INFLUENCE OF ADDITIVES ON THE CHARACTERISTICS OF STONE MATRIX ASPHALT

A Thesis

Submitted for the award of the degree of
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BINDU C.S

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Dedicated to my beloved father……………

Certificate

Certified that this thesis entitled **“INFLUENCE OF ADDITIVES ON THE CHARACTERISTICS OF STONE MATRIX ASPHALT”,** submitted to Cochin University of Science and Technology, Kochi for the award of degree of Doctor of Philosophy, under the Faculty of Engineering, is the bonafide research carried out by Smt. Bindu C.S., under my supervision and guidance at School of Engineering, Cochin University of Science and Technology. This work did not form part of any dissertation submitted for the award of any degree, diploma, associateship, fellowship or other similar title or recognition from this or any other institution.

Prof. Dr. K.S Beena
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16.01.2012

DECLARATION

I, Bindu C.S., hereby declare that the work presented in this thesis entitled **"INFLUENCE OF ADDITIVES ON THE CHARACTERISTICS OF STONE MATRIX ASPHALT",** being submitted to Cochin University of Science and Technology for the award of degree of Doctor of Philosophy under the Faculty of Engineering, is the outcome of original work done by me under the supervision of Dr. K.S Beena, Professor in Civil Engineering, School of Engineering, Cochin University of Science and Technology, Kochi. This work did not form part of any dissertation submitted for the award of any degree, diploma, associateship, fellowship or other similar title or recognition from this or any other institution.

Kochi
16.01.2012 **Bindu C.S**

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Bindu C.S

ABSTRACT

The increase in traffic growth and maintenance expenditures demands the urgent need for building better, long-lasting, and more efficient roads preventing or minimizing bituminous pavement distresses. Many of the principal distresses in pavements initiate or increase in severity due to the presence of water. In Kerala highways, where traditional dense graded mixtures are used for the surface courses, major distress is due to moisture induced damages. The Stone Matrix Asphalt (SMA) mixtures provide a durable surface course. Proven field performance of test track at Delhi recommends Stone Matrix Asphalt as a right choice to sustain severe climatic and heavy traffic conditions. But the concept of SMA in India is not so popularized and its application is very limited mainly due to the lack of proper specifications.

Development of stabilized SMA mixtures for improved pavement performance has been the focus of research all over the world for the past few decades. Many successful attempts are made to stabilize Stone Matrix Asphalt mixtures with synthetic fibres and polymers. The concept of using natural fibers and waste materials to replace these energy intensive synthetic fibres or polymer additives is a recent development in this field. India, being an agricultural economy produces fairly huge quantity of natural fibres such as coconut, sisal, banana, sugar cane, jute etc. Now- a - days the disposal of waste plastics is a major concern for an eco- friendly sustainable environment. In line with these thoughts, this research focuses on the utilization of natural fibres and waste plastics as additives to improve the performance of SMA.

This research is an attempt to study the influence of additives on the characteristics of SMA mixtures and to propose an ideal surface course for the pavements. The additives used for this investigation are coir, sisal, banana fibres (natural fibres), waste plastics (waste material) and polypropylene (polymer). A preliminary investigation is conducted to characterize the materials used in this study. Marshall test is conducted for optimizing the SMA mixtures (Control mixture-without additives and Stabilized mixtures with additives). Indirect tensile strength tests, compression strength tests, triaxial strength tests and drain down sensitivity tests are conducted to study the engineering properties of stabilized mixtures. The comparison

of the performance of all stabilized mixtures with the control mixture and among themselves are carried out. A statistical analysis (SPSS package Ver.16) is performed to establish the findings of this study.

Test results have illustrated that, the type of additive and its content play significant roles in the volumetric and mechanical characteristics as well as drain down sensitivity of SMA mixtures. All the volumetric characteristics of SMA mixtures with additives are found to be within the specified limits. Stabilized mixtures with improved stability and Marshall Quotient indicate higher rutting resistance, improved indirect tensile strength value indicates better cracking resistance and improved compressive strength value implies higher resistance to crushing. Higher values of cohesion and shear strength of mix suggest resistance to rutting by shear. Considerable increase in tangent modulus shows the improved elastic stiffness of the mixture. The shape change of the stress-strain curves is more gradual with increase in additive content in SMA and brittle type failure does not seem to occur as in the case of control mixture. Improved retained stability, indirect tensile strength ratio and index of retained strength indicate better resistance of SMA mixtures to moisture induced damages. Observed reduction in drain down values showed the influence of additive in preventing the bleeding phenomena and the drain down of the mixture. All these findings support the influence of additives in Stone Matrix Asphalt mixtures.

Based on the volumetric, mechanical and drain down characteristics of the various stabilized mixtures it is inferred that the optimum fibre content is 0.3% fibre by weight of mixture for all fibre mixtures irrespective of the type of fibre. For waste plastics and polypropylene stabilized SMA mixtures, the optimum additive contents are respectively 7% and 5% by weight of mixture.

Regarding the volumetric characteristics, fibre stabilized mixtures show higher air voids and voids in mineral aggregates than the other mixtures, but the voids filled with bitumen is more in waste plastics stabilized mixtures. But in all stabilized mixtures, the volumetric results are within the specification range. SMA mixes with waste plastics indicates the highest Marshall stability, Marshall quotient, bulk specific gravity, indirect tensile strength and compressive strength showing its better resistance against permanent deformations, cracking and crushing as compared to other

stabilized mixtures. But the shear strength value of coir fibre mix is greater than that of waste plastics mix. Even though all the mixtures show higher retained stability, tensile strength ratio and index of retained strength, addition of waste plastics in the SMA mixture gives the best result and exhibit superior water resistance property. Due to the absorptive nature of fibres, fibre stabilizers are found to be more effective in reducing the drain down of the SMA mixture. But the drain values for the waste plastics mix is also within the required specification range.

The coir fibre additive is the best among the fibres investigated. Sisal and banana fibre mixtures showed almost the same characteristics on stabilization. Waste plastics, which is the best additive among all the additives investigated, can replace the expensive polymers in SMA mixtures and shows even better performance than coir fibres. The statistical analysis authenticates the experimental findings.

The present study brings out the importance of the use of additives in Stone Matrix Asphalt and suggests an eco- friendly alternative to synthetic fibres and polymer additives. Extensive laboratory investigations carried out provide a thorough understanding of the engineering behaviour of the SMA mixture with various additives, which increases the level of confidence in the field application of this material. Waste plastics stabilized Stone Matrix Asphalt is the best among the mixtures investigated which is an ideal surface for Kerala highways contributing to environmental sustainability by replacing energy intensive synthetic fibers and polymers along with finding out an effective solution for the disposal of waste plastics.

Keywords:

Stone Matrix Asphalt, stabilizing additives, volumetric characteristics, stability and strength characteristics, drain down sensitivity, moisture susceptibility.

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LIST OF ABBREVIATIONS/SYMBOLS

SMA	Stone Matrix Asphalt
NAPA	National Asphalt Pavement Association
HMA	Hot Mix Asphalt
ASTM	American Society for Testing and Materials
NCAT	National Center for Asphalt Technology
AASHTO	American Association of State Highway and Transportation Officials
OPC	Ordinary Portland Cement
G_{mm}	Theoretical maximum specific gravity of mix
G_{mb}	Bulk specific gravity of the mix
VA	Air voids
VMA	Voids in mineral aggregate
VFB	Voids filled with bitumen
P_{be}	Effective bitumen content
V_{ab}	Volume of absorbed bitumen
MQ	Marshall Quotient
OBC	Optimum Bitumen Content
WP	Waste plastics
PP	Polypropylene
ITS	Indirect tensile strength
TSR	Tensile strength ratio
CS	Compressive strength
IRS	Index of retained strength
c	Cohesion
φ	Angle of internal friction

Chapter 1

INTRODUCTION

1.1 GENERAL

Road network is vital to the economic development, trade and social integration of a country. It facilitates smooth conveyance of both people and goods. Global competition has made the existence of efficient road transport an absolute imperative. Transport demand in India has been growing rapidly since independence. Easiness in accessibility, flexibility of operations, door-to-door service and reliability has earned road transport an increasingly higher share of both passenger and freight traffic vis-a-vis other transport modes. In recent years this demand has shifted mainly to the advantage of road transport, which carries about 87 percent and 61 per cent of passenger and freight transport respectively (COCSSO, 2011). Road transport has grown, despite significant barriers, to inter- state freight and passenger movement compared to inland waterways, railways and air which do not face rigorous enroute checks/barriers.

According to the Road Network Assessment by National Highway Authority of India, national highways constitute approximately 2% of the total road network of India, but carry nearly 40% of the total traffic. India has 67,000 km of highways connecting all the major cities and state capitals. Most of them are two-lane highways with paved roads. They are widened to four lanes and eight lanes in developed areas and large cities. As per latest reports, 19,064 km of the National Highway system still consists of single-laned roads. The government is currently working to ensure that by December 2014 the entire National Highway network consists of roads with two or more lanes (Balchand, 2010). The total road length in India had increased significantly from 3.99 lakh km as on 1951 to 42.36 lakh km as on 2008. Concomitantly, the surfaced road had increased from 1.57 lakh km to around 20.90 lakh km over the same period (GOI, 2010).

The average annual increase in maintenance expenditure increases with the increase in vehicle registrations. This demands the urgent need for building better, long-lasting, and more efficient roads preventing or minimizing bituminous pavement distresses. The condition of the roads has a direct impact on travel costs, from vehicle operations, to traffic delays and to crash-related expenses. Roads in poor condition cause vehicle wear, tear, and even damage. Also, traffic queuing and delays occur when vehicles slow down to avoid important pavement distresses (e.g., potholes) or when the road surface fails to provide safe maneuvering and/or adequate stopping conditions. Many of the principal distresses in bituminous pavements initiate or increase in severity due to the presence of water. When moisture is present in the pavement, the mechanical properties of the material deteriorate and the serviceability of the pavement gets reduced.

1.2 SCENARIO IN KERALA

Kerala can be proud of having developed a good road network compared to other States in India. Transportation infrastructure of Kerala consists of 1.62 lakh km of road, 1148 km of railways, 1087 km of inland waterways, 111 statute miles of airways and 17 ports. Even though it is comparatively better placed than other States as regards to road length, the quality of many of these roads are in poor condition.

Traffic in Kerala has been growing at a rate of 10–11% every year, resulting in high traffic intensity and pressure on the roads. Kerala's road density is nearly four times the national average, reflecting the state's high population density. Inadequate maintenance and the harsh monsoon resulted in potholed roads. The entire state of Kerala is classified as one meteorological subdivision for climatological studies. The state experiences humid and tropical monsoon climate, with seasonal heavy rainfall, followed by hot summer. The month of March is the hottest, with a mean maximum temperature of about 33˚C. The total annual rainfall varies from 3600 mm in the northern part of the state to about 1800mm in the south. The South-West monsoon (June - October) is the principal rainy season, when the state receives about 70% of its annual rainfall. Maximum rainfall is in June and July, accounting individually to about 23% of annual rainfall (Attri and Tyagi, 2010**).**

Roads in Kerala get damaged mainly on account of torrential rains during the Monsoon season. The annual road maintenance and repairs cannot withstand the severity of rains. The other reasons for the faster deterioration of roads are insufficient pavement strength to accommodate the increase in traffic (10 - 11% every year) and inadequate drainage system. Pavement shows severe distresses (cracks, large potholes, edge breaks and damaged shoulders with high edge drops).

1.3 BITUMINOUS PAVING MIXES USED IN INDIA

Bituminous mixes are used in a flexible pavement to serve the following three important functions such as improved structural strength, facilitating subsurface drainage and providing surface friction especially in wet condition. The bituminous paving mixes as specified in MoRTH specifications (MoRTH, 2001) are commonly used in India. Mixes like bituminous concrete, semi-dense bituminous concrete, premix carpet, mix-seal surfacing etc., are commonly provided as wearing courses.

Unlike most developed countries, overloading is a major concern in India. The axle loads in India are quite heavy and further the speed is low with many stop/start condition which leads to the rutting of currently used bituminous mixes in India. Several studies have shown that permanent deformation (rutting) within flexible pavement is usually confined to the top 100 to 150 mm of the pavement. This means that both the binder and wearing course mixes should be designed to be resistant to rutting. That is why in cases of heavy traffic loads and high tyre pressures, it is considered prudent to use Stone Matrix Asphalt (SMA) mix which is the apt specification as per international practice (Kandhal, 2002). The load is carried directly by the coarse aggregate skeleton due to stone-on-stone contact. This will result in a long-lasting pavement with minimum maintenance which is going to be the future concern in India. The advantages of such specifications lie not only in long life but also in the reduced cost of travel with better serviceability. Recently, the Indian Roads Congress (IRC) has adopted a tentative SMA specification, (IRC SP 79:2008) which could be used under such circumstances.

1.4 SMA FOR KERALA HIGHWAYS

Stone matrix Asphalt is the right choice to provide a strong surfacing that can handle the climate and the heavy traffic of a typical Kerala Highway. Roads in Kerala have to withstand almost six months of heavy rain and will be in a damaged condition for the major part of every year. This results in an improper communication facility. Without proper and effective communication facility like roads, economic growth will not be achieved. Increased life of Stone Matrix Asphalt pavements will justify the additional cost involved during initial construction (Kevin and Trenton, 2007). Apart from that, the huge expenses incurred for the periodic maintenance of roads can be eliminated (Normally the repair work during the rainy season will have only one or two week's life).

1.5 SCOPE OF STUDY

In Kerala highways, major distress is due to the rain induced damages. It is a well established fact in developed countries that the water induced damages are expected to be less in a gap graded mix like Stone Matrix Asphalt than traditional mixes. But application of SMA in India is very limited due to lack of proper specifications. This necessitates the need for thorough experimental and field investigations in various aspects of SMA, in context of India.

Presently, synthetic fibres or polymers are used as stabilizing additives in SMA. Replacement of expensive imported synthetic fibres and polymer additives with renewable/waste material in SMA is an environmental necessity. Here, a study on the impact of natural fibre / waste material as additives in Stone Matrix asphalt and their role in the volumetric, mechanical and drain down characteristics of the mixture is proposed. Emphasis is also given to assess the effect of water immersion on the performance of SMA mixtures with different additives. The rutting characteristics of the mix are intended to study indirectly by analyzing the stability and strength characteristics of the mixtures.

1.6 RESARCH OBJECTIVES

Considering the importance of the problem discussed, this research mainly focuses on the following objectives.

- The main objective of this study is to propose a durable surface course with Stone Matrix Asphalt by exploring the utilization of various additives such as natural fibres and waste plastics which are abundantly available and to provide an eco friendly surface for Kerala highways.

- To evaluate the role of additives
    - On the mechanical and volumetric characteristics of SMA mixtures.
    - On the moisture susceptibility of SMA mixtures.
    - In the drain down sensitivity of SMA mixtures.
- To study the effect of additives in SMA and to arrive at the optimum additive content of the mixtures.
- To propose the best natural fibre additive from the fibre stabilized SMA mixtures.
- To investigate the suitability of waste plastics to replace the expensive polymer additives in SMA.
- To suggest the best additive from all the SMA mixtures investigated.

1.7 METHODOLOGY

An extensive literature review on bituminous mixtures is to be carried out. Based on that a systematic experimental investigation has to be planned to study the volumetric, stability, strength and drain down characteristics of the mix. A statistical analysis is also intended to establish the results mathematically.

• Literature Review

Literature review has to be conducted to identify the existing situation of roads in India, issues in maintenance and other problems related with durability. Secondary data can be collected from Government documents and reports published by the research institutions. Thorough literature study has to be carried out to analyze various researches on bituminous mixtures (Dense graded, Open graded and Gap graded mixtures) with and without additives.

• Experimental Research

Based on the literature review, experimental research programme has to be formulated. As a preliminary investigation, procurement of various ingredients of

SMA and the evaluation of its properties has to be carried out. Marshall tests are proposed for the mix design of SMA (with and without additives). Indirect tensile strength test, compressive strength test and triaxial test are proposed for assessing the strength characteristics of SMA mixtures. The effects of additives against moisture induced damages on SMA mixtures can be studied by determining the retained stability, tensile strength ratio and index of retained strength of various mixtures. Drain down test is proposed on different SMA mixtures to assess the binder drain down. A comparative study on different characteristics (volumetric, mechanical and drain down) of various stabilized mixtures with varying additive contents and types has to be carried out for optimization. The ideal mix has to be proposed from the various SMA mixtures with optimum additive content.

- **Statistical Analysis**

Statistical Analysis can be employed for verifying the precision of the results of various experimental programmes proposed in this research. SPSS package is proposed for this study as an ideal tool for the selection of best SMA mix from the optimized mixes and for the comparison of various SMA mixtures. In order to test the significant difference in the various properties at various levels of additive contents, ANOVA has to be carried out and if significant interaction is found, Tukey’s Homogeneous Groups comparison should be applied to perform more detailed analysis. The optimum additive contents of every mix with respect to different parameters like stability, bulk specific gravity, tensile strength, compressive strength, cohesion, shear strength and drain down characteristics are to be identified. The significance of differences in mean values of parameters at various levels of additive contents are to be tested by ANOVA. Then a comparison of different additive stabilized mixtures at these optimum contents are to be carried out so as to arrive at the best fibre additive from the fibre stabilized mixtures by ANOVA and also the best additive among the waste plastics and polypropylene stabilized mixtures by paired t-test. A pair wise comparison is also to be made between the best among these stabilized mixtures by t-test for independent samples.

1.8 ORGANISATION OF THE THESIS

This thesis consists of ten chapters. The contents of various chapters are briefly described below.

Chapter 1 illustrates a brief description of the transport infrastructure of India and Kerala with special emphasis on the problems of Kerala highways. An outline of the bituminous paving mixes used in India and the associated problems are mentioned. Scope of the study, research objectives and methodology for the present study is also discussed.

Chapter 2 critically reviews the literature on previous studies in the field of bituminous mixtures. The classification of bituminous mixtures with special reference to SMA, its history, composition, advantages and disadvantages are discussed. A comprehensive summary of the literature associated with SMA and other bituminous mixtures with different additives like fibres, polymers and waste materials is also presented.

Chapter 3 on Material characterisation gives an overview of the materials used for the study and its properties.

Chapter 4 presents the details of the laboratory work conducted for the mix, design of the different SMA mixtures and their analysis are presented. Marshall method of mix design and the test procedure are discussed. Results of all stabilized mixtures are analyzed separately and discussed. Influence of additive content on optimum bitumen content of the SMA mixture is also discussed.

Chapter 5 explains the investigations on the indirect tensile strength of different SMA mixtures with different additive types and contents. The tensile strength ratio of various mixtures is determined to arrive at the water induced damages. Detailed descriptions of the test results of different mixtures within themselves and with control mixture are also presented in this chapter.

Chapter 6 deals with the description of the compressive strength test and the strength values of different SMA mixtures with different additive types and contents. The indices of retained strength values of different SMA mixtures and the effect of water on the strength are also discussed. A comparison of the test results of various mixtures within themselves and with control mixture is also discussed.

Chapter 7 narrates the application of triaxial test to pavement design, principles of triaxial testing, specimen fabrication, test conditions and test procedure. A detailed discussion of the triaxial test results is also included in this chapter.

Chapter 8 discusses the drain down sensitivity of the various SMA mixtures and the stabilizing capacities of different additives used for the present study. A comparison of these SMA mixtures with the control mixture is also presented.

Chapter 9 presents the statistical analysis of the experimental programme. It has been done by using SPSS package Ver.16. By using this statistical tool, the optimum additive contents of every mix with respect to different parameters stability, bulk specific gravity, tensile strength, compressive strength, cohesion, shear strength and drain down characteristics are identified using descriptive values. The significance of differences in mean values of parameters at various levels of additive contents are tested by ANOVA. Then a comparison of different additive stabilized mixtures at these optimum contents are carried out so as to arrive at the best fibre additive from the fibre stabilized mixtures by ANOVA and also the best additive among the waste plastics and polypropylene stabilized mixtures by paired t- test. A pair wise comparison is also made between the best among these stabilized mixtures by t-test for independent samples. A comparison between waste plastics stabilized and coir fibre stabilized SMA carried out by Levene's test for Equality of variances is also presented.

Chapter 10 presents the conclusions derived from this research. This chapter highlights the influence of additives on the characteristics of SMA and supports the selection of ideal stabilized SMA mix from the mixtures investigated. Scope for further research is also presented in this chapter.

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Chapter 2

REVIEW OF LITERATURE

2.1 INTRODUCTION

India being the second largest growing economy in the world, in par with other developmental activities, road infrastructure is developing at a very fast rate. Large scale road infrastructure developmental projects like National Highway Development Project (NHDP) and Pradhan Manthri Gram Sadak Yojna (PMGSY) are in progress. The spurt in the growth of traffic and overloading of vehicles decreases the life span of roads laid with conventional bituminous mixes. This also leads to the reduction in the riding quality resulting in exorbitant vehicle operating costs and frequent maintenance interventions due to premature failure of pavements. Providing durable roads has always been a problem for a country like India with varied climate, terrain condition, rainfall intensities and soil characteristics. A good amount of research is going on all over the country in this field to solve the problems associated with pavements. It is observed that Stone Matrix Asphalt mixture is an ideal mixture for long lasting Indian Highways. The literature pertaining to the bituminous mixtures is reviewed in this chapter with a detailed discussion of SMA mixtures.

2.1.1 Flexible Pavements

Flexible pavements are called "flexible" since the total pavement structure "bends" or "deflects" due to traffic loads. This pavement structure generally composed of several layers of materials which can accommodate this "flexing". In this type of pavements, material layers are usually arranged in the order of descending load bearing capacity with the highest load bearing capacity material (and most expensive) on the top and the lowest load bearing capacity material (and least expensive) on the bottom. The surface course is the stiffest and contributes the most to the pavement strength. The underlying layers are less stiff but are still important to pavement strength as well as drainage and frost protection. A typical flexible pavement structure (Fig. 2.1) consists of surface course, base course and subbase course (optional).

The surface course is the top layer in contact with traffic loads. This layer provides the characteristics such as friction, smoothness, noise control, rut resistance and drainage. In addition, it serves to prevent the entrance of excess quantities of surface water into the underlying base, sub base and subgrade courses (NAPA, 2001). The topmost layer of the surface course which is in direct contact with traffic loads is the wearing course. This can be removed and replaced as and when it becomes damaged or worn out. The wearing course can be rehabilitated before distress propagates into the underlying intermediate / binder course. This layer which constitutes the major portion of the surface course is meant to distribute the load coming over it. The base course is the layer directly below the surface course which helps in transmitting the load to the subgrade and generally consists of aggregate either stabilized or unstabilized. Bituminous mixes like Hot Mix Asphalt can also serve as a base course. Under the base course layer, a layer of less expensive / inferior quality material can be provided as subbase course material over the subgrade. The subbase course is optional in many cases.

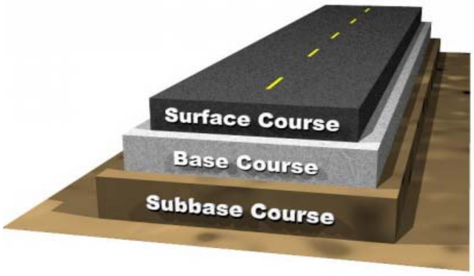

Fig. 2.1 Basic flexible pavement structure

2.2 CLASSIFICATION OF BITUMINOUS MIXTURES

A bituminous mixture is a combination of bituminous materials (as binders), properly graded aggregates and additives. Bituminous mixtures used in pavement applications are classified either by their methods of production or by their composition and characteristics.

By the *method of production*, bituminous mixtures can be classified into Hot-mix asphalt (HMA), Cold-laid plant mix, Mixed-in-place or road mix and Penetration macadam. Hot-mix asphalt is produced in hot asphalt mixing plant (or hot-mix plant) by mixing a properly controlled amount of aggregate with a controlled amount of bitumen at an elevated temperature. The mixing temperature has to be sufficiently high such that the consistency of bitumen is fluid enough for proper mixing and coating the aggregate, but not too high as to avoid excessive stiffening of the asphalt. HMA mixture must be laid and compacted when the mixture is still sufficiently hot so as to have proper workability. They are the most commonly used paving material in surface and binder courses in bituminous pavements. Cold-laid plant mix is produced in a bitumen mixing plant by mixing a controlled amount of aggregate with a controlled amount of liquid bitumen without the application of heat. It is laid and compacted at ambient temperature. Mixed-in-place or road mix is produced by mixing the aggregates with the bitumen binders in the form of emulsion (medium setting or slow setting) in proper proportions on the road surface by means of special road mixing equipment. Penetration macadam is produced by a construction procedure in which layers of coarse and uniform size aggregate are spread on the road and rolled, and sprayed with appropriate amounts of bitumen to penetrate the aggregate. The bituminous material used may be hot bitumen or a rapid setting bitumen emulsion.

Bituminous mixtures can be classified by their method of *composition and characteristics* as Dense-Graded HMA, Open-Graded HMA and Stone Matrix Asphalt (SMA). Dense-graded mixtures (Fig. 2.2) has a dense-graded aggregate gradation (aggregates are evenly distributed from coarse to fine) and have a relatively low air voids after placement and compaction. They are commonly used as surface and binder courses in bituminous pavements. The term bituminous concrete is commonly used to refer to a high-quality, dense-graded HMA mixture. A dense graded HMA mixture with maximum aggregate size of greater than 25 mm is called a large stone dense-grade HMA mix, whereas a mix with 100% of the aggregate particles passing through the 9.5mm sieve is called a sand mix.

Unlike dense-graded mixes, an open-graded HMA mixture (Fig. 2.3) has a relatively larger size aggregate that contains very little or no fines, they are designed to be water permeable. Due to less aggregate surface area, these mixes have relatively lower bitumen content than that of a dense-graded HMA mix.

Stone Matrix Asphalt (SMA) is a gap graded bituminous mixture containing a high proportion of coarse aggregates and filler with relatively less medium sized aggregates (Fig. 2.4). It has high binder content and low air voids with high levels of macro texture when laid resulting in waterproofing with good surface drainage.

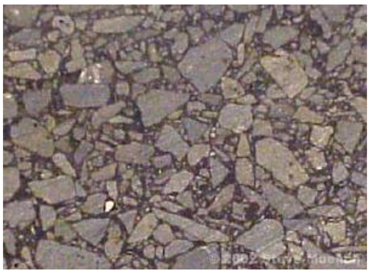

Fig. 2.2 Dense graded HMA

Fig. 2.3 Open graded HMA

Fig. 2.4 Stone Matrix Asphalt

For a comparison, a view of a typical SMA mixture and a conventional dense graded mixture (NAPA, 1999) is shown in Fig. 2.5. Cores from SMA mixtures (left) illustrate the greater percentage of fractured aggregate and higher percentage of bitumen binder, compared to the conventional Hot Mix Asphalt (HMA) mixture (right) which contains a more uniform aggregate gradation and less bitumen binder.

