6	79.02	79.64
	Rutting Life (msa)	867.03	865.05	873.01	887.2
210	ε_t (με)	141.1	141.2	141	140.7
	ε_z (με)	191.2	191.4	190.9	190.3
	Fatigue Life (msa)	95.4	95.13	95.66	96.45
	Rutting Life (msa)	1018.21	1013.4	1025.5	1040.23
220	ε_t (με)	134.5	134.6	134.4	134.1
	ε_z (με)	184.7	184.9	184.4	183.8
	Fatigue Life (msa)	114.93	114.6	115.3	116.3
	Rutting Life (msa)	1191.1	1185.24	1199.9	1217.74

There was an increase in the fatigue and rutting life with increase in the DBM layer thickness for SMA mixes with all fibres. Different fibre mixtures had actual strain values lesser than limiting strain values at different thickness of granular layer. The pavement composition for each fibre in the Stone Matrix Asphalt (SMA) mixes is shown in the **Table 5.5**

Table 5.5 Minimum DBM layer thickness for each mix

Mix Type	Allowable Horizontal Tensile Strain (με)	Allowable Vertical Compressive Strain (με)	Minimum DBM Layer Thickness (mm)
Cellulose fibre	146.24	332.4	207.24
Coconut fibre	146.53	332.4	207.51
Glass fibre	145.7	332.4	206.62
Jute fibre	144.6	332.4	205.5

It can be concluded from the **Table 5.5**, that the replacement of fibres in SMA mixes results in a slight difference in the thickness of the DBM layer.

Figure 5.1 and **Figure 5.2** shows the variation in fatigue life and rutting life with the addition of different fibres. It was observed that there is significant difference in the Fatigue and Rutting life with the addition of different fibres. Further SMA mixes with Jute fibre showed the highest Fatigue and Rutting Life as compared to other mixes.

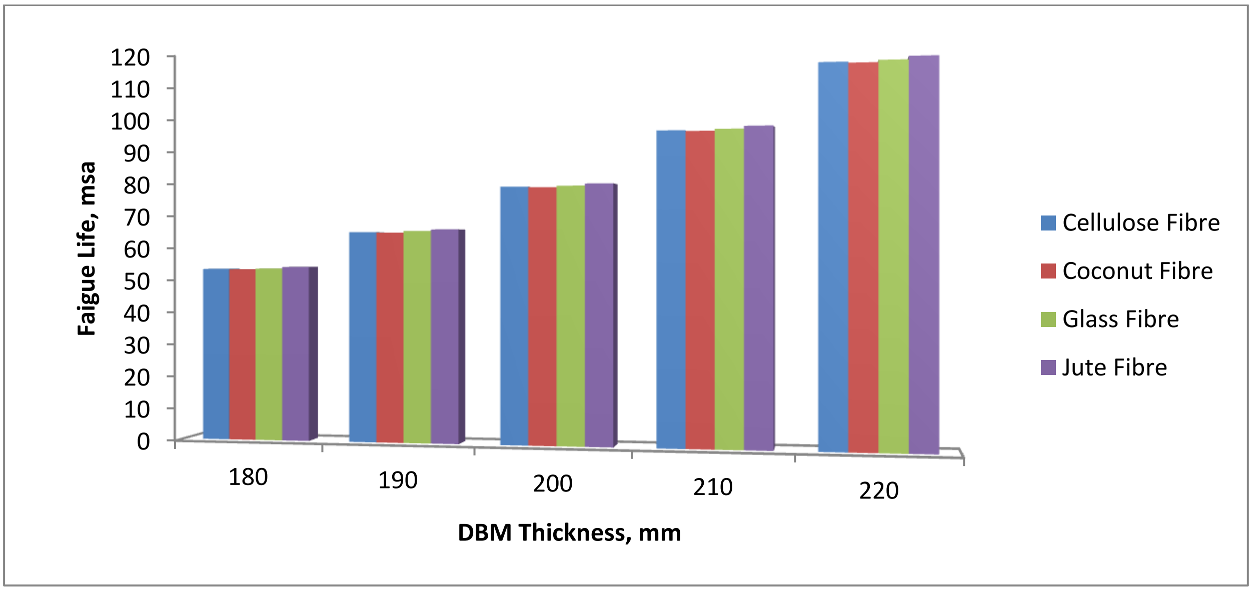

Figure 5.1 Variation in fatigue life with change in DBM layer thickness

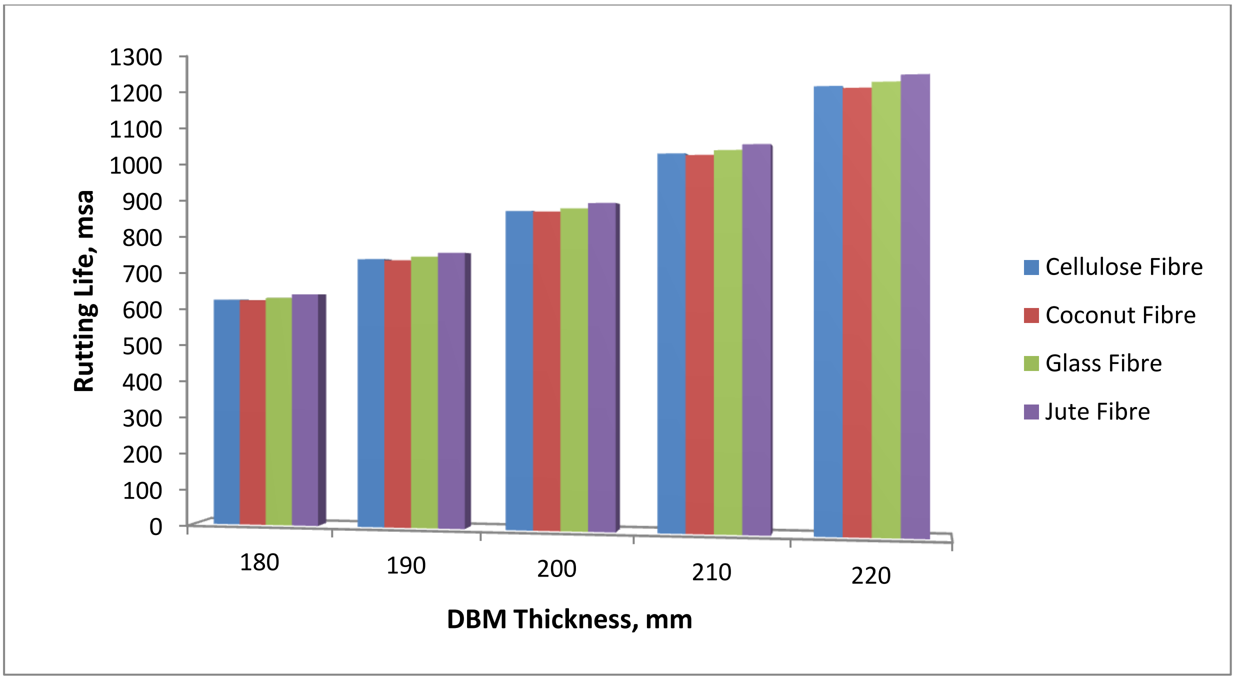

Figure 5.2 Variation in Rutting life with change in DBM layer thickness

The **Figure 5.3 and 5.4** shows variation of compressive vertical strain and horizontal tensile strain of the SMA mix with the addition of different fibres.

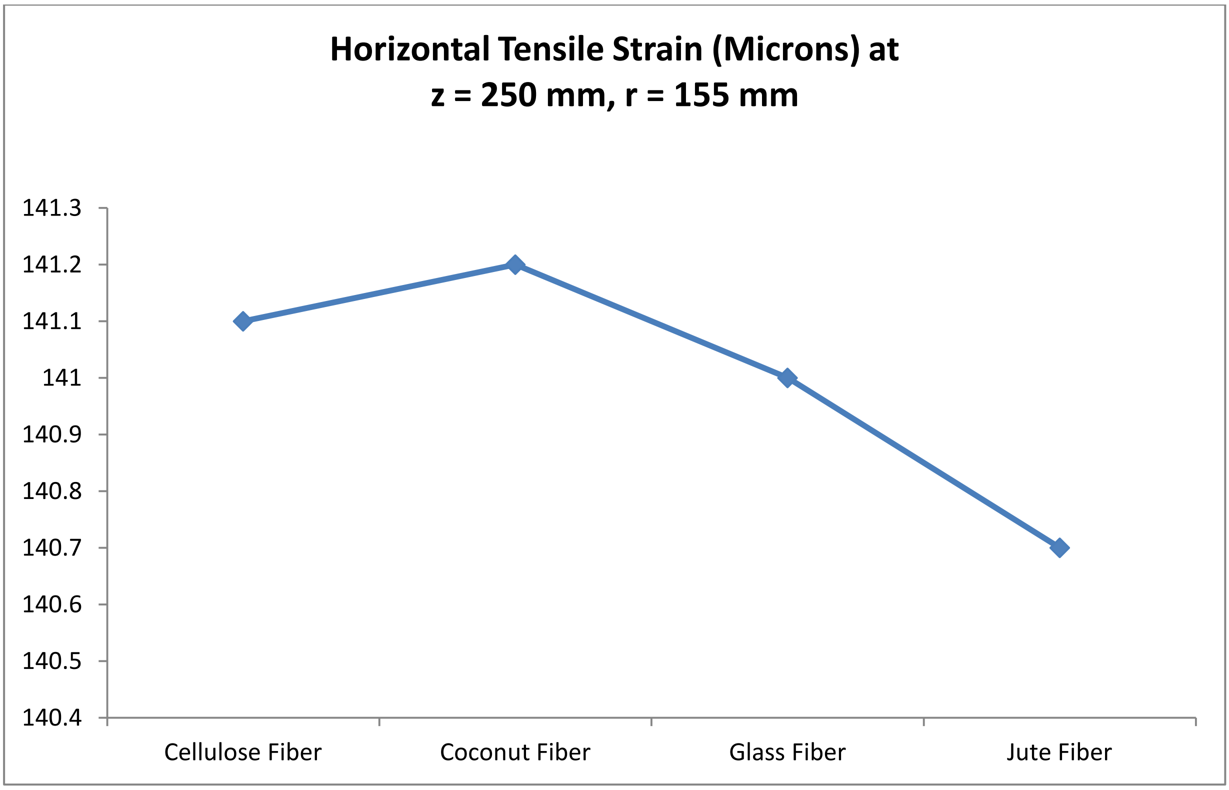

Figure 5.3 Variation of Horizontal Tensile Strain for Different Fibres

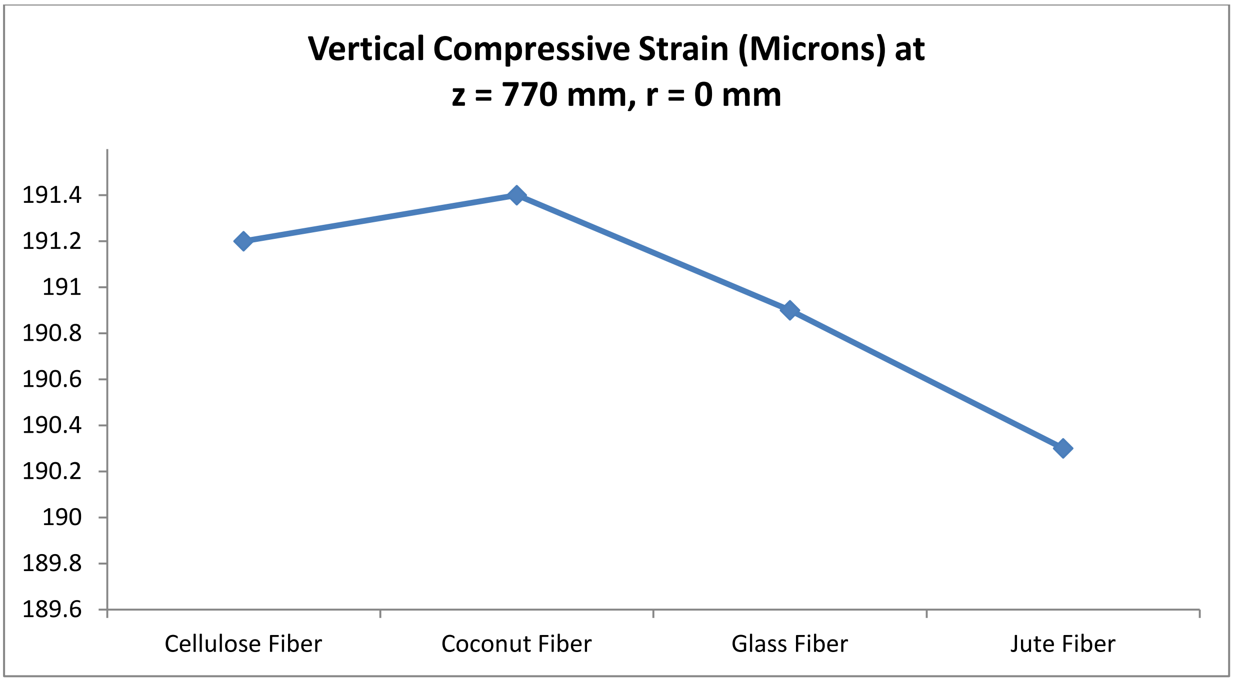

Figure 5.4 Variation of Vertical Compressive Strain for Different Fibres

It was observed that the SMA mix with Jute fibre shows less horizontal tensile strain and less compressive vertical strain as compared to other SMA mixes having different fibres and it is due to the high value of the resilient modulus of the mixture.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The major conclusions that are drawn from the study on the basis of Marshall Mix Method, Indirect Tensile Strength (ITS) Test, Drain down Test of the Stone Matrix Asphalt Mixes (SMA) mix using different fibres as their additives are as follows:-

1. Normal VG-30 grade of bitumen is tested for different percentages for Stone Matrix Asphalt (SMA) mixes and Optimum Binder Content (OBC) is calculated. The OBC for the conventional SMA mix i.e. using cellulose fibre comes out to be 6.6 % by weight of mix and the flow value is well within the specified limits as per MoRTH and IRC: SP: 79-2008.
2. The Marshall Method of mix design is conducted on the SMA mix using coconut fibre , glass fibre and jute fibre. The OBC comes out to be 6.47 %, 6.5%, and 6.5 % respectively. Thus, there is no significant difference in the Optimum Binder Content for the SMA mixes using different fibres.
3. SMA mix having Jute fibre shows better volumetric properties than all other SMA mixes apart from the Marshall Stability, where SMA mix with cellulose fibre shows the maximum stability of 997.36 kg than all other SMA mixes.
4. The Indirect Tensile Strength has been calculated for different fibres. The results show that the SMA mix with Jute fibre exhibited higher Tensile Strength than other SMA mixes which depicts that it has more resistance against fatigue cracking.
5. Drain down test results shows that SMA mix with cellulose fibre has least drain down as compared to all other mixes. Glass fibre SMA mix shows maximum drain down but all the values are well within specified limits as per MoRTH and IRC: SP: 79-2008.
6. The outcome of the Resilient Modulus results shows that the SMA mix with Jute fibre shows that maximum value of Resilient Modulus.