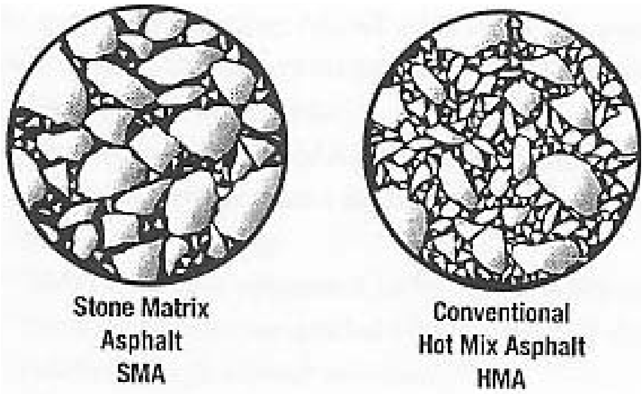

Fig. 2.5 Comparisons between SMA and conventional HMA

2.3 ADDITIVES IN BITUMINOUS MIXES

Bitumen modification / reinforcement have received considerable attention as viable solutions to enhance flexible pavement performance. The introduction of this technology to the transportation industry was mainly prompted by the unsatisfactory performance of traditional road materials exposed to remarkable increase and changes in traffic patterns. Since then, various types of modifiers for bituminous mixtures like fibres and polymers are considered. It has been possible to improve the performance of bituminous mixes used in the surfacing course of road pavements, with the help of various types of stabilizing additives. The additives such as fibres, rubbers, polymers, carbon black, artificial silica, or a combination of these materials are used to stiffen the mastic at high temperatures during production and placement, and to obtain even higher binder contents for increased durability (Pierce, 2000). Since Stone Matrix Asphalt is the focus of the present study, the literature pertaining to that has been presented as a separate session after this. The following is a review of the work done in bituminous mixes stabilized with various additives.

2.3.1 Fibre as an additive

The history of the use of fibres can be traced back to a 4000 year old arch in China constructed with a clay earth mixed with fibres or the Great Wall built 2000 years ago (Hongu and Philips,1990). However, the modern developments of fibre reinforcement started in the early 1960s (Mahrez, 2003). Zube (1956) published the earliest known study on the reinforcement of bituminous mixtures. This study evaluated various types of wire mesh placed under an overlay in an attempt to prevent reflection cracking. The study concluded that all types of wire reinforcement prevented or greatly delayed the formation of longitudinal cracks. Zube suggests that the use of wire reinforcement would allow the thickness of overlays to be decreased while achieving the same performance. No problem was observed with steel and bituminous mixture compatibility.

Fibres are added as reinforcement in bituminous mixtures. Reinforcement consists of incorporating certain materials with some desired properties within other material which lack those properties (Maurer and Gerald, 1989). Fundamentally, the principal functions of fibres as reinforcing materials are to provide additional tensile strength in the resulting composite and to increase strain energy absorption of the bituminous mixtures (Mahrez et al., 2005).

Some fibres have high tensile strength relative to bituminous mixtures, thus it was found that fibres have the potential to improve the cohesive and tensile strength of mixes. They are believed to impart physical changes to bituminous mixtures (Brown et al., 1990). Research and experience have shown that fibres tend to perform better than polymers in reducing the drain down of bituminous concrete mixtures that is why fibres are mostly recommended (Hassan et al., 2005). Because of the inherent compatibility of fibres with bitumen and its excellent mechanical properties, adding fibres to bitumen enhances material strength and fatigue characteristics while at the same time increasing ductility (Fitzgerald, 2000). According to Maurer and Gerald (1989), fibre reinforcement is used as a crack barrier rather than as a reinforcing element whose function is to carry the tensile loads as well as to prevent the formation and propagation of cracks.

Finely divided fibres also provide a high surface area per unit weight and behave much like filler materials. Fibres also tend to bulk the bitumen, so it will not run off from the aggregates during construction. In terms of efficiency, mixtures with fibre showed a slight increase in the optimum binder content compared to the control mix. In this way, adding fibres to bitumen is very similar to the addition of very fine aggregates to it. Thus, fibre can stabilize bitumen to prevent leakage (Peltonen, 1991).

It is important to know that the appropriate quantity of bitumen needed to coat the fibres depend on the absorption rate and the surface area of the fibres. It also depends on the concentration and type of fibres (Button and Lytton 1987). If the fibres are too long, it may create the so called ‘‘balling” problem, i.e., some of the fibres may lump together, and the fibres may not blend well with the bitumen. In the same way, too short fibres may not provide any reinforcing effect. They may just serve as expensive filler in the mix.

Fundamentally, fibre improves the different properties of the resulting mix. It changes the viscoelasticity of the modified bitumen (Huang and White 1996), increases dynamic modulus (Wu, Ye and Li,2007), moisture susceptibility (Putman and Amirkhanian, 2004), creep compliance, rutting resistance (Chen et al., 2004) and freeze– thaw resistance (Echols, 1989), while reducing the reflective cracking of bituminous mixtures and pavements (Echols, 1989; Tapkın et al., 2009, Maurer and Malasheskie,1989). Goel and Das (2004) reported that fibre-reinforced materials develop good resistance to ageing, fatigue cracking, moisture damage, bleeding and reflection cracking.

Serfass and Samanos (1996) examined the effects of fibre-modified bitumen on bituminous mixtures utilizing asbestos, rock wool, glass wool and cellulose fibres.

The tests conducted included resilient modulus, indirect tensile strength, rutting resistance and fatigue resistance. Three studies were performed on a test track in Nantes, France. The first study showed that, fibre modified mixtures maintained the highest percentage of voids with a 13 metric ton axle load for 1.1 million times, compared with unmodified and the other two elastomer modified mixtures. The authors concluded that the decreased susceptibility to moisture related distress in the porous mixtures tested is due to better drainage. In the second study, two million load applications were applied to fibre-modified bituminous mixture which was used as an overlay on pavements with signs of fatigue distress. After the load applications, the pavement surface was noted to have a well maintained macrostructure, and practically no cracking. Fibre modified overlays were also constructed over fatigued pavements in the third study reported by them. After 1.2 million load applications, it was observed that all of the fibre modified overlays showed no sign of fatigue related distresses or rutting compared to the unmodified samples which showed signs of distress. This was in agreement with the findings of the second study, establishing that the fatigue life of the fibre modified pavement is improved over unmodified mixtures. Fibre modification also allowed for an increase in film thickness, resulting in less ageing and improved binder characteristics. Addition of fibres also resulted in the reduction of temperature susceptibility of bituminous mixtures.

Simpson et al. (1994) conducted a research on modified bituminous mixtures using polypropylene, polyester fibres and polymers. Two blends of modified binder were evaluated. An unmodified mixture was used as a control sample. Mixtures containing polypropylene fibres were found to have higher tensile strength and resistance to cracking than the others.

Studies by Brown et al. (1990), showed that some fibres have high tensile strength relative to bituminous mixtures, thus it was found that fibres have the potential to improve the cohesive and tensile strength of bituminous mixes. They are believed to impart physical changes to bituminous mixtures by the phenomena of reinforcement and toughening. This high tensile strength may increase the amount of strain energy that can be absorbed during the fatigue and fracture process of the mix. Finely divided fibres provide a high surface area per unit weight and behave much like filler materials. Fibres also tend to bulk the bitumen so it will not run off from the aggregates during construction.

Previous researches (Marais, 1979; Chen and Lin, 2005; Amit and Animesh 2004; Tapkin, 2008) showed that the addition of fibre into bitumen increases the stiffness of the bitumen binder resulting in stiffer mixtures with decreased binder drain down. The fibre modified mixtures showed improved Marshall properties with increased stability and bulk specific gravity values compared to the control mix. Fibres appear to have the potential to improve fatigue life and deformation characteristics by increasing rutting resistance. The tensile strength and related properties of mixtures containing fibres were found to improve. In terms of workability, mixtures with fibres showed a slight increase in the optimum binder content compared to the control mix. This is similar to the addition of very fine aggregates. The proper quantity of bitumen needed to coat the fibres is dependent on the absorption and the surface area of the fibres and is therefore affected not only by different concentrations of fibres but also by different fibre types (Button and Lytton, 1987). According to Mills and Keller (1982), the degree of homogeneity of dispersion of the fibres within the mix will determine the strength of the resulting mixtures. The results obtained from the different field studies showed that the addition of fibre have a benefit since it will help to produce more flexible mixtures with more resistant to cracking (Jiang et al., 1993).

The design methods of bituminous mixtures primarily include the well-known Marshall design method and Superpave design method. In the design procedure bitumen content plays a key role in determining the engineering properties of mixture, which is determined in terms of the volumetric properties of mixture (specific gravity, air void, etc.) in both the Marshall and Superpave mixture design procedures. However, the volumetric properties of fibre-reinforced bitumen mixture are different from that of the ordinary bituminous mixture (Serfass and Samanos, 1996). Therefore, it is essential to investigate the volumetric properties of these mixtures to design more reliable ones. Fibre content plays an important role in determining the volumetric and engineering properties of bituminous mixtures. It was reported that there exists some optimum fibre content to achieve the maximum tensile strength and toughness (Chen et al., 2004). In many cases, fibre content is determined only according to the engineering practices or manufacturer's recommendation.

Bushing and Antrim (1968) used cotton fibres in bituminous mixtures. These were degradable and were not suitable as long term reinforcement. Metal wires has been proposed by Tons and Krokosky (1960), but they were susceptible to rusting with the penetration of water. Asbestos fibres were also used in pavement mixes until it was determined as a health hazard (Kietzman, 1960; Marais, 1979). With the new developments in the technology of production, natural fibre reinforced bituminous mixtures can be cost competitive when compared with modified binders.

The natural coir fibre which is a cheaper and an ecofriendly alternative to synthetic fibre, can be effectively used as a stabilizing additive in bituminous concrete (Bindu and Beena, 2009). The percentage increase in retained stability of the mixture as compared to the conventional mix was about 14% at the optimum fibre content of 0.3% and the reduction in bitumen content is 5% giving an appreciable saving in binder.

2.3.2 Polymer as an additive

Bituminous pavements have experienced accelerated deterioration due to traffic growth and climatic conditions. When a load is applied to the surface of a bituminous pavement it deforms. But bitumen, being a viscoelastic material, the majority of the deformation recovers when the load is removed. However, there is a minute amount of irrecoverable viscous deformation which remains in the bitumen and which results in a very small permanent residual strain. Accumulation of millions of these small strains due to axle loading results in the surface rutting familiar on heavily trafficked pavements. Laboratory tests that attempt to measure the rutting resistance, i.e., the resistance to permanent deformation of a bituminous mix, are: the Marshall test, static and dynamic creep tests, wheel-tracking tests, and laboratory test track tests (Robertus et al., 1995). Bitumen with polymers form multiphase systems, which usually contain a phase rich in polymer and a phase rich in bitumen not absorbed by the polymer. The properties of bitumen-polymer blends depend on the concentrations and the type of polymer used. The polymer is usually loaded in concentrations of about 4–6% by weight with respect to the bitumen. Higher concentrations of polymers are considered to be economically less viable and also may cause other problems related to the material properties (Giovanni et al., 2004).

Polymers are long-chain molecules of very high molecular weight, used by the binder industry. These can be grouped into three main categories: thermoplastic elastomers, plastomers, and reactive polymers based on the mechanism of resistance to deformation. Thermoplastic elastomers are obviously able to confer good elastic properties on the modified binder, while plastomers and reactive polymers are added to improve rigidity and reduce deformations under the load. For a polymer to be effective in road applications, it should blend with the bitumen and improve its resistance to rutting, abrasion, cracking, fatigue, stripping, bleeding, ageing, etc. at medium and high temperatures without making the modified bitumen too viscous at mixing temperatures or too brittle at low temperatures. It can also blend with aggregate and heated so as to have a coating on the aggregate which leads to an improvement in the overall performance of the pavement. Many polymers have been used in the modification process but thermoplastic elastomers are enjoying wide acceptance as road bitumen modifiers (Bonemazzi, 1996).

The load-deformation behavior of elastomers is similar to that of a rubber band which regains its initial state after the removal of load. Plastomers, on the other hand, exhibit high early strength but are less flexible and are more prone to fracture under high strains than elastomers (Mostafa and Gerardo, 2003). Examples of the plastomeric types of polymers for bitumen modification are polyethylene (PE), ethylene-vinyl acetate (EVA), and ethylene-butyl acrylate (EBA) random copolymers (Giovanni et al., 2004). Polymers have been utilized for the purpose of improving the high and low temperature characteristics of bituminous compositions, as well as to improve their toughness and durability. Additives such as styrene based polymers, polyethylene based polymers, polychloroprene, gilsonite, various oils, and many other modifiers including tall oil have been added to bitumen to enhance various engineering properties of binder (Al- Hadidy and Tan, 2008).

2.3.3 Waste material as an additive

The growth in various types of industries together with population growth has resulted in enormous increase in the production of various types of waste materials, world over. The creation and disposal of non-decaying waste materials such as blast furnace slag, fly-ash, steel slag, scrap tyres, plastics etc., have been posing difficult problems in developed as well as in developing countries. Considerable work has been done in various countries for the disposal and utilization of some of these waste products (Schroceder, L.R., 1994). Among them, the work done in India, particularly at the Central Road Research Institute (CRRI), New Delhi on the use of waste materials like fly-ash and slag in road construction is note worthy.

The history of adding recycled tyre rubber to bituminous paving material can be traced back to the 1940s when the U.S. Rubber Reclaiming Company began marketing a devulcanized recycled rubber product, called Ramflex, as a dry particle additive to bituminous paving mixture. In the mid 1960s, Charles McDonald developed a modified bituminous binder with the addition of crumb rubber called Overflex (Weidong, 2007). Huang et al., (2007) have reported on the incorporation of a number of waste streams into bitumen, including glass, steel slag, tyres and plastics. Dry process involves direct incorporation of waste plastics which is blended with aggregate before adding in bitumen, to prepare a plastic modified bituminous mix. Wet process involves simultaneous blending of bitumen and waste plastics.

According to Larry (1993), re-cycled polyethylene from grocery bags may be useful in bituminous pavements, resulting in reduced permanent deformation in the form of rutting and reduced low temperature cracking of the pavement surfacing. Zoorob (2000) and Zoorob and Suparma (2000) have reported greater durability and fatigue life in modified mixes with recycled plastics compared to polypropylene and low density polyethylene. Considerable research has been carried out to determine the suitability of plastic waste as a modifier in construction of bituminous mixes (Schroceder, 1994; Punith and Veeraragavan, 2007). Denning (1993) reported that asphalt concrete which employ polyethylene modified binders are more resistant to rutting during elevated seasonal temperatures. Goodrich (1998) reported that generally a modifier improves the properties of bituminous mixtures in many ways. Some of the improvements in the properties are improved elastic properties to withstand severe loading conditions, increase in resistance to deformation, smoother riding surface, increased stability of the mix, higher retained strength after exposure to moisture, improved skid resistance to ageing caused by atmosphere, improved resistance to low temperature cracking, higher softening point etc.. Zoorab and Suparma (2000) reported the use of recycled plastics composed predominantly of polypropylene and low density polyethylene in plain bituminous concrete mixtures with increased durability and improved fatigue life. Resistance to deformation of asphaltic concrete, modified with waste plastics consisting predominantly of low density polythene, was improved in comparison with unmodified mixes (Little, 1993). Coating of waste plastics on stone aggregate improved the physical properties of aggregates and significant improvements were observed in Marshall Stability, indirect tensile strength and rutting of bituminous concrete mixes (Sabina et al., 2009).

2.3.3.1 Processed plastic bags in bituminous mixes

Justo and Veeraraghavan (2002) compared the properties of the waste plastic modified bitumen with ordinary bitumen. It was observed that the penetration and ductility values of the modified bitumen decreased with the increase in proportion of the plastic additive, up to 12 % by weight. The softening point of the modified bitumen increased with the addition of plastic additive, up to 8.0 % by weight. Studies were carried out on Bituminous Concrete (BC) mixes using 80 / 100 grade bitumen. Further studies on BC mixes were carried out using the modified binder obtained by the addition of varying proportions of processed plastic bags (percentage by weight of bitumen) with the conventional 80 /100 grade bitumen. The optimum modified binder content fulfilling the Marshall mix design criteria was found to be 5.0 % by weight of the mix, where the bitumen consist of 8% of processed plastic (by weight of bitumen). Three fold increases in stability value is showed by the BC mix.

Marshall stability tests were conducted on samples after soaking in water at 60°C for 24 hours to study the water induced damages. Considerable resistance to water induced damages was observed for the samples. The average stability value of the BC mix with modified binder was found to increase by about 2.6 times of the mix with ordinary bitumen. Further laboratory studies on the BC mixes using this modified binder also indicated considerable increase in fatigue life under repeated application of loads.

Bindu and Beena (2010) studied the feasibility of the use of shredded waste plastics in semi-dense bituminous concrete with 60/70 penetration grade bitumen employing dry process of mixing. On heating the softened plastics, provide a thin coating on the aggregate. Marshall Stability and flow values, over a 50 samples with varying percentage bitumen by weight of mix and percentage plastics by weight of binder were evaluated. There was a 10% saving in the bitumen content which leads to a saving in national economy and also an eco-friendly method for the disposal of waste plastics. The stability value of the mix was increased by about 30%. There is also less ageing of bitumen and no bleeding. The plastic coated aggregates showed no stripping even after 96 hours of water immersion and hence avoid the use of anti-stripping agents in bituminous mixes. Water absorption was found to be less as compared to uncoated aggregates indicating its higher degree of water susceptibility.

They have also reported the performance evaluation of a road stretch of Trivandrum district in Kerala, constructed with and without plastic coated aggregates. It was observed that the pavement surface is less deteriorated and does not require any maintenance even after long service life. Comparatively better riding quality and low distress for the road sections laid when compared to the control section with ordinary mix. There is very little fretting and raveling and no potholes even after 5 years of construction on the stretch constructed using shredded plastics. The plastic road stretch was found to have a smoother surface texture as compared to the ordinary stretch.

2.4 HISTORY OF SMA

Stone Matrix Asphalt (SMA) is a hot mix asphalt, developed in Germany during the mid- 1960’s. SMA has been referred to over the years as Stone Mastic, Split Mastic, Grit Mastic, or Stone Filled Asphalt. It is gap-graded hot mix asphalt which is designed to maximize deformation (rutting) resistance and durability by using a structural basis of stone-on-stone contact.

SMA mixture is an impervious wearing surface which provides rut resistant and durable pavement surface layer (Ibrahim, 2005). It has been first introduced in

Europe for more than 20 years for resisting damage from the studded tires better than other type of HMA (Roberts et al., 1996). In recognition of its excellent performance, a national standard was set up in Germany in the year 1984. Since then the concept of SMA has spread throughout Europe, North America and Asia Pacific. Several individual countries in Europe now have a national standard for SMA and CEN, the European Committee for Standardisation is in the process of developing a European Product Standard. Because of its success in Europe, some States, through the cooperation of the Federal Highway Administration, constructed SMA pavements in the United States in 1991 (Brown et al., 1997). Wisconsin was the first SMA project followed by Michigan, Georgia, and Missouri (NAPA, 1999). Since that time the use of SMA in the US has increased significantly.

The acronym of SMA is derived from the German term Splitt Mastix (Keunnen, 2003) revealing its German origin (*Splitt*-crushed stone chips and *mastix*-the thick asphalt cement and filler). There are many definitions of SMA and some of them are stated here.

Austoroads (1993) defines SMA as *'a gap graded wearing course mix with a high proportion of coarse aggregate content which interlocks to form a stone-on-stone skeleton to resist permanent deformation. The mix is filled with a mastic of bitumen and filler to which fibres are added in order to provide adequate stability of the bitumen and to prevent drainage of the binder during transport and placement'.*

The European definition of SMA (Michaut, 1995) is *'a gap-graded asphalt concrete composed of a skeleton of crushed aggregates bound with a mastic mortar'.*

Australian Standard AS2150 (1995) defines SMA as *'a gap graded wearing course mix with a high proportion of coarse aggregate providing a coarse stone matrix filled with a mastic of fine aggregate, filler and binder'.*

The BCA (1998) defines SMA as *'a gap graded bituminous mixture containing a high proportion of coarse aggregate and filler, with relatively little sand sized particles. It has low air voids with high levels of macro texture when laid resulting in waterproofing with good surface drainage'.*

Technically, SMA consists of discrete single sized aggregates glued together to support themselves by a binder rich mastic. The mastic is comprised of bitumen, fines, mineral filler and a stabilising agent. The stabilising agent is required in order to provide adequate stability to the bitumen and to prevent the drainage of bitumen during transport and placement.

Japan and Saudi Arabia have started to use SMA paving mixtures with good success (Brown et al., 1997; Ibrahim, 2005). SMA also acquired considerable attention in Canada due to the European Asphalt Study Tour (Schimiedlin and Bischoff, 2002).

Findings from the European Asphalt Study Tour along with subsequent seminars and demonstrations have illustrated the benefits of this product on roadways throughout the U.S. (NAPA, 1999). In many countries like United States, Australia, New Zealand, China, South Korea, Taiwan and other major countries in Asia, the use of SMA is increasing in popularity amongst the road authorities and in the asphalt industry. The Wisconsin Department of Transportation and the asphalt paving industry in the state constructed a trial installation of SMA. The success of that trial was the basis of the decision to conduct a thorough evaluation of SMA. Subsequently, more projects were constructed at various locations around the state. Each project contained six test locations utilizing various fibre and polymer modified SMA mixes. At the completion of the five year evaluation period, SMA performed better than the standard Bituminous Concrete Pavements. (Schmiedlin and Bischoff, 2002)

The Indian Roads Congress (IRC) has adopted a tentative SMA specification, (IRC SP 79:2008). One test road was constructed in Delhi in October 2006, using SMA as a surfacing course.

SMA Test track in India

In India a field trial on the design and construction of Stone Matrix Asphalt Surfacing was conducted between Khajuri Chowk and Brij Puri Chowk on Road No.59 in Delhi in October 2006 (Highway Research record No: 34). A test section was laid in by the Central Institute, New Delhi on the intersection (Loni Flyover to Khajuri Chowk) of Road No. 59 which is one of the busiest corridor having mixed traffic conditions including heavy vehicles. These test sections were monitored for their performance, at six months interval (pre monsoon and post monsoon) to find out the performance of SMA surfacing on intersections. By considering the advantage of the proven field performance of this test track and in other regions of developed countries like USA with climatic conditions reasonably close to that of India, SMA can be considered as the right choice for our long lasting pavements.

2.4.1 Stone Matrix Asphalt Composition

SMA is a blend of crushed coarse aggregate, crushed fine aggregate (or sand), mineral filler, bitumen binder and stabilizing agent. These major components of SMA mixtures are shown in Fig. 2.6. A stone skeleton mixture that, when compacted, provides the gap-graded stone-on-stone structure to carry heavy traffic loads, prevent rutting, and provides long term durability. The mineral filler, fine aggregate and bitumen provides the binder adhesive to bond the stone skeleton together and to provide a cohesive mixture. Finally, additives such as fibres or polymers are used as a stabilizer to secure the mastic within the overall structure. They stiffen the resulting mastic and prevent the draining off during storage, transportation and placing of SMA. The mastic fills the voids, retains the chips in position and has an additional stabilizing effect as well as providing low air voids and thus resulting in highly durable bitumen (AAPA, 1993). Mineral fillers and additives play the role of minimizing the binder drain down, increasing the amount of binder used in the mix and improving the mix durability.

The SMA mixtures are composed to have a high coarse aggregate content (typically 70-80%), a high bitumen content (typically over 6%) and high percentage of mineral filler content (approximately 10% by weight) (Roberts et al., 1996). High coarse aggregate content results in stone-on-stone contact that produces a mixture that is highly resistant to rutting. These gap graded bituminous mixtures (minimizing medium sized aggregates and fines) result in a structurally tough skeleton (Fig. 2.7). In summary, the high stone content forms a skeleton type mineral structure which offers high resistance to deformation due to stone to stone contact, which is independent of temperature.

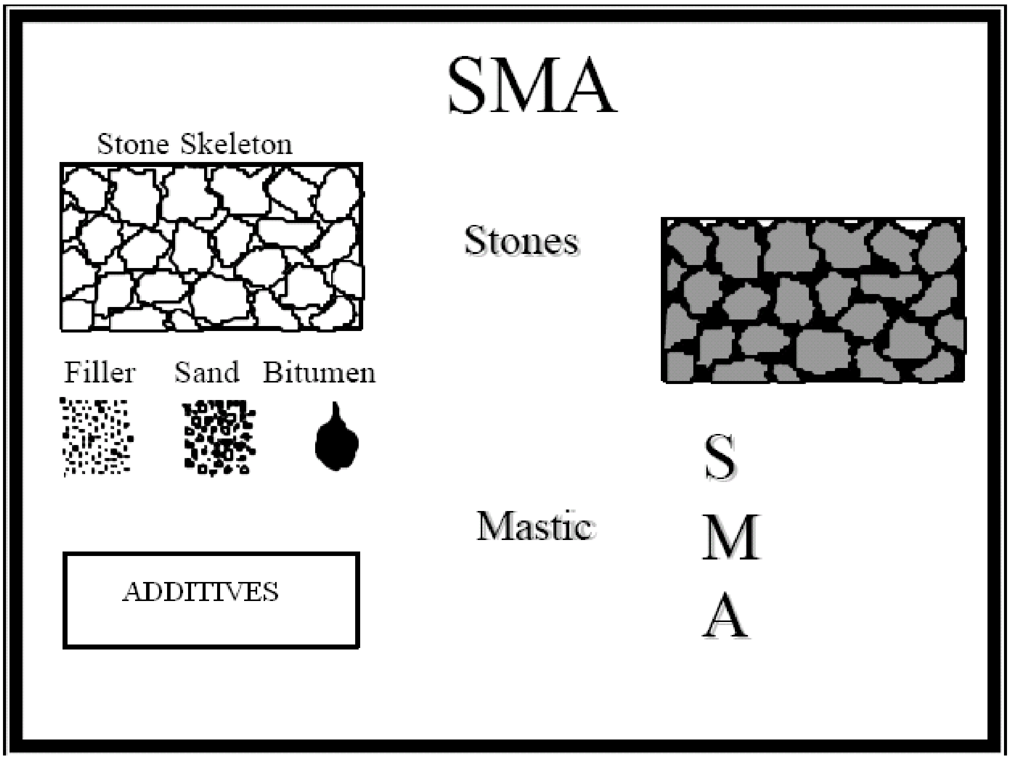

Fig. 2.6 Major components of SMA mixture

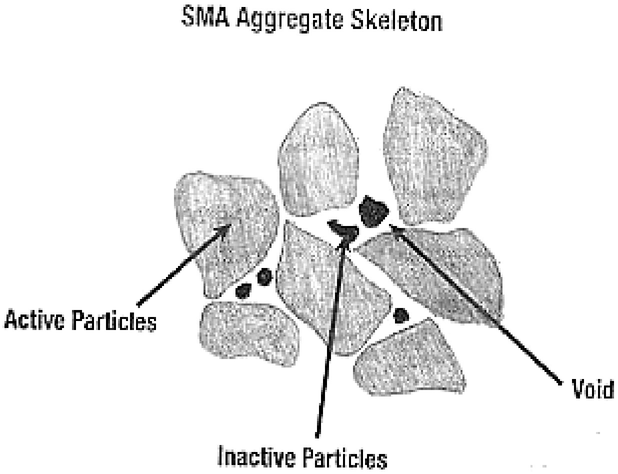

Fig. 2.7 SMA aggregate skeleton (NAPA, 1999)

Selection of materials is important in SMA design. The coarse aggregate should be a durable, fully crushed rock with a cubicle shape (maximum of 20% elongated or flat aggregate). Fine aggregate should be at least 50% crushed. Filler can be ground limestone rock, hydrated lime or flyash. In general, materials of similar quality to those used in dense graded bituminous wearing courses are required.