7. Due to high value of Resilient Modulus of SMA mix with jute fibre, it shows the least Vertical compressive Strain and Horizontal Tensile Strain when used for the design of Dual 2-Lane Carriageway using IITPAVE software.
8. The results of the IITPAVE software also show that the Fatigue Life (in msa) and Rutting Life (in msa) for the SMA mix having Jute fibre is the highest of all the mixes analyzed in this study.

6.2 Recommendations For Future Research

There is a vast scope of research studies and practical applications for Stone Matrix Asphalt (SMA) in the future. The following recommendations briefly describe the area in which further research work can be pursued in this field:

1. Modified binder can also be used for the study of properties of Stone Matrix Asphalt.
2. Further research studies can also be conducted on the properties of Stone Matrix Asphalt (SMA) by modifying the binder and simultaneously replacing of one fibre with the other.
3. A slab made of Stone Matrix Asphalt mix can be tested to check the fatigue and rutting characteristics by conducting dynamic (to and fro) loading using Hamburg wheel tracking device.
4. The tests performed in this study may be repeated at different temperatures to check the resistance of SMA mixes against fatigue cracking in varying weather conditions.

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ANNEXURE

S. No.	Vehicle Type	No. of Tyres		Wheel Load (tonnes)		Axle Load	Axle Load	EALF	EALF	Total EALF
		1st	2nd	1st	2nd	(Tonnes)	(Tonnes)			
1	1	2	4	2.86	5.40	5.72	10.8	0.599695	3.321506	3.92120161
2	1	2	4	2.55	4.47	5.1	8.94	0.37899	1.559517	1.93850664
3	1	2	4	2.02	2.18	4.04	4.36	0.149235	0.088224	0.23745931
4	1	2	4	3.29	5.92	6.58	11.84	1.050147	4.797852	5.84799929
5	1	2	4	2.77	4.33	5.54	8.66	0.527698	1.37313	1.90082811
6	1	2	4	1.83	1.78	3.66	3.56	0.100524	0.039214	0.13973817
7	1	2	4	1.96	1.76	3.92	3.52	0.132279	0.037481	0.16975994
8	1	2	4	1.74	1.60	3.48	3.2	0.082161	0.0256	0.10776059
9	1	2	4	1.74	1.51	3.48	3.02	0.082161	0.020308	0.10246862
10	1	2	4	2.95	3.90	5.9	7.8	0.67882	0.903688	1.58250788
11	1	2	4	1.87	1.76	3.74	3.52	0.109606	0.037481	0.14708662
12	1	2	4	2.62	3.57	5.24	7.14	0.422349	0.634502	1.0568511
13	1	2	4	1.77	1.85	3.54	3.7	0.087975	0.045756	0.13373095
14	1	2	4	2.04	1.85	4.08	3.7	0.155234	0.045756	0.20099002
15	1	2	4	2.11	2.25	4.22	4.5	0.177663	0.100113	0.27777566
16	1	2	4	2.61	4.30	5.22	8.6	0.415938	1.335469	1.75140713
17	1	2	4	2.36	4.21	4.72	8.42	0.278045	1.227124	1.50516858
18	1	2	4	1.37	0.93	2.74	1.86	0.031575	0.002922	0.03449748
19	1	2	4	2.00	2.05	4	4.1	0.143412	0.068988	0.21240065
20	1	2	4	2.81	5.87	5.62	11.74	0.558846	4.637805	5.19665012
21	1	2	4	2.01	2.13	4.02	4.26	0.146302	0.080404	0.22670632
22	1	2	4	1.96	2.28	3.92	4.56	0.132279	0.10556	0.23783899
23	1	2	4	1.67	3.25	3.34	6.5	0.069716	0.435806	0.50552227
24	1	2	4	2.07	6.12	4.14	12.24	0.164569	5.479813	5.64438178
25	1	2	4	1.93	1.89	3.86	3.78	0.124364	0.049843	0.17420767
26	1	2	4	1.71	1.85	3.42	3.7	0.076639	0.045756	0.12239509
27	1	2	4	2.45	6.42	4.9	12.84	0.322947	6.635905	6.95885153
28	1	2	4	3.34	6.09	6.68	12.18	1.115456	5.373153	6.48860892
29	1	2	4	2.98	6.90	5.96	13.8	0.706857	8.854344	9.56120122
30	1	2	4	2.41	6.54	4.82	13.08	0.302367	7.146132	7.44849913
31	1	2	4	3.03	6.38	6.06	12.76	0.755505	6.472063	7.22756773
32	1	2	4	2.24	5.01	4.48	10.02	0.225662	2.460996	2.68665827
33	1	2	4	2.60	4.90	5.2	9.8	0.4096	2.251875	2.66147539
34	1	2	4	2.92	4.53	5.84	9.06	0.651625	1.644951	2.29657587
35	1	2	4	3.11	4.91	6.22	9.82	0.83851	2.270314	3.10882414
36	1	2	4	2.57	5.69	5.14	11.38	0.39102	4.094578	4.48559761
37	1	2	4	2.69	6.06	5.38	12.12	0.469327	5.268058	5.73738495
38	1	2	4	2.43	7.48	4.86	14.96	0.31253	12.22831	12.5408396
39	1	2	4	1.70	3.77	3.4	7.54	0.074862	0.789088	0.86395013
40	1	2	4	1.71	4.83	3.42	9.66	0.076639	2.125928	2.20256723
41	1	2	4	2.37	5.38	4.74	10.76	0.282787	3.272571	3.55535878
42	1	2	4	2.07	5.10	4.14	10.2	0.164569	2.642657	2.80722561
43	1	2	4	2.77	5.38	5.54	10.76	0.527698	3.272571	3.80026967
44	1	2	4	2.11	2.20	4.22	4.4	0.177663	0.091506	0.269169
45	1	2	4	2.02	7.29	4.04	14.58	0.149235	11.0324	11.1816392
46	1	2	4	1.11	1.28	2.22	2.56	0.013607	0.010486	0.02409264
47	1	2	4	1.51	1.71	3.02	3.42	0.046599	0.0334	0.07999861
48	1	2	4	2.92	6.99	5.84	13.98	0.651625	9.325427	9.97705257
49	1	2	4	2.57	5.84	5.14	11.68	0.39102	4.543719	4.93473863
50	1	2	4	2.73	5.76	5.46	11.52	0.497871	4.299817	4.79768832
51	1	2	4	3.77	6.78	7.54	13.56	1.810639	8.254273	10.064912
52	1	2	4	3.60	5.97	7.2	11.94	1.505485	4.962007	6.46749229
53	1	2	4	2.91	6.04	5.82	12.08	0.642745	5.198856	5.84160072
54	1	2	4	2.54	5.70	5.08	11.4	0.37308	4.123438	4.49651742
55	1	2	4	2.76	5.97	5.52	11.94	0.520119	4.962007	5.48212605
56	1	2	4	2.57	6.24	5.14	12.48	0.39102	5.922409	6.31342903
57	1	2	4	2.56	4.33	5.12	8.66	0.38497	1.37313	1.75809947
58	1	2	4	2.77	5.86	5.54	11.72	0.527698	4.606282	5.13397997
59	1	2	4	2.07	5.55	4.14	11.1	0.164569	3.706227	3.87079555
60	1	2	4	2.93	6.34	5.86	12.68	0.660598	6.311274	6.97187212
61	1	2	4	3.77	7.18	7.54	14.36	1.810639	10.38145	12.1920845
62	1	2	4	2.70	4.98	5.4	9.96	0.476345	2.402578	2.8789225
63	1	2	4	2.70	6.41	5.4	12.82	0.476345	6.594656	7.0710011
64	1	2	4	2.88	6.17	5.76	12.34	0.616647	5.661098	6.27774507
65	1	2	4	2.51	3.98	5.02	7.96	0.355764	0.98015	1.33591304