2.4.1.1 Aggregates

The strength, toughness and rut resistance of SMA depends mostly on the aggregate in the mix which being 100% crushed aggregate with good shape (cubicle) and stringent limits for abrasion resistance, flakiness index, crushing strength and impact resistance. Fine aggregate used must be crushed as the internal friction of the fine fraction largely contributes to the overall stability of SMA.

2.4.1.2 Mineral Filler

Mineral filler is that portion passing the 0.075 mm sieve. It will usually consist of finely divided mineral matter such as rock dust, Portland cement, hydrated lime, ground limestone dust or fly ash. Mineral filler is essentially stiffening the rich binder SMA. A higher Percentage of filler may stiffen the mixture excessively, making it difficult to compact and may be resulting in a crack susceptible mixture, (Brown and Haddock, 1997). In general, amount of material passing through the 0.075 mm sieve is relatively 8-12 percent of the total amount of aggregate in the mix. Since the amount of material passing through the 0.075-mm sieve is relatively large, the SMA mixtures perform very differently from other HMA mixtures. These fines, along with the bitumen and fibre, make the mastic which holds the mix together. SMA mixtures are very sensitive to the amount of 0.075 mm (No. 200) in the mix. Handling, storing and the introduction of the mineral filler is therefore an important concern. The type of fines can also affect drain down. Brown and Mallick (1994) found that baghouse fines had much less drain down than mixtures containing marble dust. This is because the smaller particles provide more surface area for a given weight and thus tend to stiffen the binder more than coarse fines. This clearly shows the importance of the size of the particles passing the 0.075 mm sieve in SMA.

2.4.1.3 Binder

Stone matrix asphalt contains more binder than conventional dense graded mixes, with percentages ranging from about 6.0% to 7.5%. The performance of the mix is usually enhanced with polymers and fibres. These help to provide a thick coating to the aggregate and to prevent the drain down during transportation and placement. Polymer modified binders can be used to give even greater deformation resistance. Brown et al. (1997a) reported that SMA incorporating styrene butadiene styrene produced more rut resistant mixes than SMA with unmodified binder. Superior fatigue lives are also reported.

2.4.1.4 Additives

Stabilizing additives have been introduced into SMA mixes to alleviate the drain down and bleeding problems (fat spots). Because of compaction issues, storage and placement temperatures cannot be lowered. Additives have been added to stiffen the mastic at high temperatures. Fibres do the best job of preventing drain down, where polymers improve the bitumen properties at low and high temperatures. Brown and Cooley (1999) also concluded in NCHRP Report 425 that fibres do a better job than polymers to reduce drain down.

The inclusion of fibres or polymer during the mixing process as a stabilising agent has several advantages including increased binder content, increased film thickness on the aggregate, increased mix stability, interlocking between the additives and the aggregates which improves strength and reduction in the possibility of drain down during transport and paving. There are many additives in the market including cellulose, mineral rock, wool fibres, glass fibres, siliceous acid (artificial silica), rubber powder and rubber granules and polymers.

2.4.2 Stone Matrix Asphalt Properties

SMA is a hot mixture with a relatively large proportion of stones and a substantial quantity of bitumen and filler. The main concept of having a gap gradation of 100% crushed aggregates is to increase the pavement's stability through interlock and stone-to-stone contact. This mixture is designed to have 3–4% air voids and relatively high bitumen content due to the high amount of voids in the mineral aggregate. The mixture contains high filler content (10% passing the 0.075-mm sieve), and a polymer in the bitumen, or fibre (cellulose or mineral) in the mixture to prevent the drainage of bitumen. This mixture has a surface appearance similar to that of an open graded friction course; however it has low in-place air voids similar to that of a dense graded HMA.

SMA provides a mixture that offers maximum resistance to studded tyre wear. It has high resistance to plastic deformation under heavy traffic loads with high tyre pressures and also has good low temperature properties (Brown et al., 1997b; Cooley and Brown, 2003).

At the bottom, and in the layers, the voids in the aggregate structure are almost entirely filled by the mastic, while, at the surface the voids are only partially filled. It has a rough and open surface texture. This provides good skidding resistance at all speeds and facilitates the drainage of surface water (Nunn, 1994).

Stone Matrix Asphalt has excellent deformation and durability characteristics, along with good fatigue resistance. Stone matrix asphalt has a rough surface texture which offers lower noise characteristics than dense graded asphalt.

The enhanced deformation resistance, or resistance to rutting, compared to dense graded asphalt is achieved through mechanical interlock from the high coarse aggregate content forming a strong stone skeleton. In dense graded asphalt, the lean mastic provides the stability.

The improved durability of SMA comes from its slow rate of deterioration obtained from the low permeability of the binder rich mastic which cementing the aggregate together.

The increased fatigue resistance is due to higher bitumen content, a thicker bitumen film over the aggregate and lower air voids content. The higher binder content should also contribute to flexibility and resistance to reflection cracking from underlying cracked pavements. Fat spots appear to be the biggest problem. These are caused by segregation, drain down, and high bitumen content or improper amount of stabiliser (Brown, et al., 1997). The rich mastic provides good workability and fret resistance (aggregate retention). The high binder and filler content provide durable, fatigue resistant, long life bituminous surfacing for heavily trafficked areas.

The difficult task in designing an SMA mix is to ensure a strong stone skeleton with the correct amount of binder. Too much binder results in pushing the coarse aggregate particles apart, while too little results in a mix that is difficult to compact. They have high air voids and thin binder coating and hence less desirable (Wonson, 1998).

In Germany, surface courses of SMA have proven themselves to be exceptionally resistant to permanent deformation and durable surfaces subject to heavy traffic loads and severe climatic conditions (DAV, 1992). Stone Matrix Asphalt surface courses are reported to show excellent results in terms of being particularly stable and durable in traffic areas with maximum loads and under a variety of weather conditions (Wonson, 1996).

The gap-graded aggregate mixture provides a stable stone-to-stone skeleton that is held together by a rich mixture of bitumen mastic, which is a mixture of bitumen, filler, sand and stabilizing additives. Stabilizing additives can be organic or mineral fibres, or less often, polymers. They stabilize the asphalt mortar and tend to thicken or bulk the bitumen to prevent binder run-off from the aggregate. Thus, they ensure the homogeneity of the mixture. Aggregate interlock and particle friction are maximized and gives the structure its stability and strength (Susanne, 2000).

Because the aggregates are all in contact, rut resistance relies on aggregate properties rather than binder properties. Since aggregates do not deform as much as bitumen binder under load, this stone-on-stone contact greatly reduces rutting. The improved rutting resistance of the SMA mixture is attributed to the fact that it carries the load through the coarse aggregate matrix (or the stone matrix). The use of polymer or fibre, which increase the viscosity of the mixture, and the use of high filler content, which increases the stiffness of the binder, allow the SMA mixtures to have a higher binder film thickness and higher binder content without the problem of drain down of bitumen during construction. The increased durability of the SMA mixtures can be attributed to thick film thickness and the high binder content (Chen and Huang, 2008).

Summing up, the properties of a properly designed and constructed SMA can be enumerated as

i. The stone skeleton, with its high internal friction, will give excellent shear resistance.

ii. The binder rich, void less mastic will provide good durability and good resistance to cracking.

iii. The very high concentration of large stones, three to four times higher than in a conventional dense graded mixture will give superior resistance to wear.

iv. The rough surface texture than that of dense graded mixture will assure good skid resistance and proper light reflection and

v. The surface texture also provide anti-splash features during wet and rainy conditions and thus reduce hydroplaning which results from water draining through the voids in the matrix.

2.4.3 Advantages and Disadvantages of Stone Matrix Asphalt

Stone matrix asphalt has a number of advantages over conventional dense graded asphalt. These include the following:

- Resistance to permanent deformation or rutting (30-40% less permanent deformation than dense graded bituminous mixtures).
- The mechanical properties of SMA rely on the stone to stone contact so they are less sensitive to binder variations than the conventional mixes (Brown, et al, 1997a).
- Good durability due to high binder content (slow ageing), resulting in longer service life (up to 20%) over conventional mixes.
- Good flexibility and resistance to fatigue (3-5 times increased fatigue life).
- Good low temperature performance.
- Good wear resistance.
- The coarser surface texture characteristics may reduce sound from the tyre and pavement contact as well as water spray and glare.
- SMA can be produced and compacted with the same plant and equipment available for dense grade asphalt.
- More economical in the long term.
- Provide friendly and safety features including improved skid resistance on wet pavements (NAPA, 1998).
- SMA may be used at intersections and other high traffic stress situations where open graded aggregate is unsuitable.

- SMA surfacing may provide reduced reflection cracking from underlying cracked pavements due to the flexible mastic.

Apart from good stability and durability that ensures a long service life, other advantages claimed for SMA are:

a) It can be laid over a rutted or uneven surface because it compresses very little during compaction. This also helps to produce good longitudinal and transverse evenness (Nunn, 1994). There is no harm to the final evenness of the surface even when applied in different mat thicknesses.

b) If the pavement lacks stiffness, such that dense graded mixtures with conventional binder which suffer premature fatigue induced cracking, then it may be beneficial to place SMA because of its improved fatigue resistance properties (Austroads, 1997).

c) An anticipated secondary benefit of SMA is the retardation of reflection cracks (Austroads, 1997).

Perceived disadvantages of SMA include:

- Increased cost associated with higher binder and filler contents, and additive.
- High filler content in SMA may result in reduced productivity. This can be overcome by suitable plant modifications.
- Possible delays in opening to traffic as SMA mix should be cooled to prevent flushing of the binder surface.
- Initial skid resistance may be low until the thick binder film is worn off from the top of the surface by traffic.

2.4.4 Life Cycle Costing

The initial costs of SMA are 20-40% higher than conventional dense graded mixtures. To analyse whether SMA is more cost effective than conventional dense graded surfacing, the higher initial cost and the longer life expectancy of SMA is to be taken into account.

The increased initial costs of SMA compared to conventional dense graded mixtures result from the use of higher bitumen content, use of fibres, increased quality control requirements and lower production rates due to increased mixing time. However, costs vary considerably with the size of the project, and also on haul distances.

Collins (1996) reported that the State of Georgia had produced a set of life cycle costs based on the State's experience and reasonable mix designs. The analysis showed that there were savings in the order of 5% using SMA over dense graded mixtures for overlay work. The analysis used the assumptions of rehabilitation intervals of 7-10 years for dense graded mixes and 10-15 years for SMA.

However, even considering the potential for increased costs, the Georgia Department of Transport (DOT) have found the use of SMA to be quite cost effective based on improved performance and the potential for increased service life.

The Alaska DOT (NAPA, 1998), has found that approximately 15% increase in SMA cost compared to conventional mixtures is more than offset by a 40% additional life from a reduction in rutting. It appears that SMA could be cost effective with high performance, durability and frictional requirements.

Life span increase of five to ten years can be obtained in addition to the additional advantages mentioned. It is clear that the choice of SMA can be a good investment.

2.5 PREVIOUS STUDIES ON SMA

A study conducted in Ontario, Canada, by the Ministry of Transportation on SMA pavement slabs trafficked with a wheel-tracking machine gave less rut depths in comparison to that occurring in a dense friction course (Brown et al., 1997). In the United States, the Georgia Department of Transportation has also performed a significant amount of wheel tracking tests on SMA mixtures that gave positive results. In addition, SMA has a rough surface texture, which provides good friction properties after the surface film is removed by traffic. Other essential factors that enhance the feasibility of SMA in contrast to conventional hot mixture are increased durability, improved ageing properties and reduced traffic noise (NAPA, 1994).

Brown et al. (1997) carried out a study to evaluate the performance of SMA in the United States by evaluating 86 SMA projects. Data was collected on material and mixture properties, and performance was evaluated on the basis of rutting, cracking, raveling, and fat spots. The major conclusions from their study were: (i) 60% of the projects has more than 6.0% bitumen content (ii) over 90% of the SMA projects had rutting measurements less than 4 mm; (iii) SMA mixtures appeared to be more resistant to cracking than dense mixtures; (iv) there was no evidence of raveling on the SMA projects and (v) fat spots appeared to be the biggest performance problem in SMA mixtures.

HRB Report, No. 34 describes the laboratory study undertaken to evaluate the performance of Stone Matrix Asphalt mix with reference to draft specification of Indian Roads Congress. Marshall Mix design method was performed to determine the optimum binder content of SMA mixtures. The mix was designed using 50 blows to sustain heavy traffic, using three different binder contents of 6.5, 7.0 and 7.5 percent by the weight of mix. The target mixing and compaction temperatures were 175˚C and 143˚C respectively. SMA mixtures were prepared with two different stabilizing additives, by adding 0.3 percent by weight of total mixture with 60/70 penetration grade paving bitumen. The OBC has been estimated at which the air voids and the minimum voids in mineral aggregates are 4.5 and 17 percent respectively.

Production of SMA is quite similar to standard hot mix asphalt (HMA). All the feed system for HMA facility must be carefully calibrated prior to the production of SMA. Manufacturers of stabilizing additives generally assist in setting up, calibrating and monitoring the additive delivery system to the hot mix producer. Production temperatures of SMA mixtures will vary according to aggregate's moisture content, weather conditions, grade of bitumen and type of stabilizing additives. Temperature of 145˚C-160˚C can be used for the production of SMA. While adding stabilizing additives (fibres) to the aggregate mixture, the mixing time should be increased slightly. This additional time allows for the effective distribution of fibre in the aggregate mixture. After that the required amount of bituminous binder should be injected and mixed thoroughly in a mix plant. The additional time, in both the dry and wet mix cycles, may be increased from 5 to 15 seconds each.

SMA is a unique flexible pavement which had demonstrated its ability to withstand the heavy truck loadings and resist the wear of the super wide, single truck tires and the studded tires used throughout Europe (Schimiedlin and Bischoff, 2002). SMA mixes have also provided excellent service on bridge decks as a wearing surface to protect deck membranes. Two of the main benefits of SMA mixtures are its rut resistance and long term durability providing for extended performance life from 30 to 40% longer than a conventional dense-graded HMA pavement (Watson and Jared, 1995).

In addition, SMA has safety features like improved skid resistance due to the high percentage of fractured aggregate particularly on wet pavements (NAPA, 2001). Although water does not drain through SMA, its surface texture is similar to that of open-graded mixture, so that the noise generated by traffic is lower than that of dense graded mixture but equal to or slightly higher than that of open graded mixture. Therefore the coarser surface texture characteristics may reduce sound from the tyre and pavement contact as well as water spray and glare.

SMA can be produced and compacted with the same plant and equipment available for normal hot mix, using the Marshall procedure. SMA may be used at intersections and other high traffic stress situations where open graded mixture is unsuitable. For pavements with cracking or raveling it is suggested that SMA be considered for use as an overlay because it may reduce severe reflection cracking from underlying cracked pavements due to the flexible mastic. The durability of SMA should be equal, or greater than, dense graded mixtures and significantly higher than open graded mixtures.

2.6 STABILIZING ADDITIVES IN SMA

Since SMA mixes have high bitumen binder content, the binder has a tendency to drain off the aggregate and down to the bottom - a phenomenon known as "mix draindown". This can happen while the mix is in the HMA storage silos, trucks for transporting and during placement. Mix draindown is usually combated by adding stabilizing additives. It can be organic or mineral fibres or polymers. They stabilize the mixture and tend to thicken or bulk the bitumen to prevent binder run-off from the aggregate. Thus, they ensure the homogeneity of the mixture. Aggregate interlock and particle friction are maximized and gives the structure its stability and strength (Susanne, 2000).

Most SMA projects used either fibres or polymers. Fibres are usually added to SMA mixtures to overcome the draindown problem usually be encountered during mixing, transporting and compaction. Loose organic fibres, such as cellulose, and mineral fibres are generally used at the rate of 0.3% and 0.4% by weight of mixture, respectively (Brown and Manglorkar, 1993). A higher percentage of mineral fibre is used , it is typically heavier than the cellulose (Roberts et.al., 1996). Other fibre types, including glass fibre, rock wool, polyester, and even natural wool, have all been found to be suitable but cellulose fibre is generally the most cost-effective one (Mangan and Butcher, 2004).

When polymer is used, normally it was blended together with the binder prior to the delivery to the plant but in some cases it has been added at the plant itself (Roberts et al., 1996). The polymers can increase the stiffness of bitumen due to loading at high and low temperature, and drain down resistance. In addition, it can also give better binder adhesion to the aggregates particularly in wet condition (Robinson and Thagesen, 2004). Polymers are typically added to the mixture at a rate of 3.0–8.0% by weight of the binder (Ibrahim, 2005).

2.6.1 Fibre as an additive

The application of fibres in dense graded bituminous mixtures, their reinforcing effects and the improved performance of pavements have already been discussed in detail in section 2.3.1. This section deals with the review of previous works done in SMA with different synthetic fibres, waste fibres and some natural fibres like jute fibre and oil palm fibre. Fibre can stabilize bitumen to prevent binder leakage especially for the open-graded-friction courses (OGFC) and stone matrix asphalt (SMA) mixtures during the material transportation and paving (Hassan et al., 2005; Serfass and Samanos, 1996; Peltonen, 1991). Fibre changes the viscoelasticity of mixture (Huang and White, 2001) improves dynamic modulus (Wu et al., 2008), moisture susceptibility (Putman and Amirkhanian, 2004), creep compliance and rutting resistance (McDaniel, 2001; Chen et al., 2004). It reduces the reflective cracking of bituminous mixtures and pavements (Tapkin, 2008; Maurer and Malasheskie, 1989).

Polyester, polyacrylonitrile, lignin and asbestos fibres stabilized SMA mixes has been suggested by Chen and Huang (2008) and by studying the volumetric and mechanical properties, they arrived at the design method of fibre reinforced bituminous mixtures. Polyester and polyacrylonitrile fibres have higher stability due to their higher networking effect, while the lignin and asbestos fibres result in higher optimum bitumen content and VFA due to their higher absorption of bitumen. The design procedure for the fibre reinforced bituminous mixture elects the fibre type based on the characteristics of both fibre and bituminous mixture, designs the optimum bitumen content following the Marshall method, and then determines the optimum fibre content in terms of performance test results.

Behbahani et al. (2009) found that the variation of fibre type and content can lead to considerable changes in the rutting performance of Stone Mastic Asphalt mixtures. The principal functions of fibre reinforcement in bituminous mixes are to provide additional tensile strength in the resulting composite and increasing strain energy absorption of the bituminous mix. This inhibits the formation and propagation of cracks that can reduce the structural integrity of the road pavement. The idea was based on the general concept that if HMA is strong in compression and weak in tension, then reinforcement could be used to provide needed resistance to tensile stresses (Al-Qadi et al., 2003; Bushing et al., 1968; Wu et al., 2007).

Pawan Kumar et al. (2004) determined the feasibility of using coated jute fibres in SMA mixes in place of synthetic fibres. The test results indicate that the natural jute fibre can replace synthetic fibres. A slightly higher accumulated strain and subsequently lower creep modulus were observed as compared to SMA with synthetic fibre. Permanent deformations are the same for both mixes and tensile strength ratio is more than the prescribed limit.

Muniandy and Huat (2006) reported that the cellulose oil palm fibre improve the diametric fatigue performance of SMA design mix. The fatigue life increased to a maximum at a fibre content of about 0.6% and the tensile stress and stiffness also showed a similar trend in performance. The initial strains of the mix were lowest at a fibre content of 0.6%.

2.6.2 Polymer as an additive

Additives such as styrene based polymers, polyethylene based polymers, polychloroprene, gilsonite, various oils, and many other modifiers have been added to bitumen to enhance various engineering properties of bitumen (Denning and Carswell, 1993). Goodrich (1998) reported that modifier improves the properties of bituminous mixtures. For ordinary SMA, the use of unmodified bitumen together with fibrous material as a drainage inhibitor is sufficient. Under high temperatures and heavy loading, a harder bitumen grade is needed. A polymer such as polypropylene, polyethylene or styrene– butadiene–styrene modified binder may be used to substitute the fibrous material. It is possible to increase the capability of resistance to permanent deformation and to reduce the pavement failure, thereby ensuring a better bituminous mixture. SMA can control or limit the distress failure such as rutting, shoving, stripping, etc., through polymer modification.

Al- Hadidy and Tan Yi- qiu (2008) investigated the improvement in service life of the pavement or the reduction in thickness of SMA and base layer due to the modification of SMA mixtures with polyethylene. The thickness of SMA can be reduced by 34% than the unmodified mix. They exhibits improved service life and reduced temperature susceptibility.

2.6.3 Waste material as an additive

Putman and Amirkhanian (2004) used waste tire and carpet fibres in SMA and compared the performance of these stabilized mixtures with cellulose and polyester fibre stabilized mixtures. The outcomes showed that adding wastes increases the toughness of SMA mixtures, without making any significant difference in permanent deformation.

Richard et al. (2009) reported that the volume of waste polymer produced is increasing rapidly and the disposal is very difficult resulting in exceeding the waste beyond the acceptable levels. The possibility of incorporating waste polymer into bitumen as a modifier was examined. A wide range of recycled polymers were tested, including polyethylene, polypropylenes, polyether polyurethane, ground rubber, and truck tire rubber. Tests included viscosity, penetration, softening point, ageing, and rheology. Stiffness tests on samples of bituminous mixes were made using different grades of binders. The blend with 3% low density polyethylene substituted for 1% styrene butadiene had similar properties to that of Polyflex 75, although it had lower stiffness. The most impressive was a combination of low density polyethylene, bitumen and ethyl vinyl acetate. Recycled plastics comprising predominantly of polypropylene and low density polyethylene can be incorporated into conventional bituminous road surfacing mixtures. Greater durability and fatigue life have been reported for these modified mixes as compared to conventional mixes (Zorrob, 2000).

It is hoped that in near future we will have strong, durable and eco-friendly roads which will relieve the earth from all type of plastics. The use of the innovative technology not only strengthened the road construction but also increased the road life as well and will help to improve the environment.

2.7 SUMMARY

A critical review of the literature showed that Stone Matrix Asphalt is an ideal paving mixture for Indian conditions especially to our Kerala Highways. Literature shows that it has been possible to improve the performance of bituminous mixtures used in the surfacing course with the help of various types of additives like fibres, polymers and waste materials. Synthetic fibres are conventionally used in the construction of Stone Matrix Asphalt. They are not manufactured in India and are imported at a high cost. The excessive use of synthetics has led to environmental pollution. This ecological crisis has necessitated the use of bio-renewable resources and plant fibres. Resources in terms of materials consumed for construction and maintenance of roads are very scarce and limited. Therefore, there is an urgent need to identify new technologies that can work well with alternative resources such as agro based materials and renewal of existing resources without affecting the performance. Some limited studies have been reported on the use of natural fibres and waste materials in SMA. India produces fairly huge quantity of naturally occurring agro based fibres such as Coconut, Sisal, Banana and Jute fibres etc., which need to be explored for their potential applications in bituminous road construction. This will result in improving the characteristics and service life of bituminous surfacing, eventually leading to conservation of construction materials.

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Chapter 3

MATERIAL CHARACTERISATION

3.1 INTRODUCTION

The performance of bituminous surfacing depends to a great extent on the correct choice of quality and quantity of materials. Materials needed for the production of Stone Matrix Asphalt mixtures include high quality aggregates, bituminous binder, mineral filler and a stabilizer. The Materials used in this research are locally available construction materials in Kerala. The properties of the various materials used for the study are described in this chapter.

3.2 AGGREGATES

Aggregates form the major constituent of road construction materials. Since they have to bear the brunt of traffic, they should be strong enough to resist the degradation and should have enough structural stability which is offered by the mechanical interlock of aggregate in the layer. IS 2386-1963 gives the methods of tests for aggregates in road construction. Aggregate of sizes 20mm, 10mm and stone dust procured from a local quarry at Kochi, Kerala is used in the present investigation. The values obtained for various properties of aggregate are given in Table 3.1.

3.3 MINERAL FILLER

The role of mineral filler is essentially to stiffen the rich binder SMA. It is designed to fill the voids and form stiff mastic with bitumen binder and stabilizing additive. It increases the cohesion of the mix resulting in a significant increase in shear resistance. A higher percentage of filler may stiffen the mixture excessively, making it difficult to compact and may be resulting in a crack susceptible mixture, (Brown et al., 1997). In general, amount of material passing through the 0.075 mm sieve is 8-12 % of the total amount of aggregate in the mix. Commonly used mineral fillers are fly ash, hydrated lime, finely ground limestone dust and ordinary Portland cement (OPC). OPC from a local market which makes a better bond with aggregate, bitumen and additive has been used in this study. The physical properties of filler used are shown in Table 3.2.

Table 3.1 Physical properties of aggregate

Property	Values obtained	Method of Test
Aggregate impact value (%)	16	IS:2386 (IV)
Los Angeles Abrasion Value	27	IS:2386 (IV)
Combined Flakiness and Elongation Index (%)	18	IS:2386 (I)
Stripping Value	Traces	IS 6241:1971 (R2003)
Water Absorption (%)	Nil	IS:2386 (III)
Specific gravity	2.65	IS:2386 (III)

Table 3.2 Physical properties of cement

Physical property	Values obtained
Specific gravity	3.12
% passing 0.075 mm sieve (ASTM C117)	96

3.4 STABILIZING ADDITIVES

Stabilizing additive must be used to hold the binder in SMA mixture which is rich in binder content, during mixing, transportation and placement operations. In order to prevent the unacceptable drain down, fibres or polymers as stabilizing additives can be added to the mixture. Three natural fibres namely coir, sisal and banana fibre, a polymer, polypropylene and waste plastics in shredded form are used as stabilizing additives for the present study. The descriptions of these materials in detail are given below.

3.4.1 Fibre stabilizer

India has a vast resource for different natural fibres viz., jute, sisal, banana, coir fibre etc. and can be advantageously used for many construction activities. Presently, the production of natural fibres in India is more than 400 million tonnes (Saxena and Ashokan, 2011).