66	1	2	4	2.79	5.38	5.58	10.76	0.543104	3.272571	3.81567591
67	1	2	4	1.86	4.21	3.72	8.42	0.10728	1.227124	1.3344038
68	1	2	4	2.44	7.19	4.88	14.38	0.317706	10.4394	10.7571077
69	1	2	4	2.88	5.49	5.76	10.98	0.616647	3.548538	4.16518444
70	1	2	4	2.59	5.40	5.18	10.8	0.403335	3.321506	3.72484097
71	1	2	4	2.38	4.43	4.76	8.86	0.28759	1.50444	1.79203063
72	1	2	4	2.88	3.17	5.76	6.34	0.616647	0.394455	1.01110149
73	1	2	4	1.53	3.09	3.06	6.18	0.049117	0.356118	0.40523507
74	1	2	4	1.97	2.04	3.94	4.08	0.134999	0.067652	0.20265129
75	1	2	4	3.12	5.81	6.24	11.62	0.849347	4.451071	5.30041799
76	1	2	4	2.79	4.90	5.58	9.8	0.543104	2.251875	2.79497985
77	1	2	4	3.05	6.09	6.1	12.18	0.77565	5.373153	6.14880318
78	1	2	4	2.72	3.88	5.44	7.76	0.490617	0.885293	1.37590934
79	1	2	4	2.82	3.39	5.64	6.78	0.566843	0.515892	1.0827353
80	1	2	4	2.50	5.70	5	11.4	0.350128	4.123438	4.47356569
81	1	2	4	2.83	3.92	5.66	7.84	0.574926	0.922368	1.49729462
82	1	2	4	1.91	2.52	3.82	5.04	0.119289	0.15753	0.27681851
83	1	2	4	1.91	2.12	3.82	4.24	0.119289	0.078905	0.19819371
84	1	2	4	1.84	4.95	3.68	9.9	0.10274	2.345205	2.4479447
85	1	2	4	2.24	3.05	4.48	6.1	0.225662	0.338033	0.56369533
86	1	2	4	2.66	5.11	5.32	10.22	0.448738	2.663444	3.11218266
87	1	2	4	1.61	2.30	3.22	4.6	0.060224	0.109313	0.16953695

Avg. Value **3.354925004**

S. No.	Vehicle Type	No. of Tyres			Wheel load (Tonnes)			Axle Load	Axle Load	Axle Load	EALF	EALF	Total EALF
		1st	2nd	3rd	1st	2nd	3rd	(Tonnes)	(Tonnes)	(Tonnes)			
1	2	2	4	4	4.00	6.80	5.65	8	13.6	11.3	2.294598	8.012177	10.3067744
2	2	2	4	4	2.27	2.06	1.90	4.54	4.12	3.8	0.237996	0.082008	0.32000373
3	2	2	4	4	3.60	6.10	5.65	7.2	12.2	11.3	1.505485	6.356596	7.8620811
4	2	2	4	4	2.17	2.90	2.25	4.34	5.8	4.5	0.198749	0.234586	0.43333522
5	2	2	4	4	2.22	2.39	1.84	4.44	4.78	3.68	0.21771	0.106766	0.32447644
6	2	2	4	4	2.69	6.70	6.01	5.38	13.4	12.02	0.469327	8.702726	9.17205341
7	2	2	4	4	3.28	4.72	4.65	6.56	9.44	9.3	1.037437	2.570582	3.60801961
8	2	2	4	4	2.24	2.20	2.21	4.48	4.4	4.42	0.225662	0.126133	0.35179474
9	2	2	4	4	2.45	2.44	2.16	4.9	4.88	4.32	0.322947	0.149315	0.47226208
10	2	2	4	4	2.37	2.45	1.98	4.74	4.9	3.96	0.282787	0.128436	0.4112237
11	2	2	4	4	2.22	2.25	1.93	4.44	4.5	3.86	0.21771	0.101807	0.31951718
12	2	2	4	4	3.70	6.39	5.62	7.4	12.78	11.24	1.679861	6.938173	8.61803482
13	2	2	4	4	2.62	1.95	1.66	5.24	3.9	3.32	0.422349	0.056637	0.47898646
14	2	2	4	4	3.89	7.56	6.56	7.78	15.12	13.12	2.052414	13.25598	15.308396
15	2	2	4	4	2.11	1.90	1.64	4.22	3.8	3.28	0.177663	0.05237	0.23003318
16	2	2	4	4	2.21	2.32	1.80	4.42	4.64	3.6	0.213814	0.096086	0.30990017
17	2	2	4	4	3.27	6.80	5.84	6.54	13.6	11.68	1.024844	8.512584	9.53742766
18	2	2	4	4	2.94	6.52	6.27	5.88	13.04	12.54	0.669662	8.923912	9.59357475
19	2	2	4	4	2.41	2.33	2.27	4.82	4.66	4.54	0.302367	0.149315	0.45168258
20	2	2	4	4	2.12	1.92	1.58	4.24	3.84	3.16	0.181055	0.050043	0.23109801
21	2	2	4	4	2.40	2.37	1.90	4.8	4.74	3.8	0.29738	0.110862	0.40824233
22	2	2	4	4	2.01	1.85	1.94	4.02	3.7	3.88	0.146302	0.068807	0.21510875
23	2	2	4	4	1.75	2.03	1.55	3.5	4.06	3.1	0.084066	0.054778	0.13884356
24	2	2	4	4	2.15	5.47	5.42	4.3	10.94	10.84	0.191523	4.690127	4.88165016
25	2	2	4	4	1.84	2.28	1.84	3.68	4.56	3.68	0.10274	0.096086	0.19882601
26	2	2	4	4	2.22	2.06	1.67	4.44	4.12	3.34	0.21771	0.064552	0.28226185
27	2	2	4	4	2.01	1.99	1.95	4.02	3.98	3.9	0.146302	0.080363	0.22666552
28	2	2	4	4	2.35	1.81	1.52	4.7	3.62	3.04	0.273362	0.041006	0.31436816
29	2	2	4	4	3.25	5.86	6.44	6.5	11.72	12.88	1	7.63297	8.6329702
30	2	2	4	4	3.85	6.11	5.61	7.7	12.22	11.22	1.969289	6.291925	8.26121453
31	2	2	4	4	2.38	2.04	1.61	4.76	4.08	3.22	0.28759	0.059189	0.34677989
32	2	2	4	4	2.64	2.58	2.27	5.28	5.16	4.54	0.435394	0.184519	0.61991239
33	2	2	4	4	1.88	2.30	1.84	3.76	4.6	3.68	0.111969	0.097966	0.20993484
34	2	2	4	4	2.09	2.17	1.87	4.18	4.34	3.74	0.171022	0.088838	0.25985985
35	2	2	4	4	3.06	5.93	4.83	6.12	11.86	9.66	0.785873	4.470151	5.25602394
36	2	2	4	4	3.63	7.31	6.55	7.26	14.62	13.1	1.556299	12.30626	13.8625578