The inclusion of fibres during the mixing process as a stabilizing agent has several advantages including increased binder content, film thickness and the mix stability. This will result in better interlock between the aggregates and thereby improving the strength and reducing the possibility of drain down during transport and paving.

There are different types of fibres used in SMA mixtures like polymer fibre, mineral fibre, natural fibres etc.. In this study, three natural fibres namely coir, sisal and banana fibre at different percentages by weight of mixture are used. The photographs of these fibres are shown in Fig. 3.1.

3.4.1.1Coir fibre

Kerala is the home land of Indian coir industry, accounting for 61 per cent of coconut production and over 85 per cent of coir products. Coconut fibre/ coir fibre is a natural fibre derived from the mesocarp tissue or husk of the coconut fruit. The individual coconut fibre cells are narrow and hollow, with thick walls made up of cellulose. These fibres are pale when immature but later they become hardened and yellowed as a layer of lignin gets deposited on their walls. Brown coir fibres are stronger as they contain more lignin than cellulose, but they are less flexible. Coconut fibres are relatively water proof and the decomposition of fibre is generally much less than that of other natural fibres due to high lignin content. The peelings of ripe coconut were collected locally; dried and neat fibres are taken out manually. The lengths of such fibres are normally in the range of 15 to 280 mm and diameter varied from 0.1 to 1.5 mm. The average tensile strength of the fibre was found to be 70.58N/mm^2. Compared with other vegetable fibres, the coconut fibre has a cellulose content of 36% to 43%, and lignin content of 41% to 45% (Ayyar et al., 2002). The coir fibres for the present work had procured from Alappuzha and its properties are given in Table 3.3.

3.4.1.2 Sisal fibre

Sisal plantations in India yield about 2.5 tonnes dry fibre per hectare per year. The fibre is usually obtained from sisal leaves by decortications in a machine called Raspador. Sisal is a leaf fibre derived from the plant Agave Sisalana. The lustrous strands are usually creamy white, 80 to 120 cm in length and 0.2 to 0.4 mm in diameter. Sisal fibre consists of 66-72% cellulose, 12% hemi cellulose and 10–14% lignin. The superior engineering properties (diameter 50–200 micro meter, Ultimate Tensile strength 468–640 Mpa and elongation 3-7%) makes it an excellent material for manufacturing high strength textile and reinforcement in composites for various applications (Saxena and Ashokan, 2011). Sisal fibre is fairly coarse and inflexible. Generally they are used in rope making, paper industry etc.. Very few works are done by using sisal fibres in bituminous mixtures. In this work the sisal fibres is used as a stabilizing additive in Stone Matrix Asphalt mixtures and is procured from Alappuzha. Its properties are given in Table 3.3.

3.4.1.3 Banana fibre

The entire sheath of banana fibre yields good quality fibre which is highly valued in the market for its durability and strength. A large quantity of bio waste is generated every year owing to banana cultivation which needs to be disposed off. By extracting banana fibre, the waste can be effectively put to use and provide additional income to the banana farmers.

Banana fibre is a multicellular fibre. The suitability of fibre for utilization in products can be identified by the degree of polymerization of cellulose. It is a cellulose rich fibre (70%) with low lignin content (12%). Tensile strength, elongation and density are the most important mechanical properties of the fibre. The high tensile strength exhibited by the fibre indicates its resistance to wear and tear, thus facilitating its use in pavements. It is observed that single fibre tenacity, fibre bundle tenacity, fibre porosity and moisture regain is the highest for this fibre when physical and chemical properties of different natural fibres are compared (Sinha, 1974). They can be extracted from the pseudostem by removing the non fibrous tissues and other plant parts from the fibre bundles. Fibre extraction is usually practiced either by hand extraction or by mechanical means (Suma, 2009). The banana fibre required for carrying out the work had procured from Kerala Agricultural University, Banana Research station, Kannara, Thrissur, Kerala and the properties of the fibre are given in Table 3.3.

Coir fibre **Sisal fibre** **Banana fibre**

Fig. 3.1 Fibres used for the present study

3.4.2 Polymer Stabilizer

In addition to fibre stabilisation, polymer stabilisation is also used in SMA mixtures. Polymer stabilisation is mainly used to minimize the binder drain down. The polymer stabilizer increases the stiffness of the bituminous mix at high, in service temperature and/or to improve the low temperature properties of the binder material. One type of Polymer (polypropylene) shown in Fig. 3.2 manufactured by Reliance Petrochemicals is used for the present study. Their properties are shown in Table 3.4. They are typically added to the mix at percentages of 1, 3, 5, 7 and 9, by weight of mix. The polymer is added to the heated aggregate and thoroughly mixed and heated again so as to have a coating on the aggregate before adding the heated bitumen.

Fig. 3.2 Polypropylene

Fig. 3.3 Waste plastics in the shredded form

3.4.3 Waste plastics as a stabilizer

Disposal of waste materials including waste plastic bags is a menace and has become a serious problem, especially in urban areas, in terms of its misuse; it's dumping in the dustbins, clogging of drains, reducing soil fertility and aesthetic problem etc.. Waste plastics are also burnt for apparent disposal, causing environmental pollution.

Table 3.3 Properties of fibres used

Property	Coir fibre	Sisal fibre	Banana fibre
Diameter (μm)	100 - 450	50 - 200	80 - 250
Density (g/cm ^{3})	1.45	1.40	1.35
Cellulose content (%)	43	67	65
Lignin content (%)	45	12	5
Elastic modulus(GN/m^2)	4-6	9 -16	8 -20
Tenacity (MN/m^2)	131 - 175	568 - 640	529 - 754
Elongation at break (%)	15 - 40	3 - 7	1.0 – 1.2

Table 3.4 Physical properties of polypropylene

Physical properties	Result obtained
Thermal Expansion Coefficient(° /C)	14.0×10^{-5}
Melting Temperature(°C)	140 - 160
Water Absorption	0.03% after 24 hours immersion
Chemical Unit	$-CH_2-CH_2-CH_3-$
Density(g/cm^3)	0.64
Thermal Degradation Temp(°C)	270 - 300
Ignition Temperature(°C)	$>$ 700

Plastics, a versatile material and a friend to common man become a problem to the environment after its use. Today, in India nearly 12 million tonnes of plastics are used and their presence has been perceived as a serious problem in the management of solid waste. Plastics are non-biodegradable. They also have very long lifetime and the burning of plastics waste under uncontrolled conditions could also lead to generation of many hazardous air pollutants depending upon the type of polymers and additives used. However, the waste plastics can be recycled into a second life application, but after every thermal treatment, degradation of plastics takes place to a certain extent.

In India, 52,000 tons of plastics waste is produced per year. The mixing up of these waste plastics with other bio-degradable organic waste materials in the garbage of the urban areas is a serious problem. Therefore attempts are being made in some cities to limit or even to prohibit the use of the thin plastic bags for packing and other common use, so as to control this "undesirable waste material" from getting mixed up with the other organic garbage. In case, it is possible to find useful application for the waste plastics, the problem of disposal can overcome and there will be substantial scrap value for this waste product.

Waste plastics on heating soften at around 130˚C. Thermo gravimetric analysis has shown that there is no gas evolution in the temperature range of 130-180˚C. Moreover the softened plastics have a binding property. Plastic roads would be a boon for India’s hot and extremely humid climate, where temperatures frequently cross 50˚C and torrential rains create havoc, leaving most of the roads with big potholes (Verma, 2008).

Further, the waste plastics modifier should be free from dust and is to be shredded, preferably to 2-3 mm particle size. While CRRI specified that the shredded waste plastics should pass through 3 mm sieve, some researchers (Vasudevan et al, 2007; Verma, 2008) is of the opinion that it has to pass through 4.75 mm sieve and retained on 1 mm. This also indicates indirectly that the size of the shredded plastic should normally be 2-3 mm for better spread and coating over the aggregate.

Here in this study, the plastic used were the disposed carry bags, films, cups etc. with a maximum thickness of 60 microns made out of polyethylene, polypropylene and polystyrene. They are cleaned if needed and shredded to small pieces (particle size 2-3 mm) using the shredding machine. Waste plastics in shredded form is given in Fig. 3.3(above).

In wet process, at high percentage of blending, there is a chance for separation of plastics. In order to have an effective way of using higher percentage of plastics waste in the flexible pavement, dry process of blending was adopted. The aggregate is heated to 170˚C and the shredded plastics waste is added, it gets softened and coated over the aggregate. Immediately the hot Bitumen (160˚C) is added with constant mixing to give a uniform distribution. As the polymer and the bitumen are in the molten state (liquid state) they get mixed and the blend is formed at the surface of aggregate. Waste plastics modifier does not degrade while blending with hot aggregates (Sabina et al., 2009). The physical properties of plastic coated aggregates are given in Table 3.5.

Table 3.5 Physical properties of plastic coated aggregates

Property	Plastic Coated Aggregate			
Impact value (%)	14			
Abrasion value (%)	24			
Stripping value (%)	After(hrs)			
	2	24	72	96
	0	0	0	0
Water Absorption Value (%)	Nil			
Soundness value (%)	Nil			

From the table, it is evident that the plastic coating over the aggregates enhances the toughness and hardness of aggregate. The stripping and water absorption value is found to be nil showing its better adhesion with bitumen.

3.5 BITUMEN

Bitumen acts as the binder in SMA mix. Different grade of bitumen are used in different mixes like hot-mix or gap-graded mix or dense-graded mix. Bitumen of 60/70 penetration grade obtained from Kochi Refineries Limited, Kochi, was used in the preparation of mix samples. The Physical properties of bitumen are found and the results are given in Table 3.6.

Table 3.6 Physical properties of bitumen

Property	Result obtained	Test procedure as per specification
Specific Gravity @ 27°C	1	IS:1202 - 1978
Softening Point (°C) (R&B Method)	50	IS:1205 - 1978
Penetration @ 25°C,0.1 mm 100g, 5 sec	64	IS:1203 - 1978
Ductility @ 27°C (cm)	72	IS:1208 - 1978
Flash Point (°C) Fire Point (°C)	240 270	IS:1209 - 1978
Viscosity at 60 °C (Poise)	1200	IS:1206 - 1978
Elastic recovery @ 15°C (%)	11	IRC: SP:53 - 2002

3.6 SUMMARY

The procurement of the materials used for making the samples of stone matrix asphalt mixtures and their properties are discussed in this chapter. Using these materials Stone Matrix Asphalt mixtures are prepared and mix design and analysis are carried out by Marshall method of design which is explained in the next chapter.

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Chapter 4

MARSHALL MIX DESIGN AND ANALYSIS

4.1 INTRODUCTION

Suitably designed bituminous mix will withstand heavy traffic loads under adverse climatic conditions and also fulfill the requirement of structural and pavement surface characteristics. The objective of the design of bituminous mix is to determine an economical blend through several trial mixes. The gradation of aggregate and the corresponding binder content should be such that the resultant mix should satisfy the following conditions.

(i) Sufficient binder to ensure a durable pavement by providing a water proofing coating on the aggregate particles and binding them together under suitable compaction.

(ii) Sufficient stability for providing resistance to deformation under sustained or repeated loads. This resistance in the mixture is obtained from aggregate interlocking and cohesion which generally develops due to binder in the mix.

(iii) Sufficient flexibility to withstand deflection and bending without cracking. To obtain desired flexibility, it is necessary to have proper amount and grade of bitumen.

(iv) Sufficient voids in the total compacted mix to provide space for additional compaction under traffic loading.

(v) Sufficient workability for an efficient construction operation in laying the paving mixture.

There are three principal bituminous mix design methods in general use. They are Marshall Method, Hveem Method and Superpave Method. Marshall mix design is the widely used method throughout India. In this method load is applied to a cylindrical specimen of bituminous mix and the sample is monitored till its failure as specified in the ASTM standard (ASTM D1559). For the present work, the bituminous mix is designed using the Marshall Method and arrived at the volumetric properties.

4.2 MARSHALL MIX DESIGN

This test procedure is used in designing and evaluating bituminous paving mixes and is extensively used in routine test programmes for the paving jobs. There are two major features of the Marshall method of designing mixes namely, density – voids analysis and stability – flow test.

Strength is measured in terms of the 'Marshall's Stability' of the mix following the specification ASTM D 1559 (2004), which is defined as the maximum load carried by a compacted specimen at a standard test temperature of 60˚C. In this test compressive loading was applied on the specimen at the rate of 50.8 mm/min till it was broken. The temperature 60˚C represents the weakest condition for a bituminous pavement.

The flexibility is measured in terms of the 'flow value' which is measured by the change in diameter of the sample in the direction of load application between the start of loading and at the time of maximum load. During the loading, an attached dial gauge measures the specimen's plastic flow (deformation) due to the loading. The associated plastic flow of specimen at material failure is called flow value.

The density- voids analysis is done using the volumetric properties of the mix, which will be described in the following sub sections.

4.2.1 Gradation of aggregates

Gradation of aggregates is one of the most important factors for the design of SMA mixture. The sieve analysis, blending and the specified limits of the SMA mixture are given in Table 4.1 as per NCHRP - 425, TRB.

4.2.2 Volumetric properties

Fundamentally, mix design is meant to determine the volume of bitumen binder and aggregates necessary to produce a mixture with the desired properties (Roberts et al., 1996). Since weight measurements are typically much easier, weights are taken and then converted to volume by using specific gravities. The following is a discussion of the important volumetric properties of bituminous mixtures.

The properties that are to be considered, include the theoretical maximum specific gravity G_{mm}, the bulk specific gravity of the mix G_{mb}, percentage air voids VA, percentage volume of bitumen V_b, percentage void in mineral aggregate VMA and percentage voids filled with bitumen VFB.

Table 4.1 Gradation of aggregates and their blends for SMA mixture

Sieve size (mm)	Percentage passing				Adopted Grading A: B: C: D 50:30:11:9	Specified Grading NCHRB, TRB
	20 mm (A)	10 mm (B)	Stone dust (C)	Cement (D)		
25.0	100	100	100	100	100	100
19.0	98	100	100	100	99	90 -100
12.5	20	100	100	100	60	50 - 74
9.50	4	58	100	100	39	25 - 60
4.75	0	6	100	100	22	20 - 28
2.36	0	0	92	100	19	16 - 24
1.18	0	0	77	100	17	13 - 21
0.6	0	0	64	100	16	12 - 18
0.3	0	0	45	100	14	12 - 15
0.075	0	0	6	96	9	8 - 10

Theoretical Maximum Specific Gravity of the mix (G_{mm}) is defined as

$$G_{mm} = \frac{\mathrm{W_{mix}}}{Vol.\ of\ the\ (mix\ -\ air\ voids)}$$

Where, W_{mix} is the weight of the bituminous mix, G_{mm} is calculated as per ASTM D 2041 – 95.

Bulk specific gravity of mix (G_{mb})

The bulk specific gravity or the actual specific gravity of the mix G_{mb} is the specific gravity considering air voids and is found out by

$$G_{mb} = \frac{\mathrm{W_{mix}}}{\text{Bulkvolume of the mix}}$$

It is obtained by measuring the total weight of the mix and its volume. Volume is determined by measuring the dimensions of the sample or for better accuracy it can be measured by the volume of water it displaces. However, while the sample is immersed in water, some water may be absorbed by the pores of the mix. Therefore, the mix is covered with a thin film of paraffin and the volume of the sample is measured by knowing the volume of paraffin used to coat its surface. The bulk specific gravity of paraffin-coated specimen is determined in accordance with ASTM standard test procedure D1188-96.

The phase diagram of the bituminous mix is given in Fig. 4.1. When aggregate particles are coated with bitumen binder, a portion of the binder is absorbed into the aggregate, whereas the remainder forms a film on the outside of the individual aggregate particles. Since the aggregate particles do not consolidate to form a solid mass, air pockets also appear within the bitumen-aggregate mixture. Therefore, as Fig. 4.1 illustrates, the four general components of HMA are: aggregate, absorbed bitumen, bitumen not absorbed into the aggregate (effective bitumen) and air.

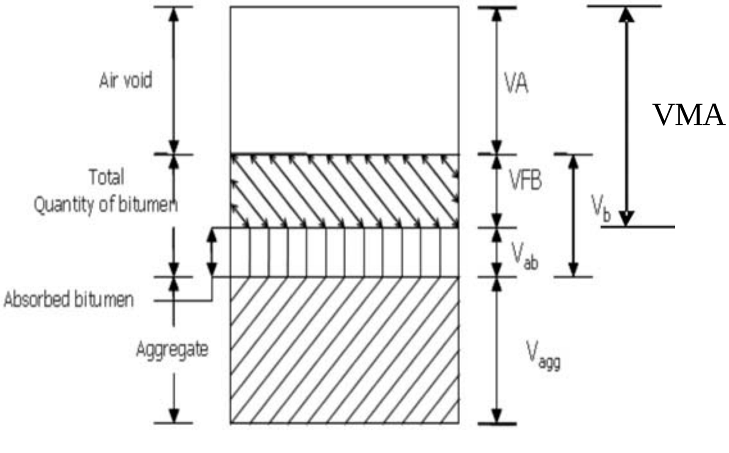

Fig. 4.1 Phase diagram of the bituminous mix

Effective Bitumen Content (P_{be})

It is the total bitumen binder content of the mixture less the portion of bitumen binder that is lost by absorption into the aggregate.

Volume of Absorbed Bitumen (V_{ab})

It is the volume of bitumen binder in the mix that has been absorbed into the pore structure of the aggregate. This volume is not accounted for the effective bitumen content.

Air voids percent (VA)

It is the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the bulk volume of the compacted paving mixture. The amount of air voids in a mixture is extremely important and closely related to stability, durability and permeability.

The voids in a compacted mixture are obtained in accordance with ASTM standard test method D3203-94. The following equation represents the percentage of air voids in the specimen.

$$VA = \frac{(G_{mm} - G_{mb)}100}{G_{mm}}$$

where G_{mm} is the theoretical specific gravity of the mix and G_{mb} is the bulk specific gravity of the mix.

Voids in mineral aggregate (VMA)

The total volume of voids in the aggregate mix (when there is no bitumen) is called Voids in Mineral Aggregates (VMA). In other words, VMA is the volume of intergranular void space between the aggregate particles of a compacted paving mixture. It includes the air voids and the volume of bitumen not absorbed into the aggregate. VMA is expressed as a percentage of the total volume of the mix.

When VMA is too low, there is not enough room in the mixture to add sufficient bitumen binder to coat adequately over the individual aggregate particles. Also, mixes with a low VMA are more sensitive to small changes in bitumen binder content. Excessive VMA will cause unacceptably low mixture stability (Roberts et al., 1996). Generally, a minimum VMA of 17% is specified. VMA can be calculated as,

$$\mathrm{VMA} = \left(1 - \frac{\mathrm{G_{mb}}\,x\,\mathrm{P_s}}{\mathrm{G_{Sb}}}\right)100$$

where P_s is the fraction of aggregates present, by total weight of the mix and G_{sb} is the bulk specific gravity of the mixed aggregates.

Voids Filled with Bitumen (VFB)

VFB is the voids in the mineral aggregate frame work filled with bitumen binder. This represents the volume of the effective bitumen content. It can also be described as the percent of the volume of the VMA that is filled with bitumen. VFB is inversely related to air voids and hence as air voids decreases, the VFB increases.

$$VFB = \frac{(VMA - VA)}{VMA} x100$$

where, VA is air voids in the mix and VMA is the voids in the mineral aggregate.

The decrease of VFB indicates a decrease of effective bitumen film thickness between aggregates, which will result in higher low-temperature cracking and lower durability of bitumen mixture since bitumen perform the filling and healing effects to improve the flexibility of mixture.

4.2.3 Role of volumetric parameters of mix

Bitumen holds the aggregates in position, and the load is taken by the aggregate mass through the contact points. If all the voids are filled with bitumen, the one to one contact of the aggregate particles may lose, and then the load is transmitted by hydrostatic pressure through bitumen, and hence the strength of the mix reduces. That is why stability of the mix starts reducing when bitumen content is increased further beyond a certain value.

During summer season, bitumen softens and occupies the void space between the aggregates and if void is unavailable, bleeding is caused. Thus, some amount of void is necessary in a bituminous mix, even after the final stage of compaction. However excess void will make the mix weak from its elastic modulus and fatigue life considerations. Evaluation and selection of aggregate gradation to achieve the specified minimum VMA is the most difficult and time-consuming step in the mix design process.

In the Volumetric method of mix design approach, proportional volume of air voids, binder and aggregates are analyzed in a compacted mixture, applying a compaction close to that of field compaction. SMA mixture design requirements is given in Table 4.2

Table 4.2 SMA mixture design criteria

Design Parameter	Design Criteria
Percent Air Voids	3 – 5%
Percent voids in mineral aggregate (VMA)	17 (minimum)
Stability value	6200 N(minimum)
Flow value	2 – 4 mm
Retained Stability (LS-283).	70% (minimum)
Draindown @ Production Temperature(AASHTO T305)	0.3 % (maximum)

4.3 MIX DESIGN

Laboratory mix designs of SMA mixtures are done by Marshall test procedure.

4.3.1 Specimen preparation

Approximately 1200g of aggregates and filler put together is heated to a temperature of 160-170˚C. Bitumen is heated to a temperature of 160˚C with the first trial percentage of bitumen (say 5.5% by weight of the mineral aggregates). Then the heated aggregates and bitumen are thoroughly mixed at a temperature of 160 - 170˚C. The mix is placed in a preheated mould and compacted by a hammer having a weight of 4.5 kg and a free fall of 45.7 cm giving 50 blows on either side at a temperature of 160˚C to prepare the laboratory specimens of compacted thickness 63.5+/-3 mm. Seventy five compaction blows were not given as in the case of dense graded bituminous mixes for heavy traffic condition, since in the gap graded mixes, this would tend to break down the aggregate more and would not result in a significant increase in density over that provided by 50 blows. SMA mixtures have been more easily compacted on the roadway to the desired density than the effort required for conventional HMA mixtures. In this research, the compaction of all the SMA samples are performed using fifty blows of the Marshall hammer on either side of the sample. The heights of the samples are measured and specimens are immersed in a water bath at 60˚C for 35±5 minutes. Samples (Fig. 4.2) are removed from the water bath and placed immediately in the Marshall loading head as shown in Fig. 4.3. The load is applied to the specimen at a deformation rate of 50.8 mm/minute. Stability is measured as the maximum load sustained by the sample before failure. Flow is the deformation at the maximum load. The stability values are then adjusted with respect to the sample height (stability corrections).

For the proposed design mix gradation, four specimens are prepared for each bitumen content within the range of 5.5 – 7.5% at increments of 0.5 percent, in accordance with ASTM D 1559 using 50 blows/face compaction standards. All bitumen content shall be in percentage by weight of the total mix. As soon as the freshly compacted specimens have cooled to room temperature, the bulk specific gravity of each test specimen shall be determined in accordance with ASTM D 2726. The stability and flow value of each test specimen shall then be determined in accordance with ASTM D 1559. After the completion of the stability and flow test, specific gravity and voids analysis shall be carried out for each test specimen to determine the percentage air voids in mineral aggregate and the percentage air voids in the compacted mix and voids filled with bitumen. Values which are obviously erratic shall be discarded before averaging. Where two or more specimens in any group of four are so rejected, four more specimens are prepared and tested.

The average values of bulk specific gravity, stability, flow, VA, VMA and VFB obtained above are plotted separately against the bitumen content and a smooth curve drawn through the plotted values. Average of the binder content corresponding to VMA of 17 % and an air void of 4% are considered as the optimum binder content (Brown, 1992). Stability and Flow values at the optimum bitumen content are then found from the plotted smooth curves and shall comply with the design parameters given in Table 4.2.

The optimum bitumen content (OBC) for the SMA mixture is determined and is found to be 6.42 % (by wt. of total mix). This SMA mixture without additives is considered as the control mixture for the subsequent studies.

Fig. 4.2 Marshall sample

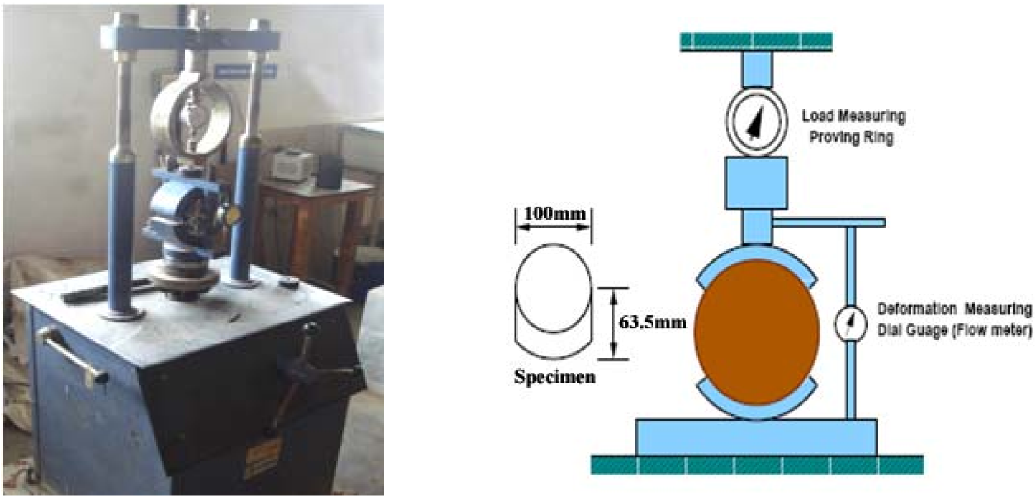

Fig. 4.3 Marshall test apparatus

4.3.2 Stabilized SMA

SMA mixtures with additives are taken as the stabilized SMA. An optimum bitumen content of 6.42 % (by wt. of total mix) as found from Marshall Control mix design is used in preparing all the stabilized mixes to maintain consistency throughout the study.

4.3.2.1 Preparation of Marshall Specimens

Marshall Stability test is conducted on stabilized SMA in more than 100 samples of 100 mm dia and 63.5 mm height by applying 50 blows on each face as per ASTM procedure (ASTM D1559, 2004). Bituminous mixes are prepared by mixing the graded aggregates with 60/70 penetration grade bitumen and additives. Three different natural fibres are used as additives in SMA mixture viz., coir, sisal and banana fibres. Waste plastics in shredded form and a polymer polypropylene are also tried as the additives. The fibre content in this research is varied between 0.1%, 0.2%, 0.3% and 0.4% by weight of mix and the polypropylene and the waste plastics content as 1%, 3%, 5%, 7% and 9% by weight of mix. The procedure adopted for the preparation of Marshall Specimen is the same as used in control mixtures (sec.4.3.1), except, the additives are added in heated aggregate prior to mixing them with heated bitumen (dry blending method). The fibre length in the mixture is preserved as a constant parameter with a value equal to 6 mm. The mixing and compaction temperatures are kept as 165˚C and 150˚C respectively (Brown and Manglorkar, 1993). A total of 120 Marshall samples for all percentages of different additives are prepared.

4.4 MOISTURE SUSCEPTIBILITY TEST

It is well known that presence of moisture in a bituminous mix is a critical factor, which leads to premature failure of the flexible pavement. The loss of adhesion of aggregates with bitumen is studied by utilising Retained Stability test to examine the effect of additive on resistance to moisture induced damage. This test measures the stripping resistance of a bituminous mixture. The test is specified in IRC: SP 53-2002 and is conducted as per ASTM D 1075-1979 specifications. The standard Marshall specimens of 100 mm diameter and 63.5 mm height are prepared. Marshall Stability of compacted specimens is determined after conditioning them by keeping in water bath maintained at 60˚C for 24 hours prior to testing. This stability, expressed as a percentage of the stability of Marshall specimens determined under standard conditions, is the retained stability of the mix. A higher value indicates lower moisture susceptibility (higher moisture damage resistance).

4.5 MARSHALL TEST RESULTS AND DISCUSSION

Results of mix design and their discussion for the fibre stabilized mixtures and the mixtures with waste plastics and polypropylene are given separately in this section.

4.5.1 Fibre stabilized mixtures

Test results of volumetric and mechanical properties of SMA mixtures using different fibres are tabulated in Table 4.3 and discussed in this section.

4.5.1.1 Marshall stability and flow value

From Table 4.3, it is evident that the presence of fibre in the SMA mixtures effectively improves the stability values, which will result in an improvement of mixture toughness. This result indicates that the mixture using fibre would result in higher performance than using the control mixture. Variation of Marshall stability and flow value with different fibre contents are given in Fig. 4.4.a and Fig. 4.4.b

Fig. 4.4.a indicates that the stability of fibre stabilized mixtures increases initially, reaches a maximum value and then decreases with increasing fibre content. Bituminous mixture is an inconsistent, non-uniform, multi-phased composite material consisting of aggregates and sticky bitumen. Therefore, excessive fibres may not disperse uniformly, while coagulate together to form weak points inside the mixture. As a result, stability decreases at high fibre contents.

Table 4.3 Variation of Marshall Properties of SMA with different % of fibres as additive.

Additive	**%**	**Stability (kN)**	**Flow (mm)**	**Marshll Quotient (kN/mm)**	**Air void (%)**	**Bulk specific gravity**	**VMA (%)**	**VFB (%)**
Nil	0	7.416	3.18	2.332	4	2.32	18.865	78.796
Coir fibre	0.1	8.19	3.14	2.609	4.14	2.318	18.935	78.135
	0.2	10.073	3.05	3.303	4.31	2.315	19.039	77.363
	0.3	**12.58**	**2.83**	**4.445**	**4.46**	**2.308**	**19.284**	**76.872**
	0.4	7.936	2.72	2.918	4.64	2.298	19.634	76.368
Sisal fibre	0.1	7.743	3.17	2.443	4.09	2.31	19.214	78.714
	0.2	8.701	3.07	2.834	4.24	2.3	19.564	78.328
	0.3	**11.862**	**2.86**	**4.148**	**4.37**	**2.291**	**19.879**	**78.017**
	0.4	8.742	2.77	3.156	4.54	2.278	20.333	77.672
Banana fibre	0.1	7.732	3.16	2.447	4.09	2.308	19.284	78.791
	0.2	8.703	3.09	2.817	4.22	2.296	19.704	78.583
	0.3	**11.854**	**2.86**	**4.145**	**4.34**	**2.286**	**20.030**	**78.333**
	0.4	8.643	2.76	3.132	4.50	2.275	20.438	77.982

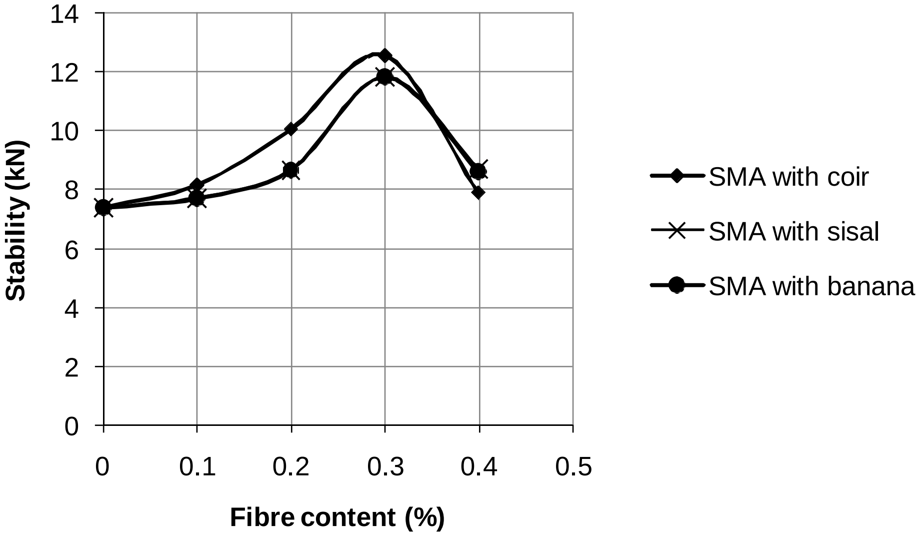

Fig. 4.4.a Variation of stability with different fibre %

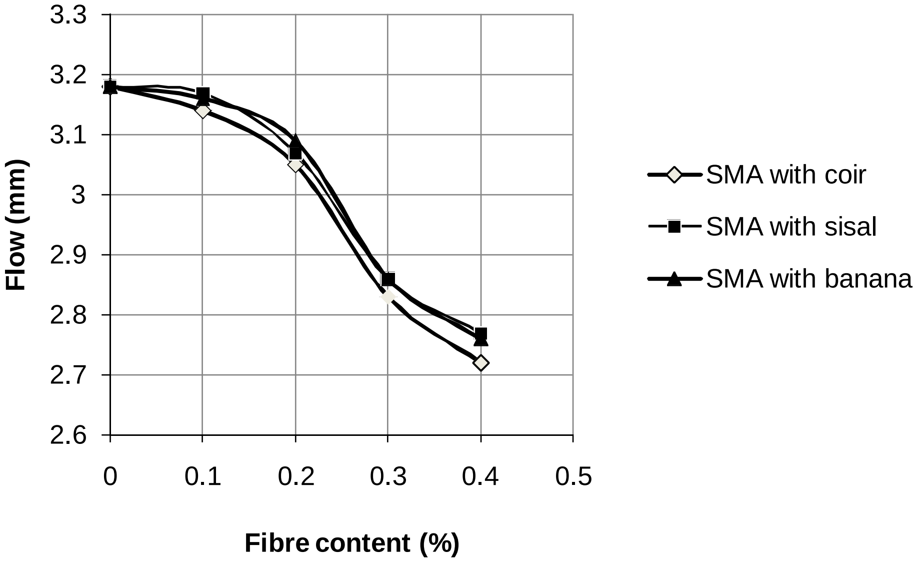

Fig. 4.4.b Variation of flow value with different fibre %

It may be noted that all fibre stabilized mixtures gave the maximum stability at 0.3% fibre content. Comparing different fibre stabilized mixtures, it is evident that the mixtures with coir fibre have the highest stability (12.58 kN), indicating their higher rutting resistance and better performance than mixtures with other fibres. The percentage increase in stability with respect to the control mixture is about 70% for SMA with coir fibre and about 60% for SMA with other fibres. This result could be attributed to fibre's adhesion and networking effects in the stabilized mixtures. The spatial networking effect was regarded as the primary factors contributing to fibre's reinforcement (Chen and Lin, 2005). This trend could be explained as follows: fibre performs as ‘‘bridge” when cracking of bitumen mixture appears and thus resists the propagation of cracking development, which is called bridging cracking effect (Li., 1992). In addition, due to the absorption of light component of bitumen (Serfass and Samanos, 1996), fibre improves the viscosity and stiffness of bitumen (Huang and White, 2001).

Flow value of SMA mixtures decreases after adding fibres, as shown in Fig. 4.4.b. Owing to the stiffness of fibres in the mixture, the mixes become less flexible and the resistance to deformation increases resulting in a low flow value. However, flow values are located within the required specification range of 2 to 4 mm (AASHTO T 245).

Marshall Quotient (MQ) also known as rigidity ratio is the ratio of stability to flow value of the mixture and the Marshall Quotient values of SMA with different fibre contents are shown in Fig. 4.4.c. It is found that MQ of the coir fibre stabilized SMA at 0.3 % fibre content is almost doubled with respect to the control mixture. It can be inferred that these stabilized SMA provide better resistance against permanent deformations due to their high stability and high MQ and also indicate that these mixtures can be used in pavements where stiff bituminous mixture is required.

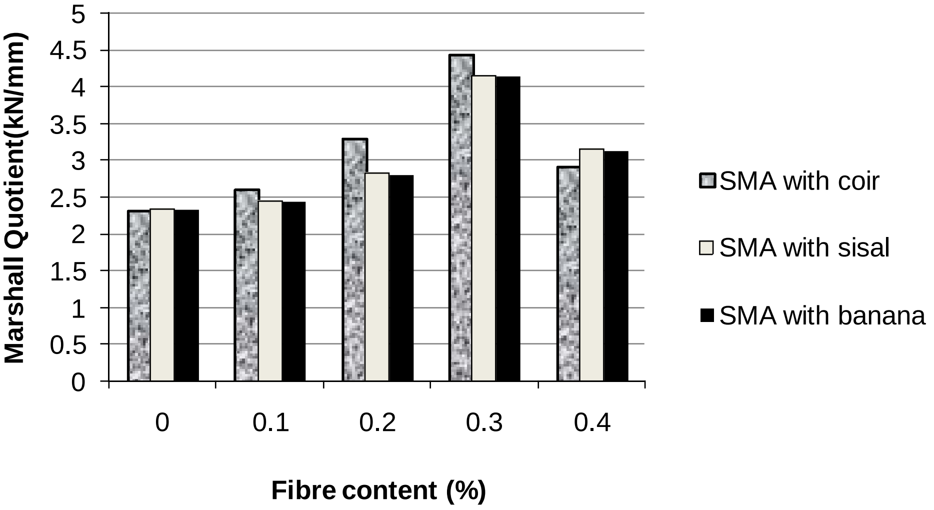

Fig. 4.4.c Variation of Marshall Quotient with different fibre %

4.5.1.2 Bulk specific gravity

The bulk specific gravity of bituminous mixture decreases with increasing fibre content in SMA as depicted in Fig. 4.4.d.

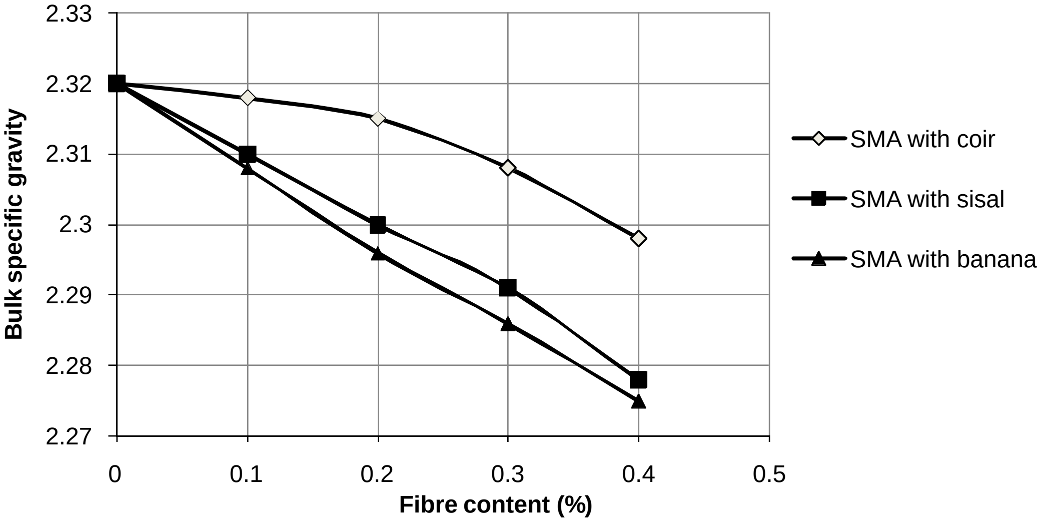

Fig. 4.4.d Variation of bulk specific gravity with different fibre %

This trend is in agreement with other research (Tapkın, 2008; Saeed and Ali, 2008). This result would be attributed due to the different specific gravities of different fibres and the much lower specific gravity of fibre than that of aggregates. Meanwhile, the elastic behavior of mixture increases with increase in fibre content, due to the elastic nature of fibres. As a result, at the same compaction effort (50 blows on both sides of Marshall sample), adding fibre reduces the specific gravity of the control mixture. However, it is noted that the coir fibre stabilized SMA has the highest specific gravity which is due to the fact that coir fibre has the maximum density (Table 3.3) as compared to other fibres. Considering the fact that higher specific gravity results in better design mixes, it can be inferred that coir fibre stabilized mixtures perform better than the other stabilized mixtures.

4.5.1.3 Air void, VMA and VFB

Excessive air voids in the mixture would result in cracking due to insufficient bitumen binders to coat on the aggregates, while too low air void may induce more plastic flow (rutting) and bitumen bleeding. Here the test results (Fig. 4.4.e) show that air void increases after adding fibres into bituminous mixtures. This may be due to the net working effect of the fibre within the mix (lower G_{mb} correlates to higher air voids). The mixtures with coir fibre has the highest air voids than the other mixtures. However, the air voids of mixtures are located within the specification range of 3% to 5% (AASHTO T 312) which support the use of these additives.

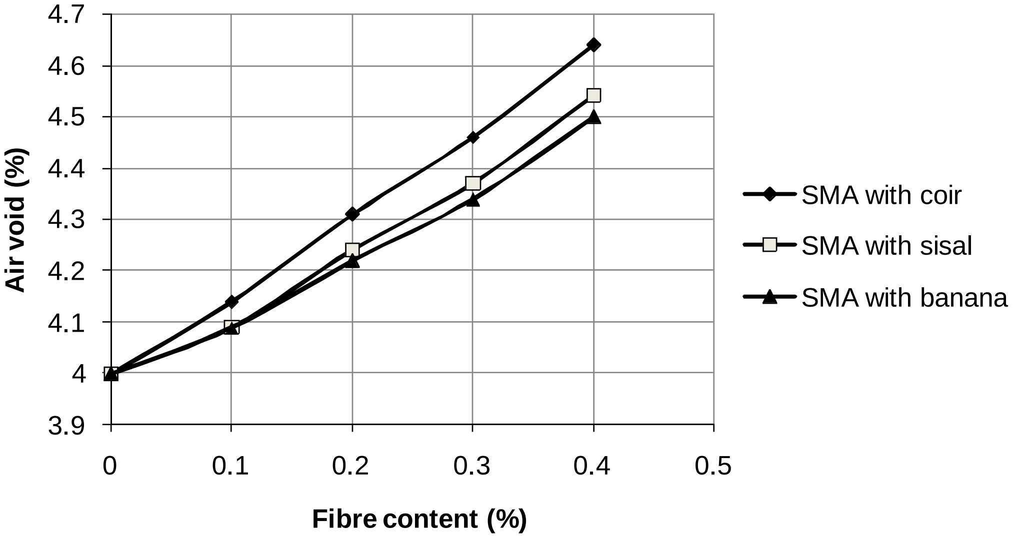

Fig. 4.4.e Variation of air void with different fibre %

Increasing the fibre content increases the VMA of SMA mixtures as shown in Fig. 4.4.f, while reduces VFB as shown in Fig. 4.4.g. With respect to the control mixture, when fibre content increases from 0% to 0.3%, air void increases by about 11.5%, VMA increases by 2.2%, while VFB decreases by 2.4% for coir fibre stabilized mixtures and the corresponding percentage changes are respectively about 9.25% increase, 5.4% increase and 1% decrease for sisal fibre stabilized mixtures and 8.5% increase, 6.2% increase and 1% decrease for banana fibre stabilized mixtures with respect to the control mixture. But all the results are within the required specification range which also supports the use of these additives.

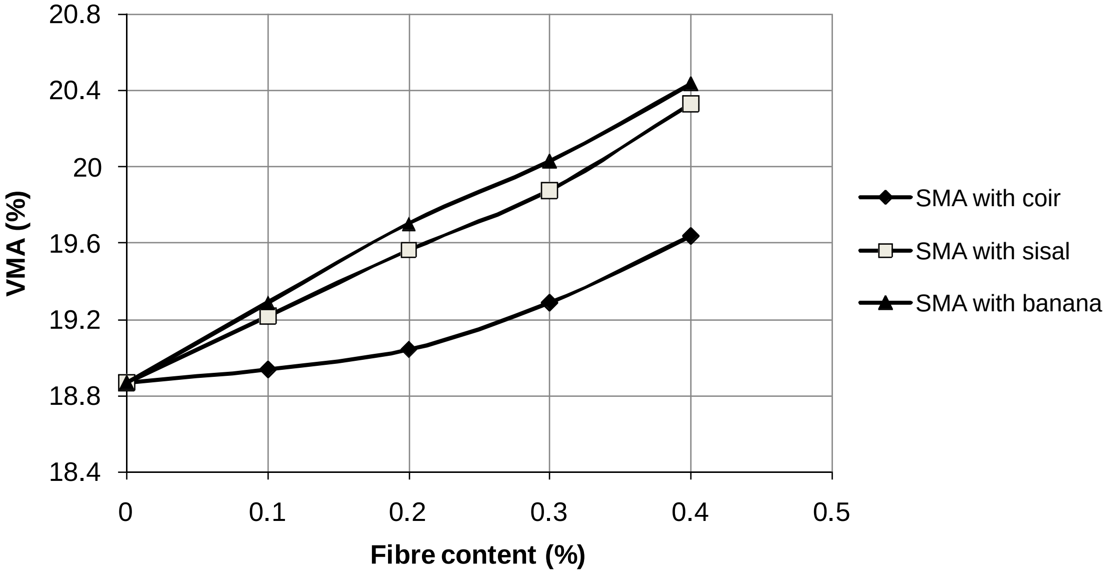

Fig. 4.4.f Variation of VMA with different fibre %

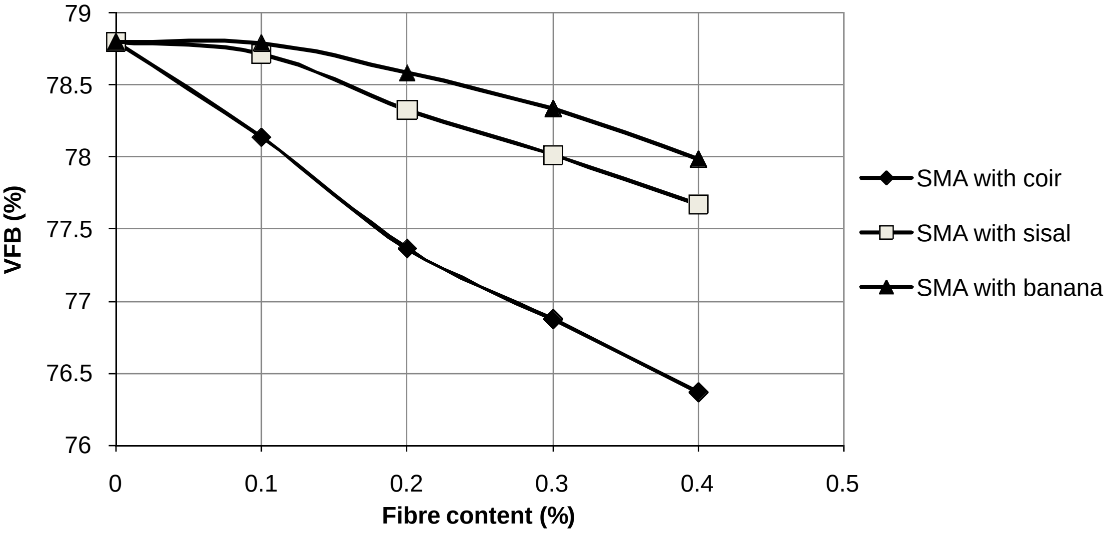

Fig. 4.4.g Variation of VFB with different fibre %

4.5.2 Waste plastics and polypropylene stabilized mixtures

The variation in different Marshall properties for various percentages of waste plastics (WP) and polypropylene (PP) contents are determined for each mix design and is given in Table 4.4.

Table 4.4 Marshall Properties of waste plastics and polypropylene stabilized SMA.

Additive	%	Stability (kN)	Flow (mm)	Marshall Quotient (kN/mm)	Air void (%)	Bulk specific gravity	VMA (%)	VFB (%)
Nil	**0**	**7.416**	**3.18**	**2.332**	**4**	**2.32**	**18.865**	**78.796**
WP	1	8.717	3.025	2.882	3.95	2.326	18.655	78.826
	3	11.18	2.916	3.834	3.91	2.33	18.515	78.882
	5	13.12	2.818	4.656	3.82	2.336	18.305	79.132
	7	**13.7**	**2.794**	**4.903**	**3.66**	**2.346**	**17.955**	**79.616**
	9	10.6	2.876	3.686	3.41	2.356	17.606	80.631
PP	1	8.252	3.085	2.675	3.94	2.328	18.585	78.800
	3	10.213	2.923	3.494	3.86	2.338	18.235	78.832
	5	**12.843**	**2.828**	**4.541**	**3.75**	**2.346**	**17.955**	**79.115**
	7	11.25	2.83	3.975	3.59	2.355	17.641	79.646
	9	10.52	2.872	3.664	3.34	2.368	17.186	80.566

4.5.2.1 Marshall stability and flow value

Fig. 4.5.a and 4.5.b represent the effect of waste plastics and polypropylene content on stability and flow value of the SMA mixtures. The figure indicates that as the additive content increases, the stability value increases initially, reaches a maximum and then decreases. The addition of 5% PP raises the Marshall stability of control mix by 73% and the percentage increase for 7% WP is 85%. This was attributed to the specific gravity of additive (less than 1) which is less than that of bitumen (Table 3.6). This serves to penetrate between particles and enhanced the interlock of aggregates, which increases the stability and decreases the flow value. Beyond this percentage of additive content the stability value decreases. This is related to the decrease in interlocking offered by bitumen binder and additive coated aggregate particles while excess additive occupy the space to be occupied by the bitumen. Test results indicate that the mixtures with waste plastics have the higher stability (13.7 kN) than mixtures with polypropylene, indicating their higher rutting resistance.

Failure in bituminous mixtures can occur within the binder (cohesive failure) or at the aggregate-binder interface (adhesive failure). It can be considered that adhesive bond strength controls the failure mechanism in the Marshall Stability test (Kok and Kuloglu, 2007). The presence of additives in the bituminous mixtures resulted in, increased adhesive bond strength which leads to increased stability values of the mixtures.

Flow value of SMA mixtures decreases initially (up to 7% WP and 5% PP) and after that there is an increase as shown in Fig. 4.5.b. This may be due to the decrease in the stone to stone contact of SMA mixtures at higher additive contents. However, flow values are located within the required specification range of 2 to 4mm (AASHTO T 245).

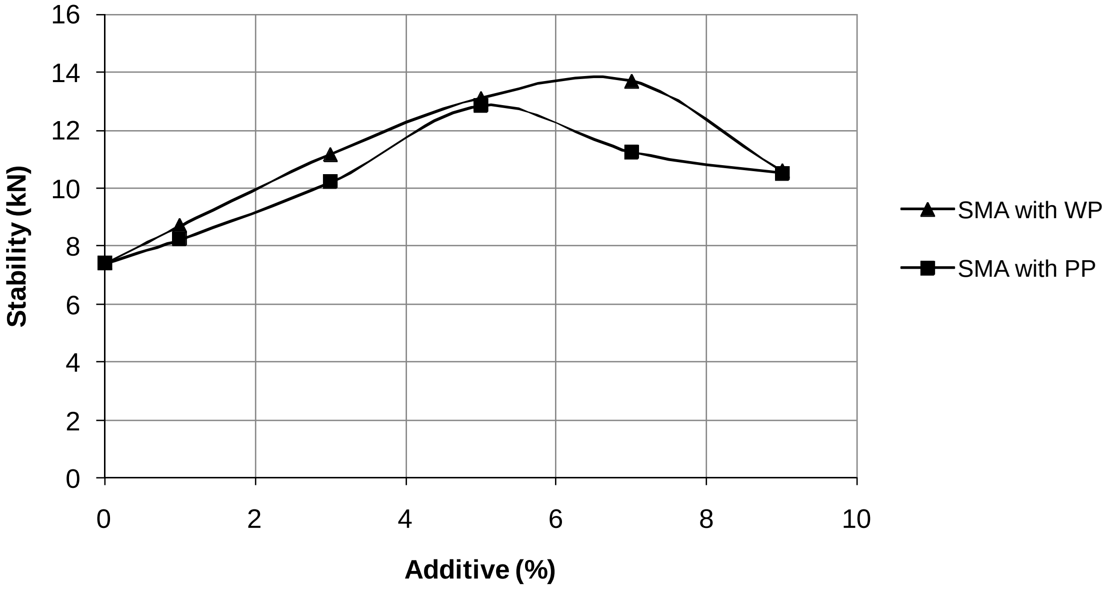

Fig. 4.5.a Variation of stability with different additive %

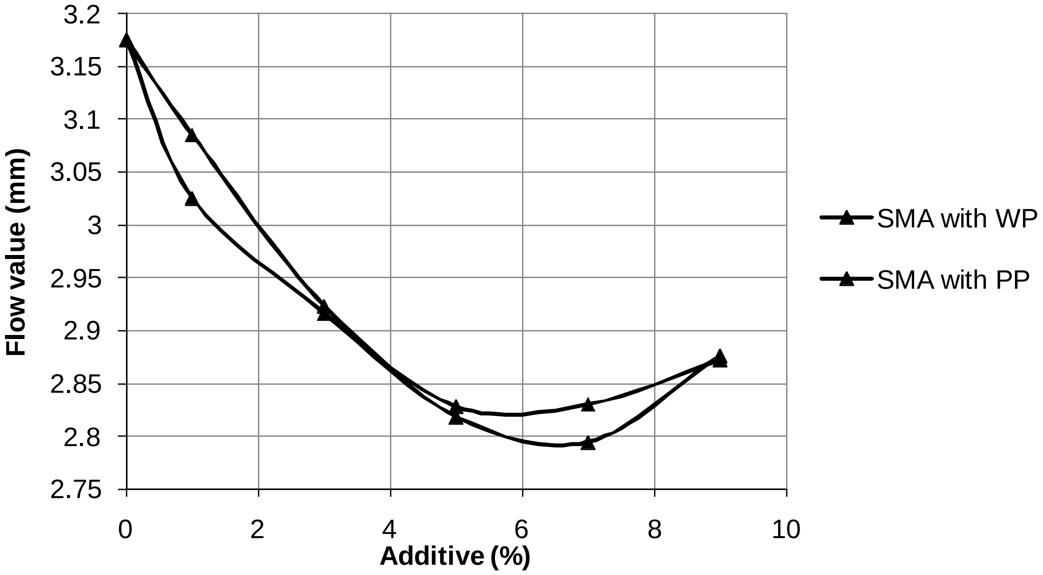

Fig. 4.5.b Variation of flow value with different additive %

From the sited results in Fig. 4.5.c, it is found that the Marshall Quotient almost doubled with respect to the control mixture at 5% PP content and 7% WP content and is found that it is slightly higher with waste plastics additive. It can be inferred that these stabilized SMA provide better resistance against permanent deformations than the control mixture.