37	2	2	4	4	2.29	2.22	2.11	4.58	4.44	4.22	0.246495	0.117226	0.36372142
38	2	2	4	4	2.54	6.90	6.59	5.08	13.8	13.18	0.37308	11.04386	11.4169402
39	2	2	4	4	2.25	2.20	2.05	4.5	4.4	4.1	0.229719	0.1088	0.33851883
40	2	2	4	4	3.19	6.98	6.25	6.38	13.96	12.5	0.928174	10.21674	11.1449174
41	2	2	4	4	2.83	5.87	6.85	5.66	11.74	13.7	0.574926	8.730147	9.30507366
42	2	2	4	4	3.52	5.53	4.83	7.04	11.06	9.66	1.376059	3.8416	5.21765949
43	2	2	4	4	2.46	5.79	5.81	4.92	11.58	11.62	0.328252	6.038166	6.36641811
44	2	2	4	4	2.46	5.79	5.81	4.92	11.58	11.62	0.328252	6.038166	6.36641811
45	2	2	4	4	3.40	6.50	6.14	6.8	13	12.28	1.197794	8.512584	9.71037838
46	2	2	4	4	3.88	6.80	6.01	7.76	13.6	12.02	2.031391	8.979862	11.0112522
47	2	2	4	4	3.88	5.79	6.55	7.76	11.58	13.1	2.031391	7.732746	9.76413696
48	2	2	4	4	3.76	6.44	5.85	7.52	12.88	11.7	1.791505	7.608178	9.39968242
49	2	2	4	4	3.85	7.06	6.64	7.7	14.12	13.28	1.969289	11.74777	13.7170579
50	2	2	4	4	3.78	7.37	6.39	7.56	14.74	12.78	1.829927	11.95493	13.784852
51	2	2	4	4	3.12	4.94	4.76	6.24	9.88	9.52	0.849347	2.952297	3.80164365
52	2	2	4	4	3.36	4.24	5.01	6.72	8.48	10.02	1.142414	2.441406	3.58382064
53	2	2	4	4	3.31	4.27	4.02	6.62	8.54	8.04	1.075916	1.575039	2.65095516
54	2	2	4	4	3.77	3.80	5.16	7.54	7.6	10.32	1.810639	2.14934	3.95997955
55	2	2	4	4	3.33	5.83	4.99	6.66	11.66	9.98	1.102157	4.570694	5.67285125
56	2	2	4	4	3.13	5.70	4.67	6.26	11.4	9.34	0.860288	3.856454	4.716742
57	2	2	4	4	3.12	6.76	6.13	6.24	13.52	12.26	0.849347	9.206293	10.0556395
58	2	2	4	4	2.73	5.83	5.40	5.46	11.66	10.8	0.497871	5.303861	5.80173251
59	2	2	4	4	2.89	5.02	4.89	5.78	10.04	9.78	0.625256	3.216383	3.84163894
60	2	2	4	4	2.71	5.84	5.40	5.42	11.68	10.8	0.483441	5.322778	5.80621942
61	2	2	4	4	2.21	2.80	2.20	4.42	5.6	4.4	0.213814	0.208427	0.42224036
62	2	2	4	4	4.02	7.43	6.40	8.04	14.86	12.8	2.340835	12.20006	14.5408913
63	2	2	4	4	3.91	6.97	5.91	7.82	13.94	11.82	2.09495	9.177757	11.272707
64	2	2	4	4	3.23	6.36	5.40	6.46	12.72	10.8	0.975611	6.378263	7.35387369
65	2	2	4	4	3.01	6.47	5.86	6.02	12.94	11.72	0.735754	7.707711	8.44346493
66	2	2	4	4	3.03	6.95	5.98	6.06	13.9	11.96	0.755505	9.321101	10.0766057
67	2	2	4	4	1.95	1.89	1.79	3.9	3.78	3.58	0.1296	0.06116	0.19075957
68	2	2	4	4	3.13	7.68	6.98	6.26	15.36	13.96	0.860288	15.40313	16.2634188
69	2	2	4	4	2.78	5.84	5.44	5.56	11.68	10.88	0.53536	5.398953	5.93431244
70	2	2	4	4	3.73	6.40	5.91	7.46	12.8	11.82	1.73501	7.657823	9.39283276
71	2	2	4	4	2.73	5.75	4.96	5.46	11.5	9.92	0.497871	4.38764	4.88551153
72	2	2	4	4	2.03	5.40	4.80	4.06	10.8	9.6	0.152213	3.609722	3.76193507
73	2	2	4	4	2.95	6.78	6.20	5.9	13.56	12.4	0.67882	9.466118	10.1449375
74	2	2	4	4	5.39	11.71	11.07	10.78	23.42	22.14	7.565221	89.80241	97.3676326
75	2	2	4	4	2.10	1.74	1.76	4.2	3.48	3.52	0.174319	0.050043	0.22436183

76	2	2	4	4	3.58	7.18	6.69	7.16	14.36	13.38	1.472308	12.34181	13.8141211
77	2	2	4	4	3.37	6.93	5.40	6.74	13.86	10.8	1.156075	7.707711	8.86378649
78	2	2	4	4	1.71	2.39	2.34	3.42	4.78	4.68	0.076639	0.166924	0.24356278
79	2	2	4	4	3.79	4.43	4.32	7.58	8.86	8.64	1.849368	1.954814	3.80418176
80	2	2	4	4	4.16	6.90	5.86	8.32	13.8	11.72	2.684355	8.840479	11.524834
81	2	2	4	4	3.06	6.83	6.27	6.12	13.66	12.54	0.785873	9.821059	10.6069314
82	2	2	4	4	3.79	6.79	5.46	7.58	13.58	10.92	1.849368	7.509612	9.35897985
83	2	2	4	4	3.08	6.83	5.74	6.16	13.66	11.48	0.806621	8.325575	9.1321957
84	2	2	4	4	2.72	6.63	6.01	5.44	13.26	12.02	0.490617	8.512584	9.00320065
85	2	2	4	4	2.83	6.50	5.43	5.66	13	10.86	0.574926	6.755148	7.33007489
86	2	2	4	4	1.93	2.11	1.57	3.86	4.22	3.14	0.124364	0.06116	0.18552388
87	2	2	4	4	3.77	6.32	5.14	7.54	12.64	10.28	1.810639	5.751904	7.56254286
88	2	2	4	4	4.05	8.50	6.22	8.1	17	12.44	2.411497	15.65685	18.0683455
89	2	2	4	4	4.33	2.91	5.21	8.66	5.82	10.42	3.15078	1.449764	4.6005442
90	2	2	4	4	2.92	4.11	5.62	5.84	8.22	11.24	0.651625	2.98899	3.64061547
91	2	2	4	4	3.37	3.32	4.05	6.74	6.64	8.1	1.156075	0.983882	2.13995753
92	2	2	4	4	3.65	6.04	5.02	7.3	12.08	10.04	1.590882	4.989921	6.5808027
93	2	2	4	4	3.75	6.74	7.61	7.5	13.48	15.22	1.772522	14.14102	15.9135416
94	2	2	4	4	1.94	1.65	1.18	3.88	3.3	2.36	0.126962	0.02139	0.14835232
95	2	2	4	4	3.14	5.97	5.27	6.28	11.94	10.54	0.871335	5.322778	6.19411314
96	2	2	4	4	2.08	2.10	0.92	4.16	4.2	1.84	0.167772	0.02774	0.1955118
97	2	2	4	4	3.02	3.98	3.90	6.04	7.96	7.8	0.74558	1.285814	2.03139366
98	2	2	4	4	3.46	6.13	5.90	6.92	12.26	11.8	1.284609	6.984505	8.26911394
99	2	2	4	4	3.73	6.61	6.22	7.46	13.22	12.44	1.73501	9.036073	10.7710829
100	2	2	4	4	4.13	5.35	6.13	8.26	10.7	12.26	2.607755	5.792162	8.3999165
101	2	2	4	4	2.73	5.81	5.08	5.46	11.62	10.16	0.497871	4.690127	5.18799876
102	2	2	4	4	2.07	1.98	1.85	4.14	3.96	3.7	0.164569	0.071758	0.23632662

Avg. Value **6.611148843**

S. No.	Vehicle Type	No. of Tyres				Wheel Load (Tonnes)				Axle Load (Tonnes)	Axle Load (Tonnes)	Axle Load (Tonnes)	Axle Load (Tonnes)	EALF	EALF	Total EALF
		1st	2nd	3rd	4th	1st	2nd	3rd	4th							
1	3	2	4	4	4	3.47	7.12	6.32	6.02	6.94	14.24	12.64	12.04	1.299524	9.113795	10.413319
2	3	2	4	4	4	4.01	2.65	7.59	6.39	8.02	5.3	15.18	12.78	2.31763	4.860679	7.1783083
3	3	2	4	4	4	2.17	1.80	1.88	1.81	4.34	3.6	3.76	3.62	0.198749	0.057732	0.2564813
4	3	2	4	4	4	4.06	3.22	5.98	5.33	8.12	6.44	11.96	10.66	2.435402	2.832633	5.2680355
5	3	2	4	4	4	3.79	2.77	7.38	6.99	7.58	5.54	14.76	13.98	1.849368	5.484931	7.3342994
6	3	2	4	4	4	3.80	2.82	6.46	6.21	7.6	5.64	12.92	12.42	1.868964	3.658757	5.5277211
7	3	2	4	4	4	3.89	3.42	6.89	6.24	7.78	6.84	13.78	12.48	2.052414	4.767821	6.8202345
8	3	2	4	4	4	2.90	3.94	6.01	5.77	5.8	7.88	12.02	11.54	0.633955	3.88095	4.5149054
9	3	2	4	4	4	2.07	3.17	5.45	5.15	4.14	6.34	10.9	10.3	0.164569	2.284881	2.4494504
10	3	2	4	4	4	2.70	2.78	6.83	6.40	5.4	5.56	13.66	12.8	0.476345	4.175353	4.6516984
11	3	2	4	4	4	2.40	2.57	6.96	5.84	4.8	5.14	13.92	11.68	0.29738	3.546691	3.8440711
12	3	2	4	4	4	3.18	2.51	6.75	5.67	6.36	5.02	13.5	11.34	0.91659	3.157673	4.0742627

Avg. Value **5.19439897**

S. No.	Vehicle Type	No. of Tyres				Wheel Load (Tonnes)				Axle Load	Axle Load	Axle Load	Axle Load	EALF	EALF	EALF	Total EALF
		1st	2nd	3rd	4th	1st	2nd	3rd	4th	(Tonnes)	(Tonnes)	(Tonnes)	(Tonnes)				
1	5	2	2	4	4	3.97	3.44	7.25	7.20	7.94	6.88	14.5	14.4	2.22653	1.255164	14.53933	18.021028
2	5	2	2	4	4	3.19	2.23	5.40	5.80	6.38	4.46	10.8	11.6	0.928174	0.221659	5.247413	6.3972457
3	5	2	2	4	4	4.93	4.69	7.28	5.49	9.86	9.38	14.56	10.98	5.294857	4.336685	8.868225	18.499768
4	5	2	2	4	4	3.92	3.85	7.47	6.36	7.84	7.7	14.94	12.72	2.116464	1.969289	12.20006	16.285809
5	5	2	2	4	4	2.04	3.13	2.88	2.55	4.08	6.26	5.76	5.1	0.155234	0.860288	0.289916	1.3054384
6	5	2	2	4	4	2.27	2.71	2.35	2.68	4.54	5.42	4.7	5.36	0.237996	0.483441	0.213474	0.9349115
7	5	2	2	4	4	2.55	1.69	2.47	2.04	5.1	3.38	4.94	4.08	0.37899	0.073116	0.137968	0.590074
8	5	2	2	4	4	3.55	3.76	7.28	6.93	7.1	7.52	14.56	13.86	1.423574	1.791505	13.5972	16.812277
9	5	2	2	4	4	3.29	2.78	5.50	5.06	6.58	5.56	11	10.12	1.050147	0.53536	4.14695	5.7324569
10	5	2	2	4	4	2.64	2.45	2.09	2.07	5.28	4.9	4.18	4.14	0.435394	0.322947	0.099873	0.8582132
11	5	2	2	4	4	2.02	2.66	3.78	3.28	4.04	5.32	7.56	6.56	0.149235	0.448738	0.828499	1.4264726
12	5	2	2	4	4	2.00	2.55	3.33	3.19	4	5.1	6.66	6.38	0.143412	0.37899	0.602648	1.1250496
13	5	2	2	4	4	2.02	2.31	3.68	3.26	4.04	4.62	7.36	6.52	0.149235	0.25522	0.77359	1.1780456
14	5	2	2	4	4	1.99	2.45	2.72	2.53	3.98	4.9	5.44	5.06	0.140566	0.322947	0.253344	0.7168561
15	5	2	2	4	4	1.97	2.75	2.43	2.56	3.94	5.5	4.86	5.12	0.134999	0.512622	0.206764	0.8543856
16	5	2	2	4	4	2.25	1.83	1.69	1.90	4.5	3.66	3.38	3.8	0.229719	0.100524	0.055392	0.3856356
17	5	2	2	4	4	3.20	3.04	7.03	6.81	6.4	6.08	14.06	13.62	0.939867	0.765528	12.23538	13.940775
18	5	2	2	4	4	3.74	2.89	6.00	6.15	7.48	5.78	12	12.3	1.753691	0.625256	7.267386	9.6463327
19	5	2	2	4	4	2.95	2.88	5.35	4.88	5.9	5.76	10.7	9.76	0.67882	0.616647	3.652377	4.9478443
20	5	2	2	4	4	4.61	4.03	6.72	6.30	9.22	8.06	13.44	12.6	4.048277	2.364214	9.583344	15.995835
21	5	2	2	4	4	2.15	2.33	1.84	2.01	4.3	4.66	3.68	4.02	0.191523	0.264174	0.073268	0.5289652

Avg. Value 6.484924673

S. No.	Vehicle Type	No. of Tyres					Wheel Load (Tonnes)					Axle Load	Axle Load	Axle Load	Axle Load	Axle Load	EALF	EALF	EALF	Total EALF
		1st	2nd	3rd	4th	5th	1st	2nd	3rd	4th	5th	(Tonnes)	(Tonnes)	(Tonnes)	(Tonnes)	(Tonnes)				
1	6	2	2	4	4	4	3.56	3.17	7.45	5.82	7.20	7.12	6.34	14.9	11.64	14.4	1.439682	0.905115	11.15833	13.503129
2	6	2	4	4	4	4	2.24	6.23	6.50	5.95	7.42	4.48	12.46	13	11.9	14.84	0.225662	5.884536	9.90648	16.016678
3	6	2	4	4	4	4	2.04	6.50	5.25	7.62	7.75	4.08	13	10.5	15.24	15.5	0.155234	6.9729	11.48901	18.617143