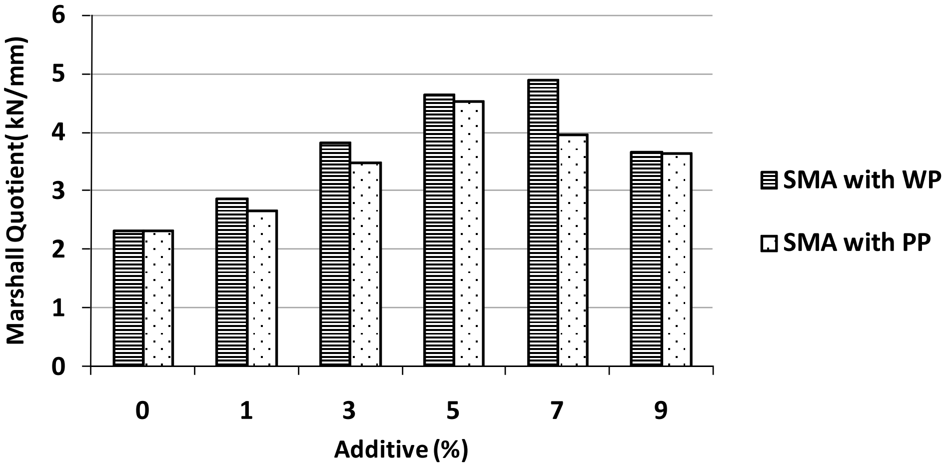

Fig. 4.5.c Variation of Marshall Quotient with additive content

4.5.2.2 Air void and bulk specific gravity

The density of WP and PP is much less than that of aggregates and they will penetrate into the aggregates and a proper coating is formed over it. Owing to the filling property offered by these additives resulting in a less air void in the stabilized mixture as compared to the control mixture (Fig. 4.5.d). But the values are within the specified limit of 3 to 5% which support the use of these additives. Bulk specific gravity of SMA mixture depends on the air voids. Less air voids lead to reduction in bulk volume of the SMA mixture, as a result bulk specific gravity of SMA mix increases with an increase in additive content as shown in Fig. 4.5.e.

4.5.2.3 VMA and VFB

It can be observed from Fig. 4.5.f that VMA decreases by the addition of additives to the bituminous mixtures. This may be due to the decrease of bulk specific gravity as indicated by equation for VMA (Section 4.2.2). But all the results are within the specification range which also supports the use of these additives. VFB of mixtures have an increase after adding additive into the mixture, as shown in Fig. 4.5.g. VFB which represents the volume of the effective bitumen content in the mixture is inversely related to air voids and hence as air voids decreases, the VFB increases. Both additives, waste plastics and polypropylene show the similar trend.

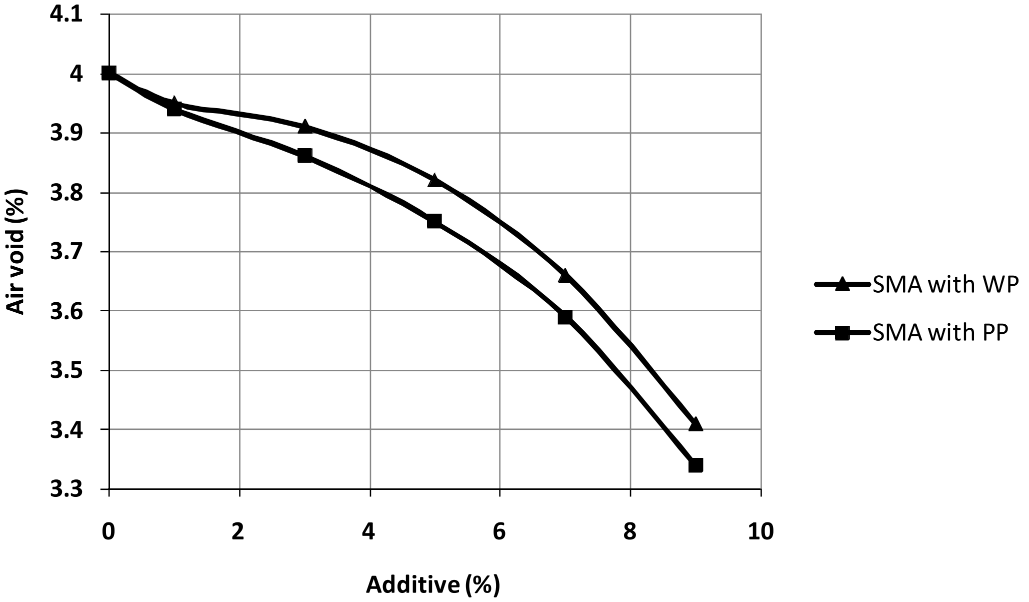

Fig. 4.5.d Variation of air void with different additive %.

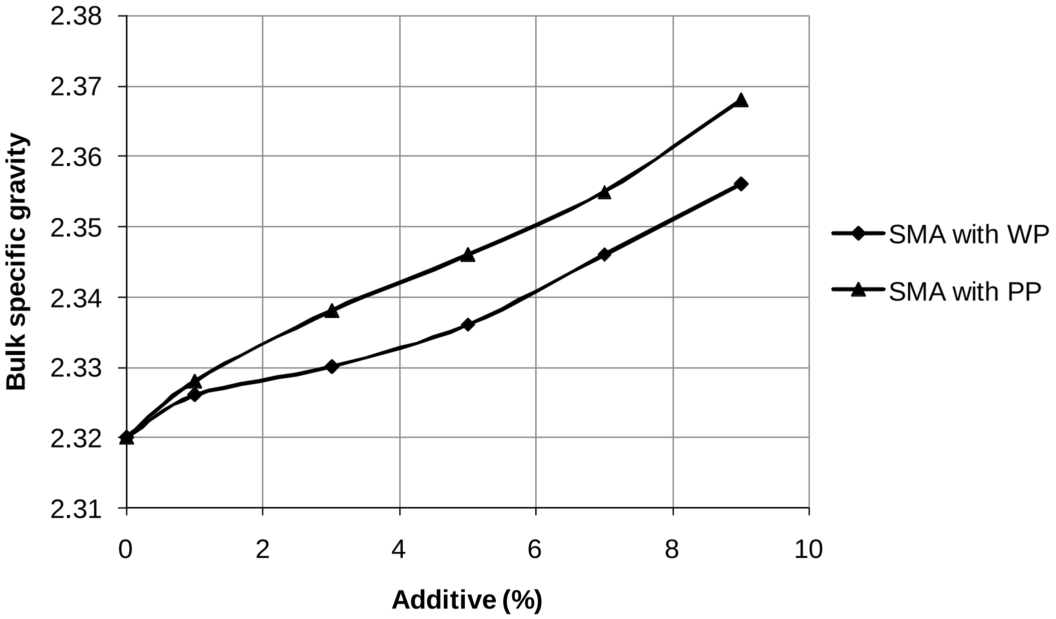

Fig. 4.5.e Variation of bulk specific gravity with different additive %

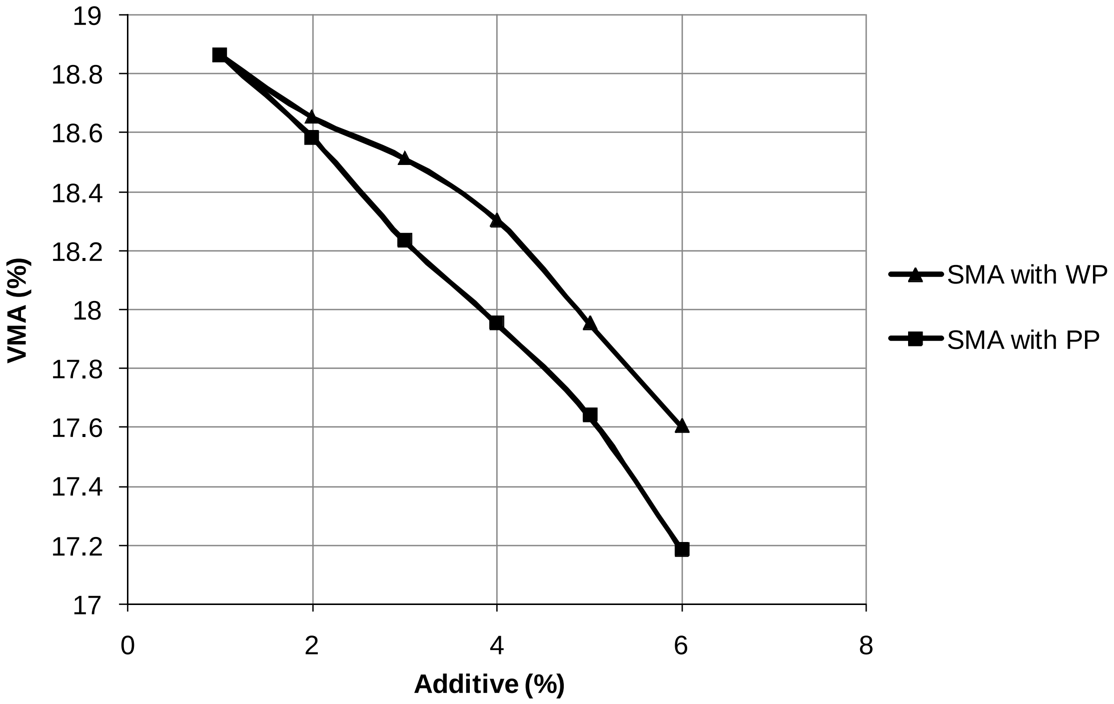

Fig. 4.5.f Variation of VMA with different additive %

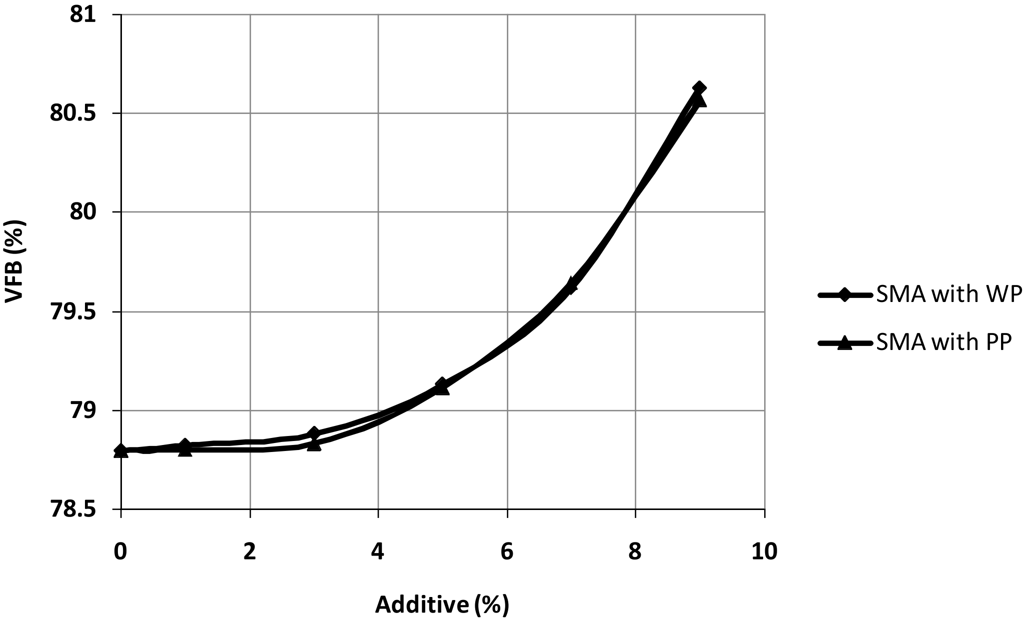

Fig. 4.5.g Variation of VFB with different additive %

4.5.3 Moisture susceptibility

From Table 4.5 and 4.6, it can be observed that the retained stability is significantly higher in the stabilized SMA mixtures as compared to the control mixture. Retained stability value of more than 70% (Table 4.2) is suggested as a criterion for a mixture to be resistant to moisture induced damages. It is seen that for the control mixture, it is only 69 %, supporting the need for an additive in SMA mixture. It also shows that the retained stability of the mixture increases with increasing additive content initially up to 0.3% for fibre, 7% for waste plastics and 5% for polypropylene and beyond these contents, the value is found to be decreasing. Addition of 7% waste plastics in SMA resulted in the highest retained stability of 98%. Among the fibre stabilized mixtures, coir fibre stabilized mixture exhibits the maximum value (95%). These results show that the presence of additives in the Stone Matrix Asphalt mixture leads to a higher protection against water damage.

Both the cohesive properties of the bitumen and the adhesion of the bitumen to the aggregate surfaces may affect as a result of exposing the bituminous mixtures to moisture. Additive incorporation into bituminous mixtures helps to reduce the high level of moisture damage that was noted in the control mix. Among the fibre stabilized mixtures, the coir fibre stabilized mixes showed lower moisture susceptibility than those of the other fibre mixes at the same fibre concentration. 0.3% fibre concentrated mixes showed better resistance to water damage than that at other concentration. Higher fibre concentration may have far too high void contents (balling effect) which allow more water penetration into SMA mixtures.

In plastics stabilized and polypropylene stabilized SMA mixtures, the coating of molten-plastics or polypropylene over the aggregate results in lesser voids and a reduction in the water absorption of the mix. This, obviously results in higher retained stability for the stabilized mixtures than the control mixture.

Table 4.5 Retained stability of SMA mixtures with fibres

Additive (%)	**Retained stability (%)**		
	Coir fibre	**Sisal fibre**	**Banana fibre**
0	69	69	69
0.1	84	82	81
0.2	90	89	88
0.3	**95**	**93**	**93**
0.4	92	90	90

Table 4.6 Retained stability of SMA mixtures with WP and PP

Additive content (%)	Retained stability (%)	
	Polypropylene	Waste plastic
0	69	69
1	82	81
3	89	86
5	**96**	92
7	94	**98**
9	90	97

4.5.4 Influence of additive content on Optimum binder content

All the results discussed above are based on the tests conducted on SMA samples with different additives at a binder content of 6.42%, which is the optimum binder content (OBC) of the Control SMA mixture. In order to study the influence of additive content on OBC, the binder content is varied from 5.5 to 7.5% at an increment of 0.5% for each percentage of additive content for different additives. A total of 230 samples are prepared for this purpose and the Marshall tests have been conducted. The OBC is obtained for each fibre stabilized mixtures at fibre contents of 0.1%, 0.2%, 0.3% and 0.4%. It is the average of the bitumen content corresponding to 4% air void and 17% VMA and is given in Table 4.7. For PP and WP stabilized mixtures, additive content is varied from 1% to 9% at an increment of 2% and the corresponding OBC is tabulated in Table 4.8.

Table 4.7 Optimum Binder Content at various % of fibre content

Fibre Content (%)	Optimum Binder content (%)		
	Coir	Sisal	Banana
0	6.42	6.42	6.42
0.1	6.46	6.45	6.45
0.2	6.52	6.51	6.52
0.3	**6.58**	**6.56**	**6.57**
0.4	6.54	6.52	6.53

Table 4.8 Optimum Binder Content at various % of WP and PP content

Additive content (%)	**Optimum bitumen content (%)**	
	SMA with WP	**SMA with PP**
0	6.42	6.42
1	6.45	6.44
3	6.50	6.47
5	**6.52**	6.50
7	6.50	**6.52**
9	6.48	6.50

Test results show that the OBC varies depending on the type and dosage of additives and it increases initially and then decreases with increasing additive content. OBC increases by about 2.5% when fibre content increases from 0% to 0.3% and by about 1.6% when PP content increases from 0% to 5% and WP content from 0% to 7%.

This result is explained as follows: Adding fibre requires more bitumen to wrap onto its surface due to its absorption of light components of bitumen as compared to polymer (Serfass and Samanos, 1996). With an increase in fibre content, specific surface area increases and fibre absorbs more bitumen and thus OBC increases (Wo D., 2000). However, after the fibre content reaches a certain value, excessive fibres are unable to disperse uniformly in the mixture and susceptible to coagulate, which actually does not improve the total specific areas, thus OBC decreases.

The resulted OBC for the fibres can be ranked in a decreased order as follows: coir fibre > banana fibre > sisal fibre > no fibre. This result is primarily due to the different specific areas and the resulted different bitumen absorptions of different fibres. The coir fibre has a loose structure with the highest specific surface area, which results in the highest absorption of bitumen among these fibres (Table 4.7). But when all the additives for the present investigation are analysed, it is evident that waste plastics stabilized mixtures having the least bitumen content is more economical.

4.6 COMPARISON OF VARIOUS STABILIZED MIXTURES

Test results have illustrated that type of additive and its content play significant role in the volumetric and mechanical properties of bituminous mixtures. Meanwhile, results have clearly shown that different additives have different reinforcing effects. Therefore, choice of appropriate additive type, design of optimum bitumen content, and design of optimum additive content would be among the primary objectives for the design of additive -reinforced bituminous mixtures.

Based on the Marshall test results discussed previously, an optimum fibre content of 0.3% is recommended for fibre stabilized SMA mixtures, with which fibre mixture exhibits the highest stability, Marshall Quotient and the residual stability and also the specified volumetric characteristics. For the other additive stabilized mixtures, the optimum additive content is 7% for waste plastics and 5% for polypropylene respectively. The choice of additive type would consider both additive characteristics and its reinforcement effects.

The variations of volumetric and mechanical properties of SMA at the optimum additive content with different additives are shown in the Fig. 4.6.a to Fig. 4.6. h. It is observed that the additives have great impact on the properties of the gap graded SMA mixture with rich binder content. There is significant improvement in the characteristics of control mixture after adding additives, showing the influence of additives on Stone Matrix Asphalt.

The percentage increase in stability value is significant at the optimum additive content. The flow value of SMA mixtures decreases with an increase in additive content. Stability and the Marshall quotient are almost doubled. Retained stability result indicates that the extent of moisture induced damage is more for the control mixture and it doesn’t fulfill the minimum criteria of 70%. But for all stabilized mixtures, the value is more than 90% which supports the role of additives in SMA mixture to reduce the moisture induced damages. Less flow value for the SMA mixture with waste plastics shows the increased resistance of the mixture to plastic flow. Regarding the voids, fibre stabilized mixtures show higher air voids and voids in mineral aggregates than the other mixtures, but the voids filled with bitumen is more in plastics stabilized mixtures. But in all stabilized mixtures, all the volumetric characteristics are within the specification range which also supports the use of these additives.

Among the fibre stabilized mixtures, coir stabilized SMA mix gives the best results as compared to the other two stabilized mixtures. But, among all the mixtures investigated, waste plastics stabilized SMA exhibits the highest stability, retained stability, Marshall Quotient and bulk specific gravity as compared to the other mixtures. So this waste material can be used as an effective additive in SMA instead of expensive polymers and fibre additives.

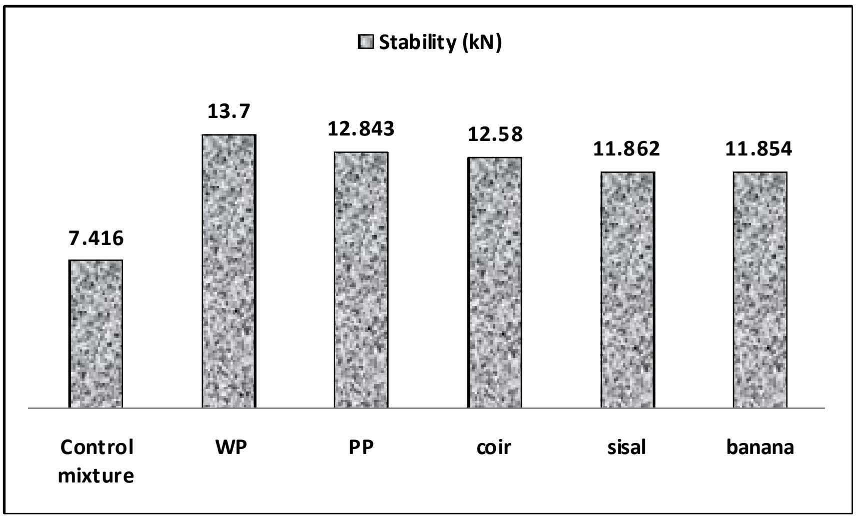

Fig. 4.6.a

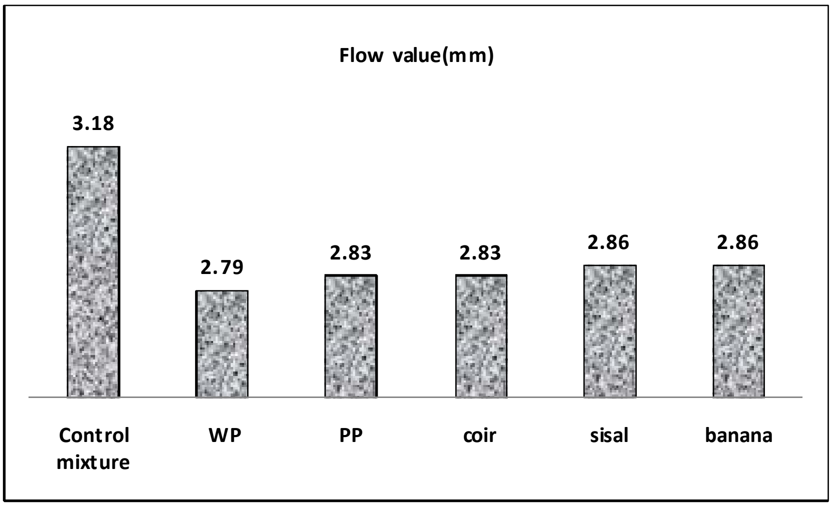

Fig. 4.6.b

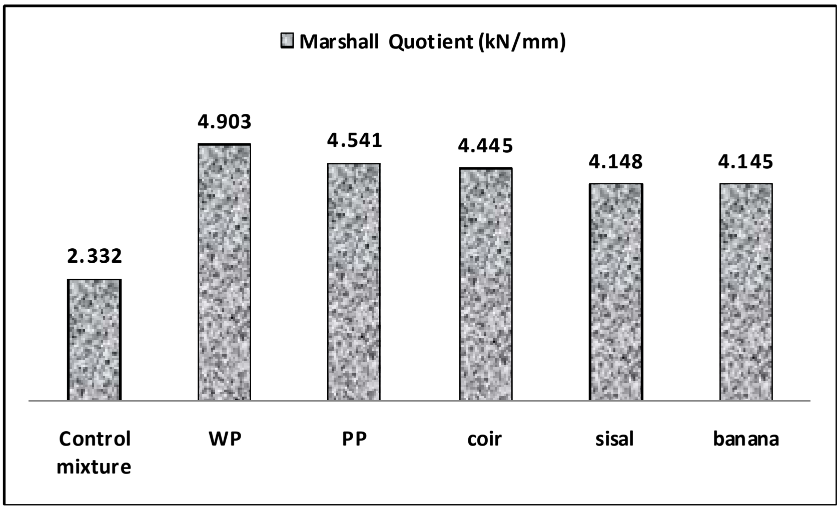

Fig. 4.6.c

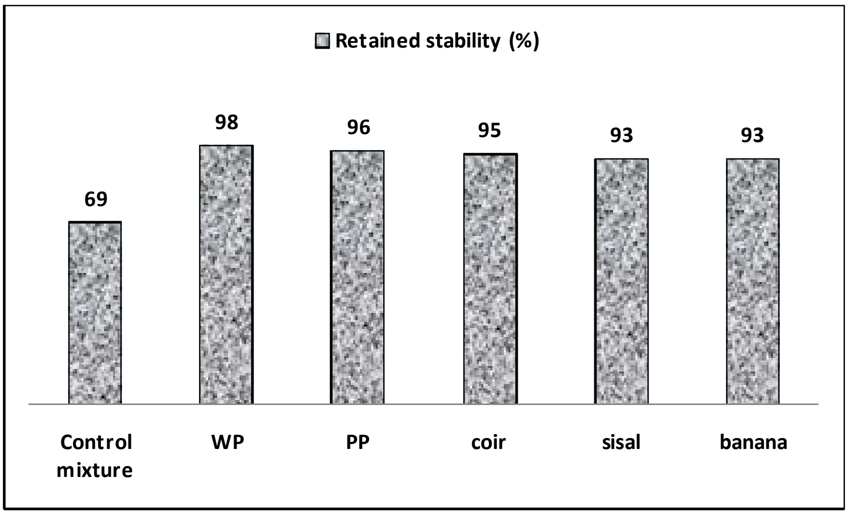

Fig. 4.6.d

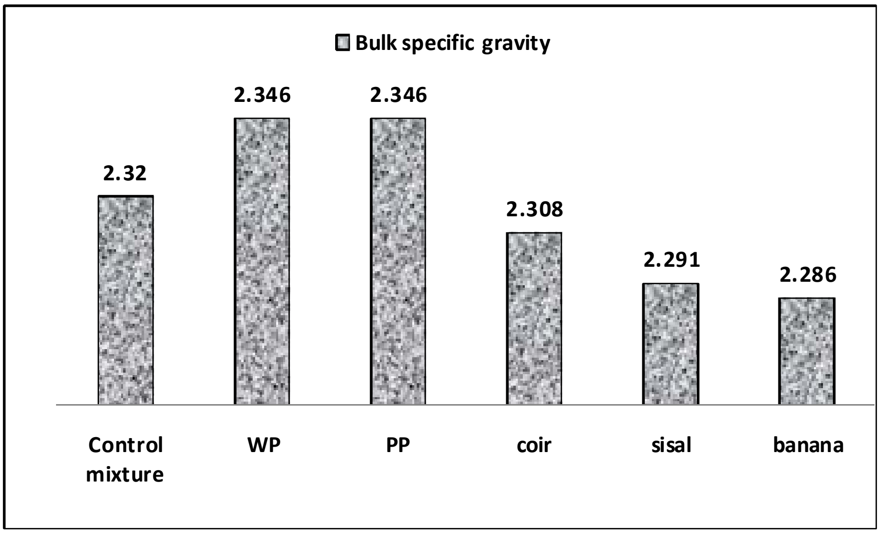

Fig. 4.6.e

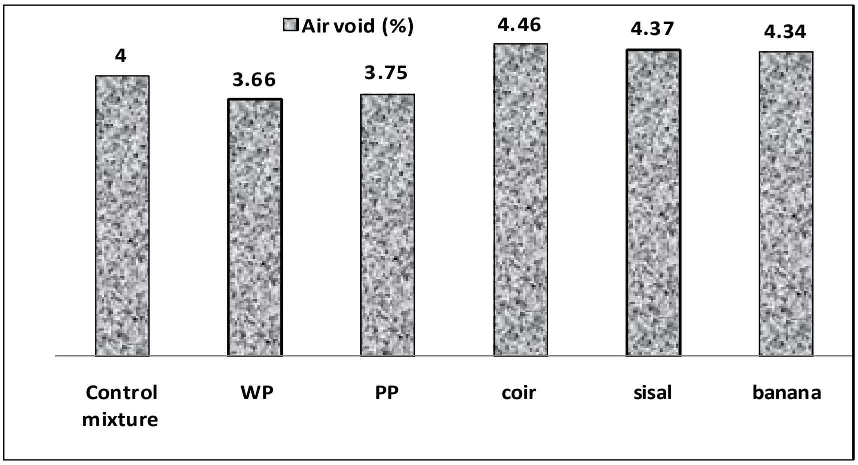

Fig. 4.6.f

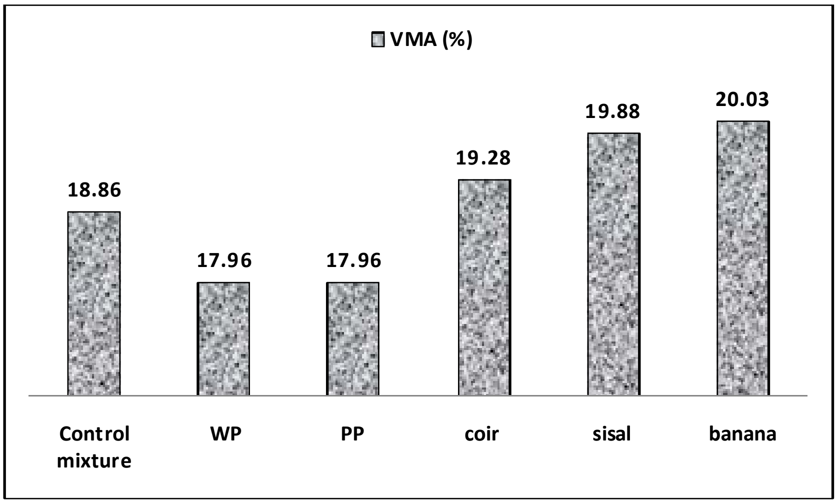

Fig. 4.6.g

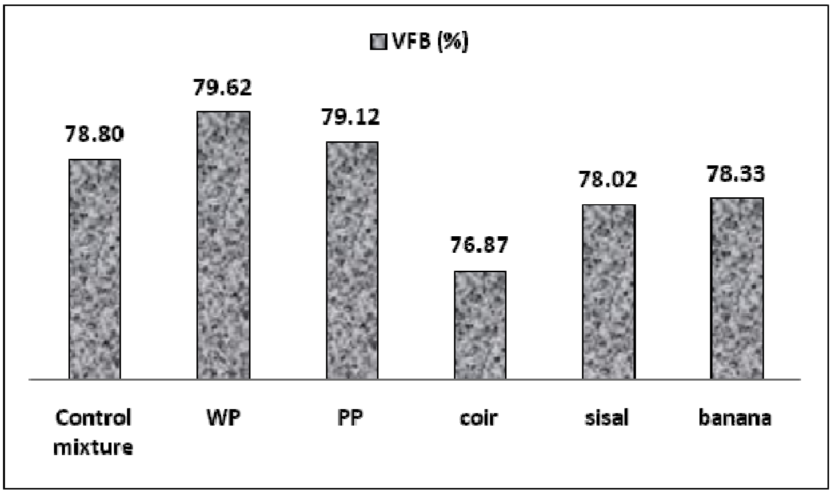

Fig. 4.6.h

Fig.4.6 Comparison of the volumetric and mechanical properties of different stabilized mixtures.