Avg. Value 16.04565

S. No.	Vehicle Type	No. of Tyres		Wheel Load (tonnes)		Axle Load	Axle Load	EALF	EALF	Total EALF
		1st	2nd	1st	2nd	(Tonnes)	(Tonnes)			
1	8	2	4	1.17	1.52	2.34	3.04	0.016796	0.020851	0.03764752
2	8	2	4	2.15	2.35	4.3	4.7	0.191523	0.119133	0.310655599
3	8	2	4	2.77	3.00	5.54	6	0.527698	0.316406	0.844104474
4	8	2	4	1.33	2.10	2.66	4.2	0.028046	0.075969	0.104015282
5	8	2	4	2.37	3.82	4.74	7.64	0.282787	0.83179	1.114576926
6	8	2	4	1.20	1.37	2.4	2.74	0.018586	0.013761	0.032346996
7	8	2	4	2.99	3.55	5.98	7.1	0.716393	0.620402	1.336795328
8	8	2	4	3.07	4.55	6.14	9.1	0.796196	1.674193	2.470389506
9	8	2	4	2.68	3.28	5.36	6.56	0.462387	0.452122	0.914508884
10	8	2	4	2.64	3.15	5.28	6.3	0.435394	0.384594	0.819987598
11	8	2	4	1.30	1.44	2.6	2.88	0.0256	0.016796	0.04239616
12	8	2	4	2.44	3.51	4.88	7.02	0.317706	0.59291	0.91061595
13	8	2	4	2.75	3.77	5.5	7.54	0.512622	0.789088	1.301710101
14	8	2	4	3.08	3.84	6.16	7.68	0.806621	0.849347	1.65596737
15	8	2	4	2.67	3.02	5.34	6.04	0.455524	0.324929	0.780452855
16	8	2	4	1.41	2.00	2.82	4	0.035428	0.0625	0.097927704
17	8	2	4	2.66	3.25	5.32	6.5	0.448738	0.435806	0.884544538
18	8	2	4	1.89	3.04	3.78	6.08	0.11437	0.333622	0.447992195
19	8	2	4	2.71	2.94	5.42	5.88	0.483441	0.291843	0.775284318
20	8	2	4	2.65	3.22	5.3	6.44	0.442028	0.419936	0.861964677
21	8	2	4	2.43	3.03	4.86	6.06	0.31253	0.329254	0.641783568
22	8	2	4	1.61	2.24	3.22	4.48	0.060224	0.098345	0.158569024
23	8	2	4	2.20	2.43	4.4	4.86	0.20997	0.136203	0.346172531
24	8	2	4	1.61	2.52	3.22	5.04	0.060224	0.15753	0.217753674
25	8	2	4	2.21	2.37	4.42	4.74	0.213814	0.12324	0.337054251
26	8	2	4	1.56	1.15	3.12	2.3	0.053084	0.006832	0.059916216
27	8	2	4	2.37	3.39	4.74	6.78	0.282787	0.515892	0.798679366
28	8	2	4	2.79	3.70	5.58	7.4	0.543104	0.732094	1.275198601
29	8	2	4	2.53	3.23	5.06	6.46	0.367239	0.425177	0.792416222
30	8	2	4	2.86	3.90	5.72	7.8	0.599695	0.903688	1.503383251
31	8	2	4	2.59	3.08	5.18	6.16	0.403335	0.35153	0.754865133
32	8	2	4	2.43	3.49	4.86	6.98	0.31253	0.579511	0.892041034
33	8	2	4	2.72	3.72	5.44	7.44	0.490617	0.748052	1.238668535
34	8	2	4	0.99	1.32	1.98	2.64	0.00861	0.011859	0.020469293
35	8	2	4	2.67	4.30	5.34	8.6	0.455524	1.335469	1.790993495
36	8	2	4	2.75	3.98	5.5	7.96	0.512622	0.98015	1.492771608
37	8	2	4	3.54	4.16	7.08	8.32	1.407601	1.169859	2.577459682
38	8	2	4	1.16	1.94	2.32	3.88	0.016229	0.055331	0.071560053
39	8	2	4	2.33	3.02	4.66	6.04	0.264174	0.324929	0.589102603
40	8	2	4	2.33	3.02	4.66	6.04	0.264174	0.324929	0.589102603
41	8	2	4	2.74	4.04	5.48	8.08	0.505206	1.040604	1.545810368
42	8	2	4	3.35	4.80	6.7	9.6	1.128875	2.0736	3.202474815
43	8	2	4	2.60	3.47	5.2	6.94	0.4096	0.566341	0.975940909
44	8	2	4	3.25	3.73	6.5	7.46	1	0.756128	1.756128072
45	8	2	4	3.31	3.75	6.62	7.5	1.075916	0.772476	1.848392606
46	8	2	4	3.27	3.72	6.54	7.44	1.024844	0.748052	1.772895547
47	8	2	4	2.58	3.03	5.16	6.06	0.397142	0.329254	0.726395211
48	8	2	4	2.84	4.76	5.68	9.52	0.583096	2.005339	2.588435014
49	8	2	4	2.60	3.82	5.2	7.64	0.4096	0.83179	1.241389601
50	8	2	4	2.78	2.33	5.56	4.66	0.53536	0.115129	0.65048851
51	8	2	4	2.75	3.89	5.5	7.78	0.512622	0.894455	1.407076991
52	8	2	4	2.38	3.59	4.76	7.18	0.28759	0.64884	0.936430718
53	8	2	4	2.36	4.05	4.72	8.1	0.278045	1.050945	1.328990003
54	8	2	4	2.33	3.23	4.66	6.46	0.264174	0.425177	0.689351455
55	8	2	4	1.71	2.10	3.42	4.2	0.076639	0.075969	0.152608347
56	8	2	4	2.93	4.01	5.86	8.02	0.660598	1.010038	1.670635232
57	8	2	4	3.23	4.78	6.46	9.56	0.975611	2.039255	3.014866304
58	8	2	4	2.29	4.51	4.58	9.02	0.246495	1.616092	1.862587664
59	8	2	4	2.21	3.18	4.42	6.36	0.213814	0.399456	0.613269361
60	8	2	4	3.03	4.22	6.06	8.44	0.755505	1.238825	1.994329176
61	8	2	4	2.87	4.00	5.74	8	0.608127	1	1.6081268
62	8	2	4	2.27	3.86	4.54	7.72	0.237996	0.86718	1.10517618

63	8	2	4	2.66	3.30	5.32	6.6	0.448738	0.46325	0.911988654
64	8	2	4	3.15	4.73	6.3	9.46	0.882488	1.95526	2.837748293
65	8	2	4	3.00	4.75	6	9.5	0.726025	1.988541	2.714565649
66	8	2	4	3.76	4.62	7.52	9.24	1.791505	1.779623	3.571127334
67	8	2	4	3.73	4.74	7.46	9.48	1.73501	1.971848	3.706857455
68	8	2	4	3.73	4.28	7.46	8.56	1.73501	1.310796	3.045805615
69	8	2	4	2.14	2.50	4.28	5	0.187984	0.152588	0.340572221
70	8	2	4	2.62	4.04	5.24	8.08	0.422349	1.040604	1.462953254
71	8	2	4	2.86	3.79	5.72	7.58	0.599695	0.805966	1.405661644
72	8	2	4	3.38	4.62	6.76	9.24	1.169859	1.779623	2.949481261
73	8	2	4	2.19	4.27	4.38	8.54	0.206178	1.298588	1.504766776
74	8	2	4	2.56	2.68	5.12	5.36	0.38497	0.201511	0.586480794
75	8	2	4	3.18	5.41	6.36	10.82	0.91659	3.346178	4.262768262
76	8	2	4	2.26	2.14	4.52	4.28	0.23383	0.081925	0.315754795
77	8	2	4	2.06	1.93	4.12	3.86	0.161412	0.054199	0.215610608
78	8	2	4	3.08	4.16	6.16	8.32	0.806621	1.169859	1.97647937
79	8	2	4	2.45	3.08	4.9	6.16	0.322947	0.35153	0.674477142
80	8	2	4	3.33	4.05	6.66	8.1	1.102157	1.050945	2.153102405
81	8	2	4	1.24	1.49	2.48	2.98	0.021191	0.019253	0.040444387
82	8	2	4	2.74	2.37	5.48	4.74	0.505206	0.12324	0.628446849
83	8	2	4	2.29	3.19	4.58	6.38	0.246495	0.404504	0.650999161
84	8	2	4	2.80	3.89	5.6	7.78	0.550933	0.894455	1.445387751
85	8	2	4	2.13	2.54	4.26	5.08	0.184495	0.16259	0.347085557
86	8	2	4	2.12	2.88	4.24	5.76	0.181055	0.268739	0.449793342
87	8	2	4	2.90	3.47	5.8	6.94	0.633955	0.566341	1.200296079
88	8	2	4	2.10	2.87	4.2	5.74	0.174319	0.265025	0.439344077
89	8	2	4	2.44	3.80	4.88	7.6	0.317706	0.814506	1.132212575
90	8	2	4	1.97	2.87	3.94	5.74	0.134999	0.265025	0.400024758
91	8	2	4	4.92	8.62	9.84	17.24	5.252027	21.56697	26.81899541
92	8	2	4	2.98	2.13	5.96	4.26	0.706857	0.080404	0.787261227
93	8	2	4	2.25	2.50	4.5	5	0.229719	0.152588	0.382306738
94	8	2	4	3.34	4.05	6.68	8.1	1.115456	1.050945	2.166401284

Avg. Value **1.447966429**

S. No.	Vehicle Type	No. of Tyres		Wheel Load (tonnes)		Axle Load (Tonnes)	Axle Load (Tonnes)	EALF	EALF	Total EALF
		1st	2nd	1st	2nd					
1	9	2	4	0.91	1.47	1.82	2.94	0.006147	0.01824	0.0243868
2	9	2	4	1.60	2.10	3.2	4.2	0.058742	0.075969	0.1347108
3	9	2	4	1.56	2.65	3.12	5.3	0.053084	0.192639	0.2457229
4	9	2	4	1.66	2.85	3.32	5.7	0.068061	0.257715	0.325776
5	9	2	4	1.04	1.16	2.08	2.32	0.010486	0.007073	0.0175586
6	9	2	4	1.08	1.43	2.16	2.86	0.012194	0.016334	0.0285289
7	9	2	4	1.18	1.55	2.36	3.1	0.017378	0.022547	0.0399247
8	9	2	4	1.21	1.50	2.42	3	0.019214	0.019775	0.038989
9	9	2	4	1.12	1.76	2.24	3.52	0.014104	0.037481	0.0515848
10	9	2	4	0.83	0.82	1.66	1.64	0.004254	0.001766	0.0060199
11	9	2	4	0.80	1.04	1.6	2.08	0.003671	0.00457	0.0082411
12	9	2	4	1.98	2.18	3.96	4.36	0.137761	0.088224	0.2259852
13	9	2	4	1.84	2.56	3.68	5.12	0.10274	0.167772	0.2705118
14	9	2	4	1.21	2.30	2.42	4.6	0.019214	0.109313	0.1285265
15	9	2	4	0.96	1.34	1.92	2.68	0.007613	0.012594	0.0202074
16	9	2	4	1.07	1.32	2.14	2.64	0.011749	0.011859	0.0236082
17	9	2	4	1.78	3.76	3.56	7.52	0.08998	0.780749	0.8707291
18	9	2	4	1.07	1.30	2.14	2.6	0.011749	0.011157	0.0229057
19	9	2	4	1.24	1.57	2.48	3.14	0.021191	0.023733	0.0449244
20	9	2	4	1.03	1.52	2.06	3.04	0.010088	0.020851	0.0309396
21	9	2	4	0.42	0.54	0.84	1.08	0.000279	0.000332	0.0006111
22	9	2	4	1.33	1.50	2.66	3	0.028046	0.019775	0.0478215
23	9	2	4	1.16	1.41	2.32	2.82	0.016229	0.01544	0.0316689
24	9	2	4	2.15	5.18	4.3	10.36	0.191523	2.812413	3.0039356
25	9	2	4	1.86	1.55	3.72	3.1	0.10728	0.022547	0.1298268
26	9	2	4	1.18	1.35	2.36	2.7	0.017378	0.012975	0.0303524
27	9	2	4	2.01	2.24	4.02	4.48	0.146302	0.098345	0.2446471
28	9	2	4	0.87	1.06	1.74	2.12	0.005135	0.004932	0.0100666
29	9	2	4	0.87	1.06	1.74	2.12	0.005135	0.004932	0.0100666
30	9	2	4	0.98	1.04	1.96	2.08	0.008267	0.00457	0.0128372
31	9	2	4	1.18	2.02	2.36	4.04	0.017378	0.065038	0.0824155
32	9	2	4	0.78	0.62	1.56	1.24	0.003318	0.000577	0.003895
33	9	2	4	2.05	3.04	4.1	6.08	0.1583	0.333622	0.4919222
34	9	2	4	1.40	1.54	2.8	3.08	0.034433	0.021971	0.056404
35	9	2	4	1.15	2.00	2.3	4	0.015677	0.0625	0.0781768
36	9	2	4	1.21	2.15	2.42	4.3	0.019214	0.083467	0.1026804
37	9	2	4	1.18	2.32	2.36	4.64	0.017378	0.113165	0.1305428
38	9	2	4	2.08	3.11	4.16	6.22	0.167772	0.365428	0.5332
39	9	2	4	0.91	0.83	1.82	1.66	0.006147	0.001854	0.0080004
40	9	2	4	1.41	3.12	2.82	6.24	0.035428	0.370151	0.4055783
41	9	2	4	1.34	3.36	2.68	6.72	0.028899	0.497871	0.5267706
42	9	2	4	1.06	3.03	2.12	6.06	0.011316	0.329254	0.3405695
43	9	2	4	1.41	3.33	2.82	6.66	0.035428	0.480327	0.5157547
44	9	2	4	1.42	3.37	2.84	6.74	0.036443	0.503825	0.5402684
45	9	2	4	1.71	1.81	3.42	3.62	0.076639	0.041925	0.1185643
46	9	2	4	2.31	5.50	4.62	11	0.25522	3.574463	3.8296828
47	9	2	4	1.70	4.58	3.4	9.16	0.074862	1.718787	1.7936487
48	9	2	4	1.02	1.68	2.04	3.36	0.009702	0.031117	0.0408191
49	9	2	4	1.95	3.53	3.9	7.06	0.1296	0.606539	0.7361392
50	9	2	4	0.42	0.87	0.84	1.74	0.000279	0.002238	0.0025168
51	9	2	4	1.55	1.96	3.1	3.92	0.051736	0.057648	0.1093841
52	9	2	4	0.90	1.27	1.8	2.54	0.005881	0.010162	0.0160427
53	9	2	4	2.33	3.09	4.66	6.18	0.264174	0.356118	0.6202921
54	9	2	4	3.73	4.52	7.46	9.04	1.73501	1.630474	3.3654832
55	9	2	4	1.46	3.35	2.92	6.7	0.040727	0.491971	0.5326973
56	9	2	4	2.91	4.78	5.82	9.56	0.642745	2.039255	2.6820001
57	9	2	4	0.87	1.33	1.74	2.66	0.005135	0.012223	0.0173577
58	9	2	4	1.75	2.39	3.5	4.78	0.084066	0.127453	0.2115191

Avg. Value **0.413343802**