4.7. SUMMARY

The mix design and analysis of SMA mixtures stabilized with three natural fibres (coir, sisal and banana), a waste material (shredded waste plastic) and a polymer (polypropylene) are discussed in this chapter.

While increasing the percentage of additives in the mixture, Marshall stability and retained stability of the mixture increases with respect to the control mixture and obtained the maximum value at 0.3% fibre, 5% polypropylene and 7% waste plastic content, beyond which these values show a decreasing trend. The flow value of the mixtures decreases with respect to the control mixture. At any stage in all cases, the values are within the required specified limits. As percentage fibre additive increases in the SMA mixture, bulk specific gravity and VFB decreases while VMA and air void increases irrespective of the type of fibre. In the case of other additives, the increase in additive content resulted in an opposite trend for the above volumetric properties. But all the results are within the specified limits.

Adding additives to Stone Matrix Asphalt mixture has shown improvement in the volumetric and mechanical properties of the mixture. It can be inferred that these stabilized SMA provide better resistance against permanent deformations (rutting) and also indicate that these mixtures could be used in pavements where stiff bituminous mixture is required.

Among the natural fibres, based on Marshall Mix design, coir fibre gives the best result at 0.3 % fibre content with a percentage increase in stability value of about 70% and Marshall Quotient of 90% with respect to the control SMA. The retained stability value is 95%. It can be observed that the highest Marshall stability is achieved by specimens with 7% waste plastics and the percentage increase is about 82% with respect to the control SMA. This mixture also exhibits the highest retained stability of 98%. The Marshall quotient is also doubled with respect to the control mixture. It can be concluded that waste plastics stabilized Stone Matrix Asphalt mixture provide better resistance against permanent deformations due to their high stability and high MQ and it contributes to recirculation of plastic wastes as well as to the protection of the environment. The effective utilisation of the waste plastics for SMA mixtures will result in substantial increase in the scrap value for this otherwise "undesirable waste material", which are getting littered all over the urban areas. This will also lead to an ecofriendly sustainable construction method.

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Chapter 5

INDIRECT TENSILE STRENGTH CHARACTERISTICS

5.1 INTRODUCTION

The tensile properties of bituminous mixtures are of interest to pavement engineers because of the problems associated with cracking. Although SMA is not nearly as strong in tension as it is in compression, SMA tensile strength is important in pavement applications. The indirect tensile strength test (IDT) is used to determine the tensile properties of the bituminous mixture which can further be related to the cracking properties of the pavement. Low temperature cracking, fatigue and rutting are the three major distress mechanisms. A higher tensile strength corresponds to a stronger cracking resistance. At the same time, mixtures that are able to tolerate higher strain prior to failure are more likely to resist cracking than those unable to tolerate high strains (Tayfur et al., 2007).

A lot of research work has been reported on the performance of bituminous pavements relating the tensile strength of bituminous mixtures (Zhang et al., 2001; Behbani et al, 2009; Anderson et al., 2001). A higher tensile strength corresponds to a stronger low temperature cracking resistance (Huang et al., 2004). The test provides information on tensile strength, fatigue characteristics and permanent deformation characteristics of the pavement materials.

The resistance of bituminous mixtures to fatigue cracking is dependent upon its tensile properties, notably its tensile strength and extensibility characteristics. Fatigue has been defined in the literature as the phenomenon of fracture under repeated or fluctuating stresses. The layers in a flexible pavement structure are subjected to continuous flexing as a result of the traffic loads that they carry, resulting in tensile stresses and strains at the bottom of the bituminous layers of the pavement. The magnitude of the strain is dependent on the overall stiffness of the pavement. Indirect tensile strength test is an indicator of strength and adherence against fatigue, temperature cracking and rutting.

Tensile strength is typically used as SMA performance measure for pavements because it better simulates the tensile stresses at the bottom of the SMA surface course when it is subjected to loading. These stresses are typically the controlling structural design stresses. Tensile strength is difficult to measure directly because of secondary stresses induced by gripping a specimen so that it may be pulled apart. Therefore, tensile stresses are typically measured indirectly by a splitting tensile test.

5.2 LABORATORY TESTING FOR INDIRECT TENSILE STRENGTH

The tensile characteristics of bituminous mixtures are evaluated by loading the Marshall specimen along a diametric plane with a compressive load at a constant rate acting parallel to and along the vertical diametrical plane of the specimen through two opposite loading strips. This loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametrical plane, ultimately causing the specimen tested to fail by splitting along the vertical diameter. A 13 mm (1/2″) wide strip loading is used for 101 mm diameter specimen to provide a uniform loading with which produces a nearly uniform stress distribution. The static indirect tensile strength of a specimen is determined using the procedure outlined in ASTM D 6931. A loading rate of 51mm/minute is adopted. Tensile failure occurs in the sample rather than the compressive failure. Plywood strips are used so that the load is applied uniformly along the length of the cylinder. The compressive load indirectly creates a tensile load in the horizontal direction of the sample. The peak load is recorded and it is divided by appropriate geometrical factors to obtain the split tensile strength using the following equation:

$$S_t = \frac{2000\ P}{\pi\ tD}$$

S_t = IDT strength, kPa

P = maximum load, N

t = specimen height immediately before test, mm

D = specimen diameter, mm

The values of indirect tensile strength may be used to evaluate the relative quality of bituminous mixtures in conjunction with laboratory mix design, testing and for estimating the resistance to cracking. The results can also be used to determine the resistance to field pavement moisture when results are obtained on both water-conditioned and unconditioned specimens. Many researchers used this test (Wallace and Monismith, 1980; Kennedy and Hudson ,1968; Kandhal ,1979; Ibrahim, 2000). The method has been standardised by both the British Standard Institutions and the ASTM. The indirect tensile mode of testing like the one presented in Fig. 5.1 can be used to establish the tensile properties of bituminous mixtures to evaluate the performance of the pavement. The forces acting during the test is shown in Fig. 5.2.

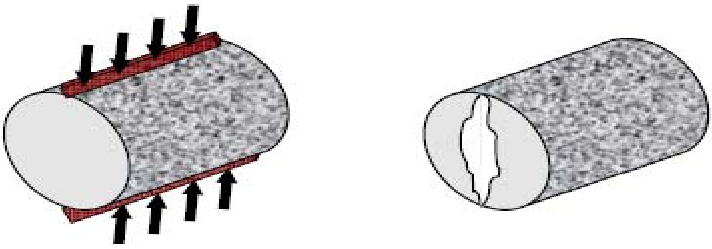

Fig. 5.1 Schematic of Indirect tensile test setup

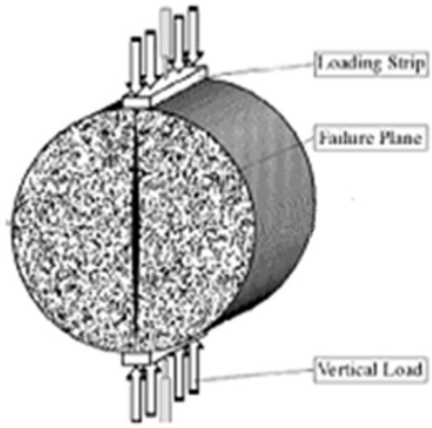

Fig. 5.2 Forces acting during split tensile test

5.2.1 Tensile strength ratio (TSR)

Moisture damage in bituminous mixes refers to the loss of serviceability due to the presence of moisture. The extent of moisture damage is called the moisture susceptibility.

The ITS test is a performance test which is often used to evaluate the moisture susceptibility of a bituminous mixture. Tensile strength ratio (TSR) is a measure of water sensitivity. It is the ratio of the tensile strength of water conditioned specimen, (ITS wet, 60˚C, and 24 h) to the tensile strength of unconditioned specimen (ITS dry) which is expressed as a percentage. A higher TSR value typically indicates that the mixture will perform well with a good resistance to moisture damage. The higher the TSR value, the lesser will be the strength reduction by the water soaking condition, or the more water-resistant it will be.

A total of 200 Marshall specimens of Stone Matrix Asphalt stabilized with different additives are prepared. 40 specimens are prepared for each additive and divided into two groups (20 specimens each). The first group was immersed in a water bath at 60˚C, for a period of 24 hours (conditioned sample). The samples are then removed from the water bath and kept at a temperature of 25˚C for a period of 2 hours. Other set of samples (unconditioned sample) are kept at a temperature of 25˚C for a period of 2 hours without soaking. These specimens are then mounted on the conventional Marshall testing apparatus and loaded at a deformation rate of 51mm/min and the load at failure is recorded at each case. Then the tensile strength of water conditioned as well as unconditioned specimen for each additive stabilized mixture is determined. Samples before and after failure are shown in Fig. 5.3

Fig. 5.3 Sample before (left) and after (right) failure

5.3 RESULTS AND DISCUSSIONS

The indirect tensile strength results of SMA mixtures with different additives at various percentages both for conditioned and unconditioned samples are given in Table 5.1. It is evident that all the stabilized SMA mixtures showed higher tensile strength than the control mixtures irrespective of the type of additive. This is because of the improved stiffness of stabilized mixture than the control mixture. The presence of additives in the bituminous mixture strengthens the bonding between the aggregate provided by the binder and as a result, the mixtures had the highest stiffness. The results also indicate that tensile strength increases as the additive content increases, reaches a maximum value and then decreases.

It is also observed that for all SMA mixtures, the tensile strength decreases with conditioning regardless of the type of additive. But the percentage decrease in strength due to the conditioning of the sample decreases with the increase in additive content. For the control mixture, the percentage decrease in strength due to conditioning is about 48 %, while at higher additive contents, for all the additives, the percentage decrease is very less (< 3%).

5.3.1 Fibre stabilized SMA

The variations of indirect tensile strength of Stone Matrix Asphalt mixtures with different percentages of fibre contents are given in Fig. 5.4 to 5.6. The tensile strength of SMA mixes with fibre additive shows increasing trend up to 0.3% and it is found to be decreasing at 0.4% fibre content. This behavior is because, the tensile strength is related primarily to a function of the binder properties, and its stiffness influences the tensile strength. Presence of fibre in the mixture makes it stiffer. The addition of fibre beyond a certain level can increase the viscosity of binder, which results from the effects of increase in volume of fibre particles due to the absorption of binder. Therefore, this increase in viscosity inhibits the ability of the binder to coat adequately on the surface of aggregates, thereby lead to the potential loss of bonds between the fibre, binder and the aggregate.

Table 5.1 Indirect tensile strength results for stabilized SMA mixtures

Additive	**%**	**ITS, Unconditioned (MPa)**	**ITS, Conditioned (MPa)**	**%TSR (MPa)**
Nil	**0**	**0.8143**	**0.4253**	**52.23**
Coir fibre	0.1	0.851	0.709	83.31
	0.2	1.0983	1.059	96.42
	0.3	**1.1242**	**1.1048**	**98.27**
	0.4	1.0831	1.0521	97.14
Sisal fibre	0.1	0.8313	0.6915	83.18
	0.2	1.0619	1.0114	95.24
	0.3	**1.1057**	**1.0766**	**97.37**
	0.4	1.0538	1.0153	96.35
Banana fibre	0.1	0.8272	0.6941	83.91
	0.2	1.065	1.0107	94.90
	0.3	**1.1018**	**1.0762**	**97.68**
	0.4	1.054	1.015	96.30
Waste Plastics	1	1.0228	0.8992	87.92
	3	1.1913	1.1469	96.27
	5	1.2141	1.1824	97.39
	7	**1.242**	**1.2287**	**98.93**
	9	1.2149	1.1642	95.83
Polypropylene	1	1.0076	0.8619	85.54
	3	1.1337	1.0555	93.10
	5	**1.1693**	**1.14**	**97.49**
	7	1.1672	1.13	96.81
	9	1.1245	1.04	92.49

A comparison of tensile strength characteristics for the three fibre stabilized SMA mixtures both for unconditioned and conditioned are given in Fig. 5.7.a and Fig. 5.7.b. All the fibre stabilized SMA mixtures have the maximum tensile strength at 0.3% fibre content by weight of mix for both conditioned and unconditioned SMA mixtures. The percentage increase in strength for the coir fibre stabilized mixture (0.3% fibre content) with respect to the control mixture is 38% and 160% respectively for unconditioned and conditioned samples. This increase is about 36% and 153% respectively for both sisal and banana fibre stabilized mixtures. The improvement in indirect tensile strength would be due to fibre's absorption and adhesion of bitumen which improves the interface adhesion strength and fibre's networking and bridging cracking effects. Fibres possess greater modulus and elongation than bitumen, performing as bridges to resist cracking propagation and material failure. It sustain greater stress and strain before material failure, resulting in improved toughness. Fibre reinforcing effect increases initially with increasing fibre content; but at high fibre content (more than 0.3%) may induce coagulation and thus reducing its reinforcing effect. The higher amount of fibre in the mixture may not have beneficial effect and may deteriorate its deformation properties. In fibre stabilized mixtures, large amount of fibre leads to higher surface area that must be coated by bitumen, and consequently, the aggregate particles and fibre would not be fully coated with bitumen. This results in less stiff mixture which leads to the failure of the mixture. Test results show that coir fibre stabilized mixtures has the highest tensile strength as compared to the other two mixtures.

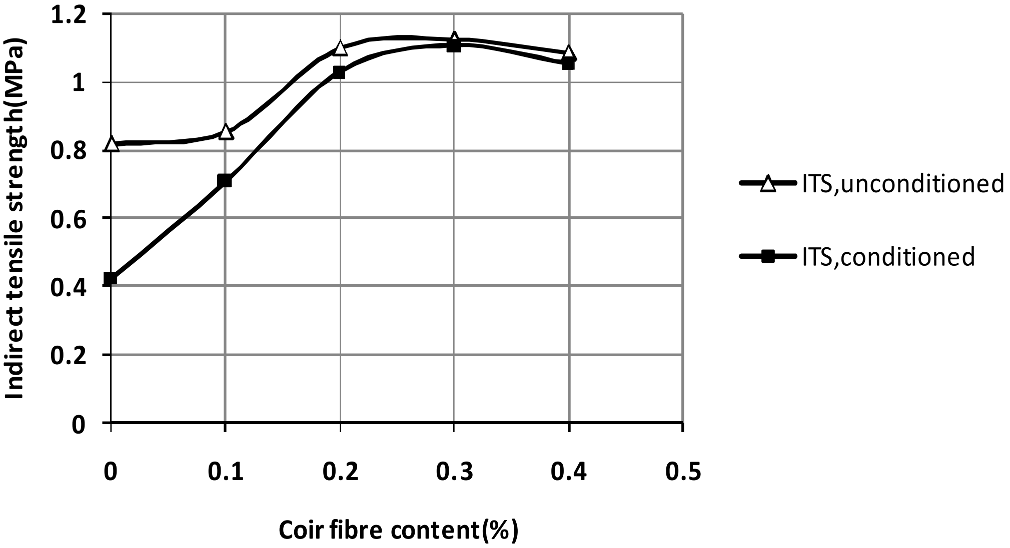

Fig. 5.4 Variation of indirect tensile strength of SMA with coir fibre contents

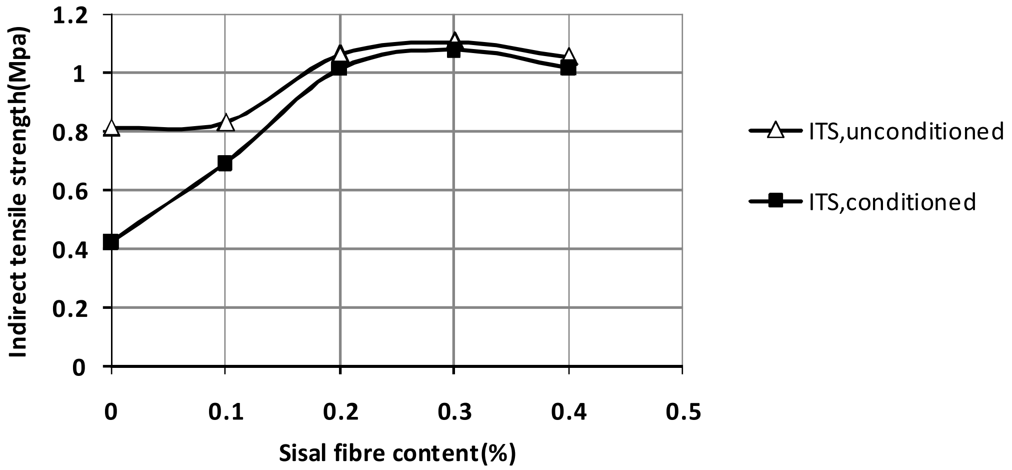

Fig. 5.5 Variation of indirect tensile strength of SMA with sisal fibre contents

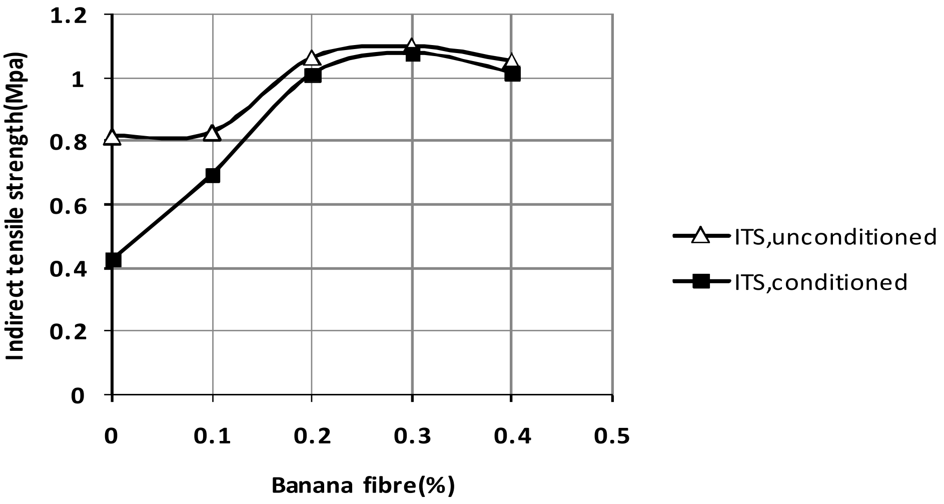

Fig. 5.6 Variation of indirect tensile strength of SMA with banana fibre contents

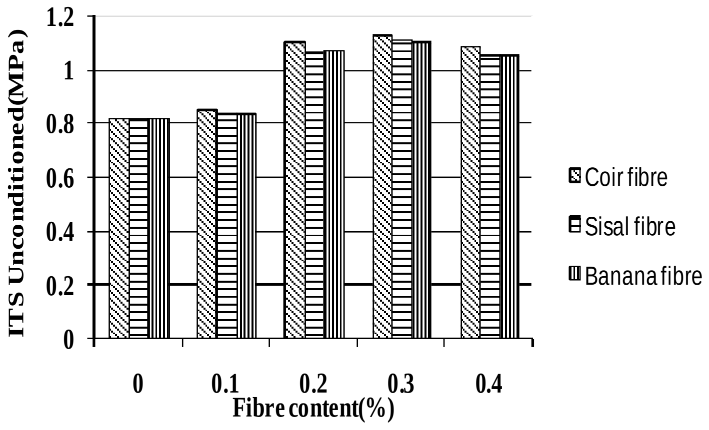

Fig. 5.7.a Variation of indirect tensile strength of SMA (unconditioned) with different fibre contents

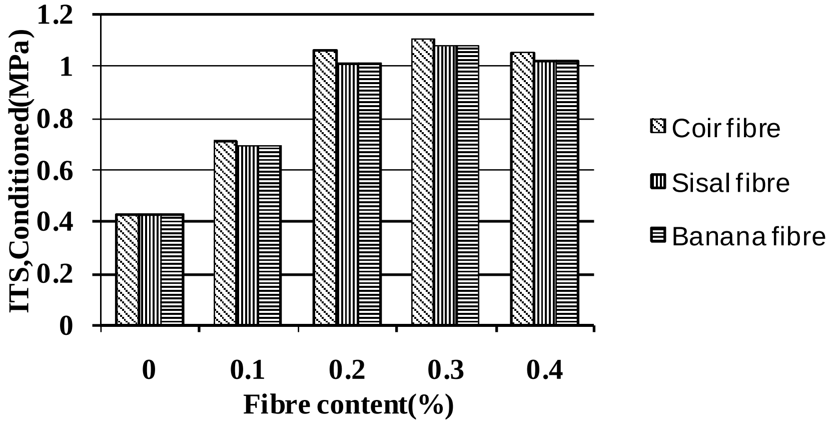

Fig. 5.7.b Variation of indirect tensile strength of SMA (conditioned) with different fibre contents

5.3.2 SMA stabilized with WP and PP

Variation of indirect tensile strength of both WP and PP stabilized mixtures are given in Fig. 5.8. The waste plastics and polypropylene stabilized SMA mixtures show an increase in tensile strength up to 7 % and 5% respectively. The presence of additive in the SMA mixture enhances the adhesion between aggregate and bitumen, which leads to a decrease in the stripping of SMA and results in an increased tensile strength.

SMA mixture stabilized with 7% waste plastics shows a percentage increase (maximum) of 53% and 189% with respect to the control mixture for unconditioned and conditioned samples respectively and with 5% polypropylene the corresponding values are 44% and 168% respectively. This indicates that the mixtures containing additives have higher values of tensile strength at failure under static loading and the inclusion of additives improve the cracking potential. This would also suggest that stabilized mixtures are capable of withstanding larger tensile strains prior to cracking.

5.3.3 Comparison of different SMA mixtures

Comparisons of the maximum indirect tensile strength of SMA with different additives are given in Fig. 5.9 and the percentage increase in strength of SMA mixtures with respect to the control mixture is given in Fig. 5.10.

It is evident that the percentage increase in strength is very high in the case of all conditioned samples of stabilized SMA with respect to the control mixture. The maximum percentage increase is for SMA with waste plastics and the minimum for that with banana fibre (189% and 153% respectively). The tensile strength value for specimens with coir fibre is higher as compared to that with sisal and banana fibres (shows approximately similar strength). Stabilized mixtures with WP and PP have the higher strength than that with fibres. The mix containing 7% WP by weight of mix produced the highest tensile strength, which would be due to the strengthened bonding between the aggregates (due to the presence of additives in the SMA mixture). The mixtures had the highest stiffness and the percentage increase in strength is about 11% at both unconditioned and conditioned SMA mixture as compared to coir fibre stabilized mixture. This is due to the fact that the SMA mixture with WP is stiffer than the other stabilized mixtures. It can be concluded that waste plastics additives demonstrate a slightly better cracking resistance as compared to fibre additives. This may be due to the fact that in SMA stabilized with WP, comparatively better adhesion exhibits between bitumen and waste plastics coated aggregates due to inter molecular bonding.

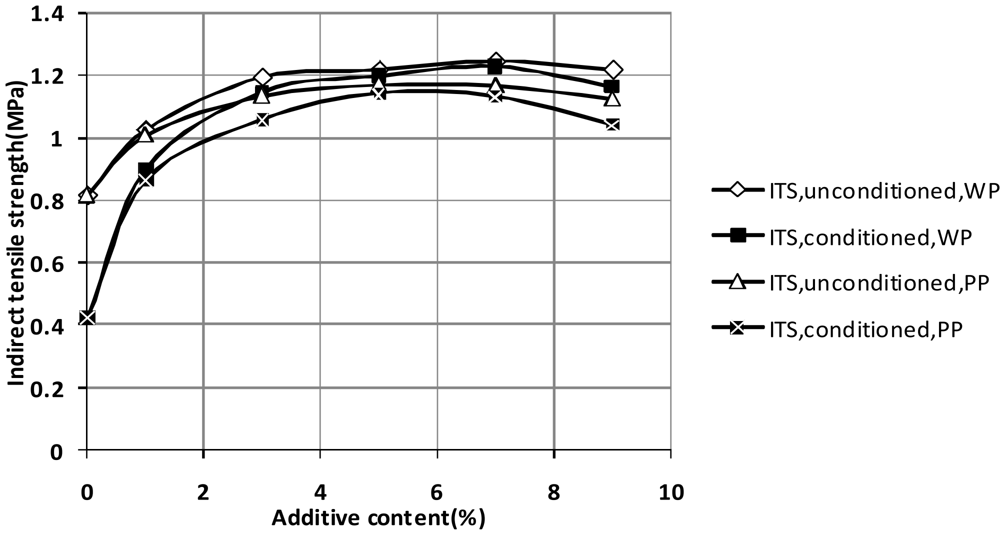

Fig. 5.8 Variation of indirect tensile strength of SMA with WP and PP contents

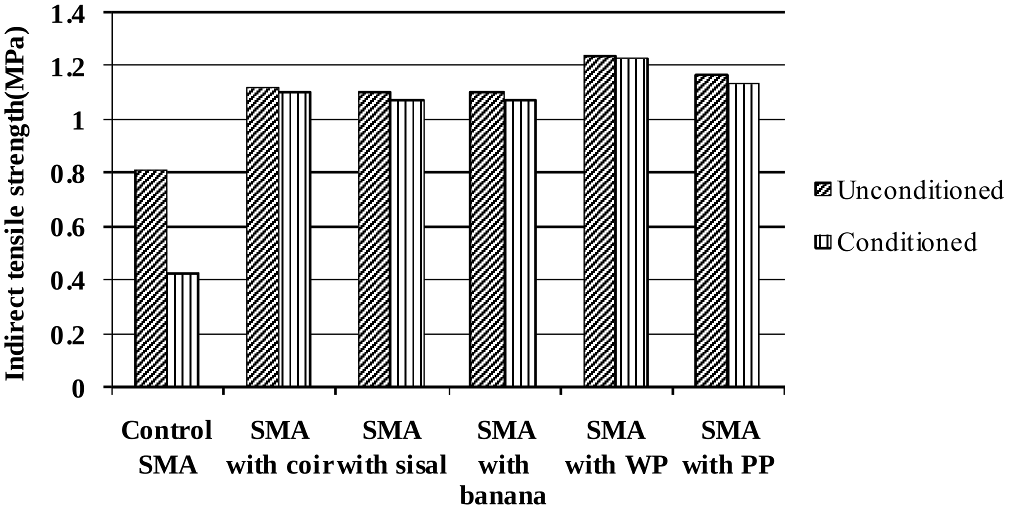

Fig. 5.9 Comparison of maximum indirect tensile strength of SMA with different additives

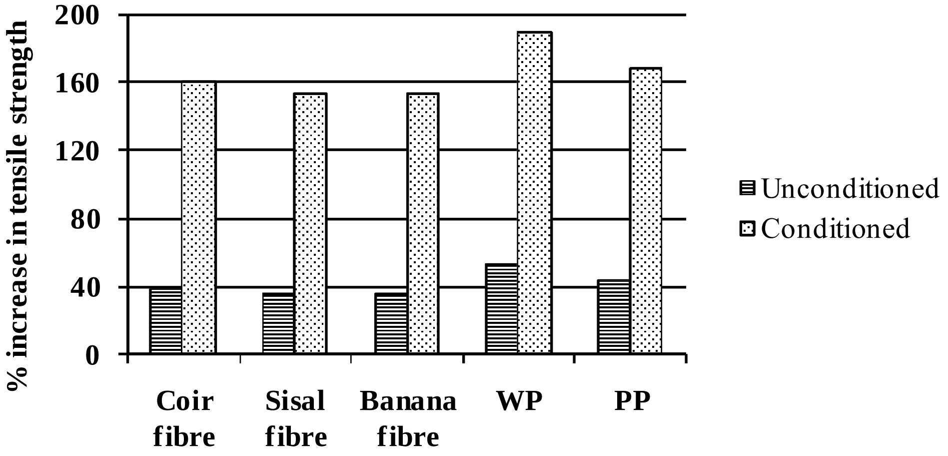

Fig. 5.10 Comparison of % increase in indirect tensile strength (maximum) of SMA with different additives with respect to the control mixture.

5.3.4 Moisture susceptibility of SMA mixtures

As given in Table 5.1, the tensile strength ratio (TSR) values of the control mixture is nearly 52% which is less than 70%, a minimum TSR value set forth by AASHTO T283. This illustrate that the control mixture has more significant moisture susceptibility. The tensile strength ratios for the mixes containing the additives are greater than the specification limits. From these results, it can be concluded that the presence of additives significantly reduces the moisture induced damage of the SMA mixture. This also indicates that additives do not cause the mixture to weaken when exposed to moisture.

The results also indicate that the tensile strength ratio which represents the moisture susceptibility increased up to a certain percentage of additives and after that, it is found to be decreasing. In fibre stabilized mixtures, the decrease in TSR at higher fibre content may be due to the balling effect of the fibres in the mix and in the case of WP and PP stabilized mixtures this may be due to the weakening of the bond between the aggregate and binder.

From Fig. 5.11, it is evident that among the fibre stabilized mixtures SMA with coir fibre gives a slightly higher tensile strength ratio than the SMA with other fibres. The specimens containing sisal and banana fibre produced almost similar results. Fig. 5.12 indicates that SMA mixture containing WP has slightly higher TSR than SMA with PP.

From, Fig. 5.13, it is evident that all the stabilized mixtures give higher tensile strength ratio than the control mixture, indicating its lesser water induced damage. SMA stabilized with WP has slightly lesser moisture susceptibility when compared to SMA mixtures with other additives.

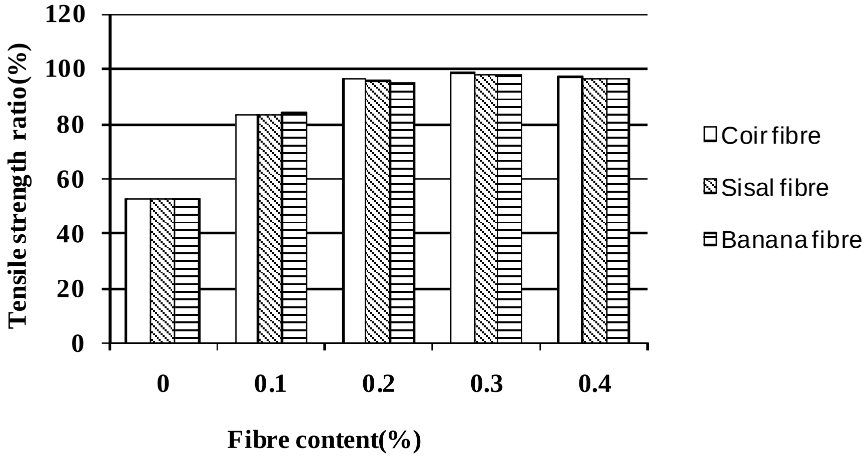

Fig. 5.11 Variation of tensile strength ratios of SMA with different fibre contents

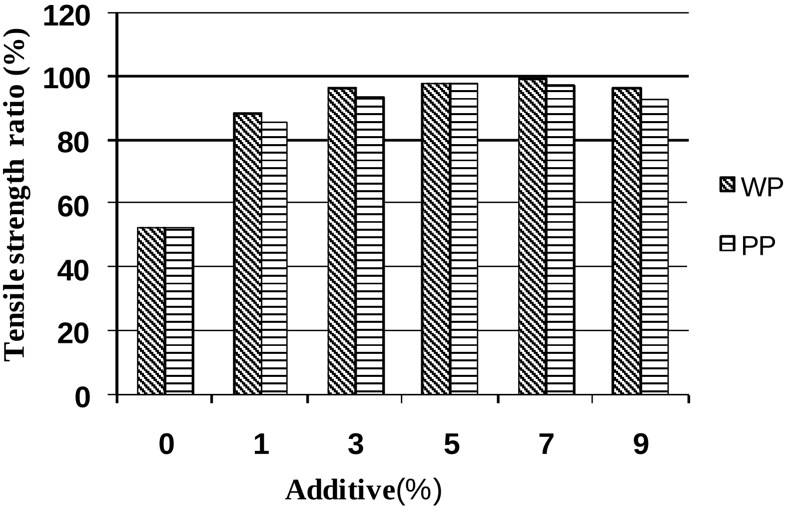

Fig. 5.12 Variation of tensile strength ratios of SMA with different additive contents

The indirect tensile strength ratio is an indication of the amount of strength loss, due to the effect of water. It is increasing with respect to the control mixture when additives are added and the increase is somewhat similar. From Fig. 5.13 it can be concluded that all stabilized mixes satisfy the minimum required tensile strength ratios of 70% indicating their better moisture resistance than the control mixture. WP stabilized specimens have a slightly higher tensile strength ratio than the other stabilized mixtures.

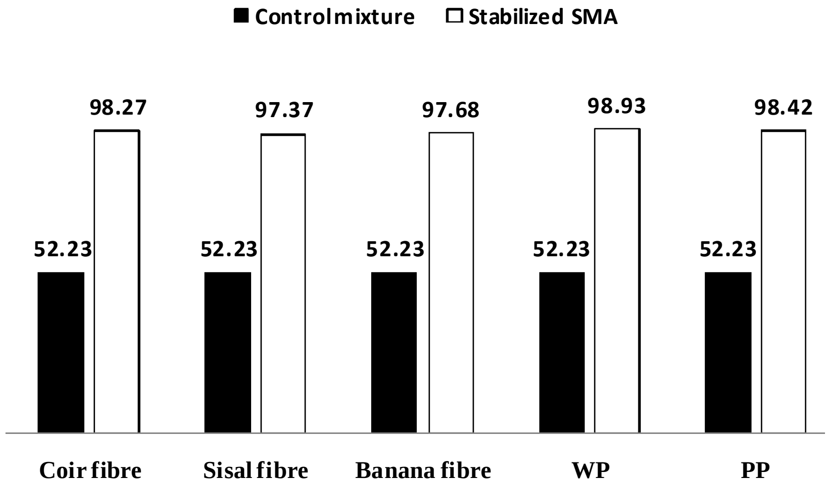

Fig. 5.13 Variation of Tensile strength ratio (%) with different additives in SMA

5.4 SUMMARY

The indirect tensile strength test is used to determine the tensile properties of the Stone Matrix Asphalt mixture which can be further related to the cracking properties of the pavement. The tensile strength ratio of bituminous mixtures is an indicator of their resistance to moisture susceptibility and a measure of water sensitivity.

Based on the test results, it can be concluded that the SMA stabilisation improves the cracking resistance of the mixture as compared to the control mix. All the additives improve the adhesion property of the bitumen to aggregate. The indirect tensile strength values are found to be much higher when additives are incorporated in SMA mixtures and the effect is more influential in the conditioned state. It is also observed that for a particular additive, the tensile strength decreases by conditioning the sample. But this decrease is considerable in the control mixture and also the tensile strength ratio goes very much below the specification limits. This substantiates the need of additives in SMA mixtures.

Coir, sisal and banana fibres have improved indirect tensile strength with respect to the control mixture. SMA mixtures with waste plastics have the highest strength followed by the mix with polypropylene. Even though all stabilized SMA mixtures show higher indirect tensile strength and tensile strength ratio, addition of 7% waste plastics in the SMA mixture resulted in the highest tensile strength and exhibit superior water resistance property.

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Chapter 6

COMPRESSIVE STRENGTH CHARACTERISTICS

6.1 INTRODUCTION

Compressive strength is the capacity of pavement materials to withstand axially directed compressive forces. The bituminous mixture starts crushing, when the compressive stress due to loads exceeds the strength of the mixture. They should possess resistance to crushing to withstand the stresses due to traffic loads. Along with other physical properties of the mixture, the compressive strength also plays a major role in mixture characteristics, which is one of the most important factors determining its suitability for use under the given loading and environmental conditions as a highway paving material.

6.2 COMPRESSIVE STRENGTH OF SMA MIXTURES

This test measures the compressive strength of compacted bituminous mixtures. The test specimens are cylinders of 101.6 mm in diameter and 101.6 ± 2.5 mm in height. The size of test specimens has an influence on the results of the compressive strength test.

Aggregate is heated to slightly above the mixing temperature to allow for dry mixing prior to adding the bitumen binder. In no case the mixing temperature should exceed 175˚C. Preheat the bowl and batch of aggregate in an oven to a temperature that complies with the aggregate temperature. This will result in an acceptable temperature after dry mixing. With the bowl of aggregate, quickly pour the prescribed mass of hot bitumen on the hot aggregate and immediately mix the bitumen into the aggregate. The mixing shall be completed within 90 to 120 s, during which time the temperature should have dropped to about 3 to 5˚C above the compacting temperature. This will result in the mixture being at the compacting temperature when compaction begins, which may commence immediately. For preparing the stabilized mixtures, additives are added in heated aggregate prior to mixing them with heated bitumen.

An optimum bitumen content of 6.42 % as found from Marshall control mix design (by wt. of total mix) is used in preparing all the stabilized mixes to maintain consistency throughout the study. A total of 200 Marshall specimens are prepared for the five different additives at different percentages of additives. Allow the test specimens to cool at room temperature for at least 2 hours after removal from the oven. Test specimens are subjected to axial compression at a uniform vertical deformation rate of 3.2mm/min. The compressive strength is determined by dividing the maximum vertical load obtained during deformation at the rate specified by the original cross-sectional area of the test specimen (ASTM D 1074 – 09). The compressive strength is reported as the average of three specimens in each case. In order to know the temperature effect on the compressive strength of mixtures, the tests are carried out at two different temperatures 25˚C and 60˚C (which represent the intermediate and high pavement temperatures). Sample after failure is shown in Fig. 6.1.

Fig. 6.1 Sample after failure

6.2.1 Effect of water on compressive strength

In order to investigate the effect of water on the compressive strength of SMA mixtures with different additives, the index of retained strength is determined. This value is an indicator of their resistance to moisture susceptibility. The test was conducted at a temperature of 25˚C and the load at which the specimen fails is taken as the dry strength of the bituminous mix. Conditioned specimens are prepared by placing the samples in a water bath maintained at 60˚C for 24 hours and after that keeping the samples at 25˚C for two hours. These conditioned specimens are then tested for their strength. The ratio of the compressive strength of the water-conditioned specimens to that of dry specimens is taken as the index of retained strength. The indices of retained strength for different mixtures with different type and varying percentage of additives are determined.

6.2.1.1 Effect of soaking period

In order to investigate the effect of soaking period on compressive strength of bituminous mixtures, the compressive strength of stabilized SMA samples are determined after immersing in water bath at 60˚ C for a period of 12hrs, 24hrs, 48hrs and 96hrs.

6.3 RESULTS AND DISCUSSION

The variation of the compressive strength with increasing percentage of additive content for the two different temperatures, viz. 25˚C and 60˚C for each additive are shown in Table 6.1 and 6.2. All stabilized mixtures shows higher compressive strength than the control mixture. This may be due to the increase in stiffness of the SMA mix. Presence of additive may strengthen the bonding between the aggregates provided by the binder and thereby enhancing the stone to stone contact. This will result in increasing the resistance to crushing. It is also observed that the compressive strength decreases with the increase in temperature. But the percentage decrease in strength decreases with the increase in additive content up to a certain level.

Table 6.1 Compressive strength (MPa) of fibre stabilised SMA samples at 25˚C and 60˚C

% fibre	Compressive strength of SMA samples with					
	Coir fibre		Sisal fibre		Banana fibre	
	25˚C	60˚C	25˚C	60˚C	25˚C	60˚C
0	5.0997	4.1323	5.0997	4.1323	5.0997	4.1323
0.1	5.1879	4.2526	5.1603	4.2202	5.1494	4.2011
0.2	5.7084	5.2243	5.5814	5.1456	5.5402	5.0068
0.3	**5.9622**	**5.868**	**5.7954**	**5.6666**	**5.7572**	**5.5683**
0.4	5.9601	5.8467	5.7996	5.6623	5.7496	5.5421

Table 6.2 Compressive strength (MPa) of WP and PP stabilised SMA samples at 25˚ C and 60˚ C

% Additive	Compressive strength of SMA samples with			
	Waste Plastics		**Polypropylene**	
	25˚C	60˚C	25˚C	60˚C
0	5.0997	4.1323	5.0997	4.1323
1	5.4256	5.0908	5.2982	4.8265
3	5.9642	5.7899	5.8083	5.6018
5	6.2516	6.1495	**6.0276**	**5.8954**
7	**6.3601**	**6.2606**	5.5674	5.1701
9	5.8777	5.6232	5.1525	4.4264

6.3.1 Fibre stabilized mixtures

In the case of fibres, coir fibre stabilized SMA shows the maximum compressive strength as compared to sisal and banana fibre mixtures. From Fig. 6.2 and 6.3, it is evident that all fibre stabilized mixtures show the maximum value of compressive strength at 0.3% fibre content. It can also be seen that fibre reinforcing effect increases initially with increasing fibre content, but at high fibre content, they could induce coagulation of fibres and thus reduce its reinforcing effect. This can be the reason why the strength of SMA mixes decreases beyond 0.3% fibre content.

Fig. 6.4 and 6.5 show the percentage increase in compressive strength for fibre stabilized SMA mixtures at 25˚ C and 60˚C with respect to the control mixture. It can be observed that the percentage increase in strength with respect to the control mixture at 0.3% fibre content for coir fibre stabilized mixes at 25˚ C and 60˚ C are 17% and 42% respectively. Similarly, the percentage increase in strength is about 14% and 13% at 25˚C for sisal and banana fibre respectively and the respective increase at 60˚C are about 37% and 35%. Thus coir fibre stabilized mixture shows the higher resistance to crushing than the other fibre stabilized mixtures.

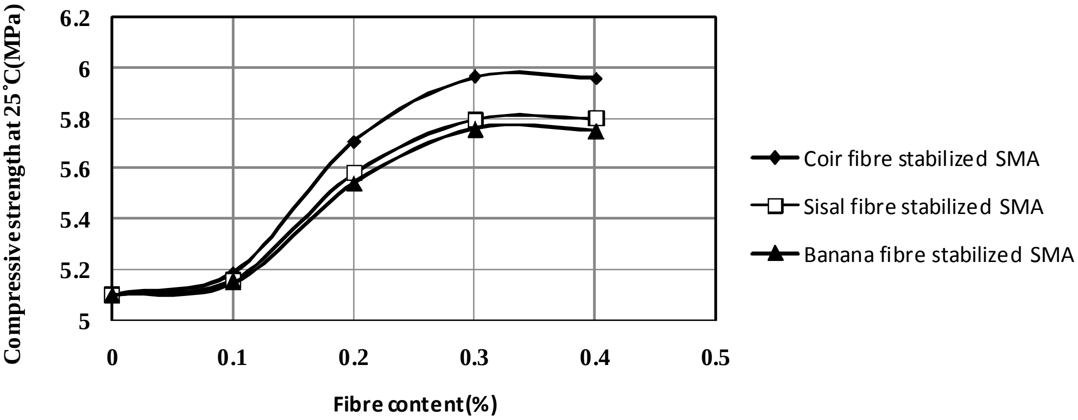

Fig. 6.2 Variation of compressive strength at 25°C with various fibre contents

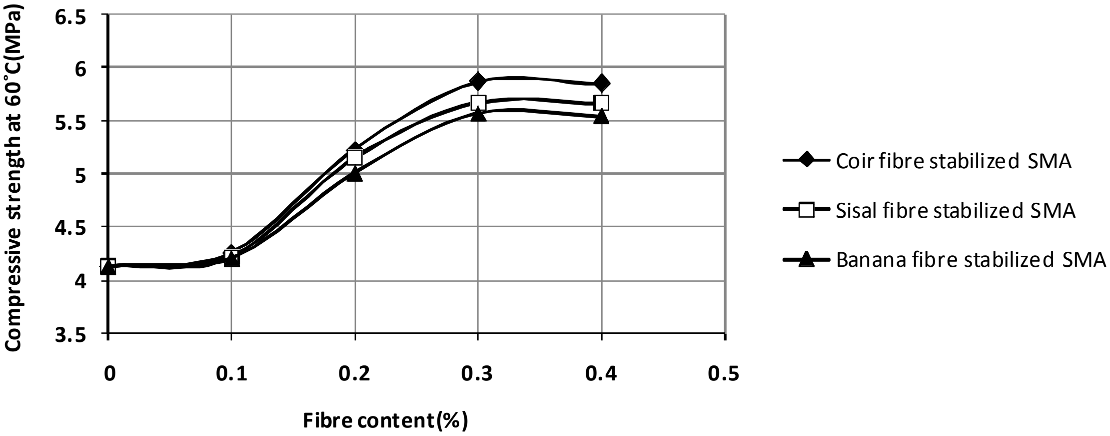

Fig. 6.3 Variation of compressive strength at 60°C with various fibre contents

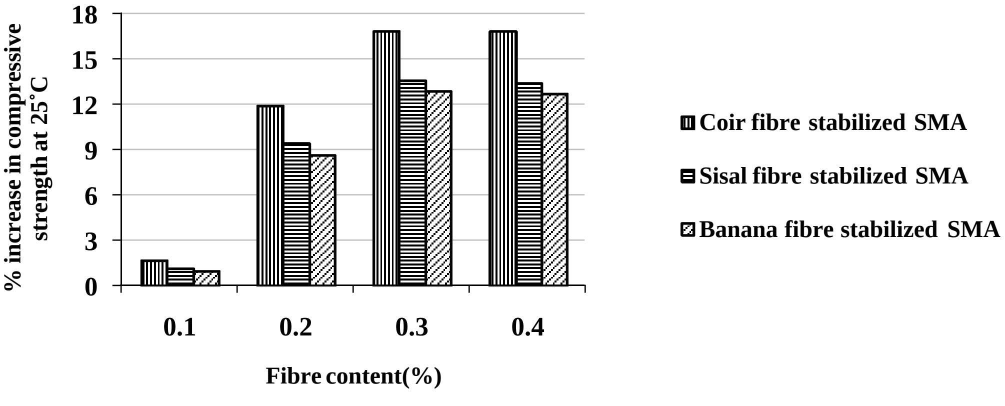

Fig. 6.4 Percentage increase in compressive strength at 25°C with respect to the control mixture for fibre stabilized SMA

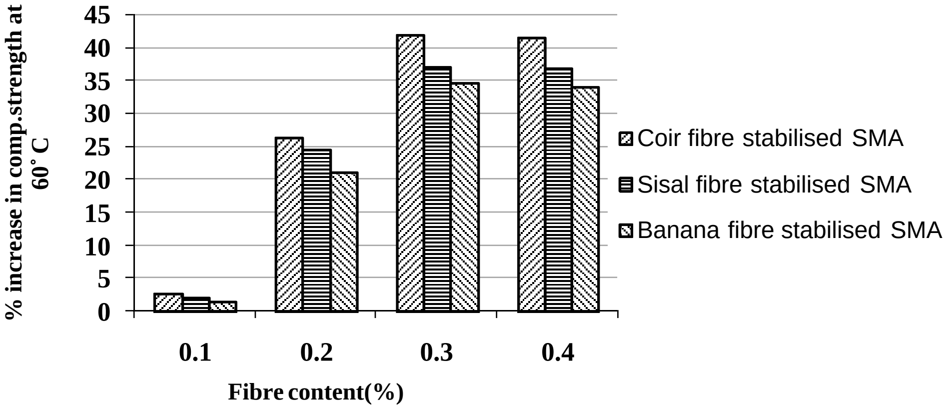

Fig. 6.5 Percentage increase in compressive strength at 60°C with respect to the control mixture for fibre stabilized SMA

6.3.2 SMA mixtures with WP and PP

It can be observed from Fig. 6.6 that the maximum value of compressive strength is obtained for the SMA mixtures at 7% WP content and 5% PP content and the strength decreases beyond this additive content. This decrease in strength maybe due to the decrease in interlocking offered by the bitumen binder and the additive coated aggregates.

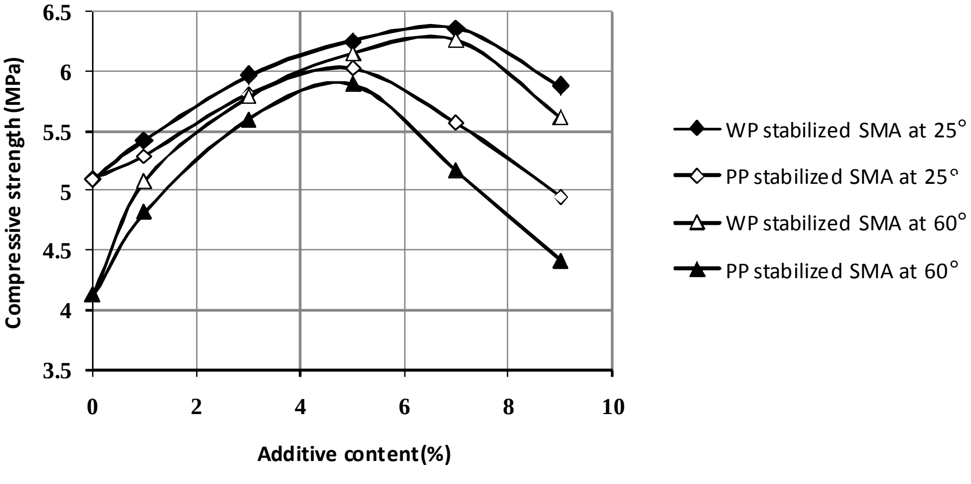

Fig. 6.6 Variation of compressive strength with various percentages of WP and PP

Fig. 6.7 shows the percentage increase in compressive strength with respect to the control mixture for WP and PP stabilized SMA at 25°C and 60° C respectively. It is evident that at 25° C, the percentage increase in compressive strength with respect to the control mixture is 25% and 18% respectively and at 60°C, the percentage increase is 52% and 43% respectively for SMA stabilized with 7% waste plastics and 5% polypropylene. The waste plastics stabilized mixture shows the higher percentage increase as compared to PP stabilized mixtures. Fig. 6.8 shows the variation of maximum compressive strength of SMA mixtures at 60°C with different additives and also with the control mixture. Additives in the mixture enhances the compressive strength of the control mixture to a great extent. Among the different mixtures investigated waste plastics stabilized SMA mixtures shows the highest compressive strength.

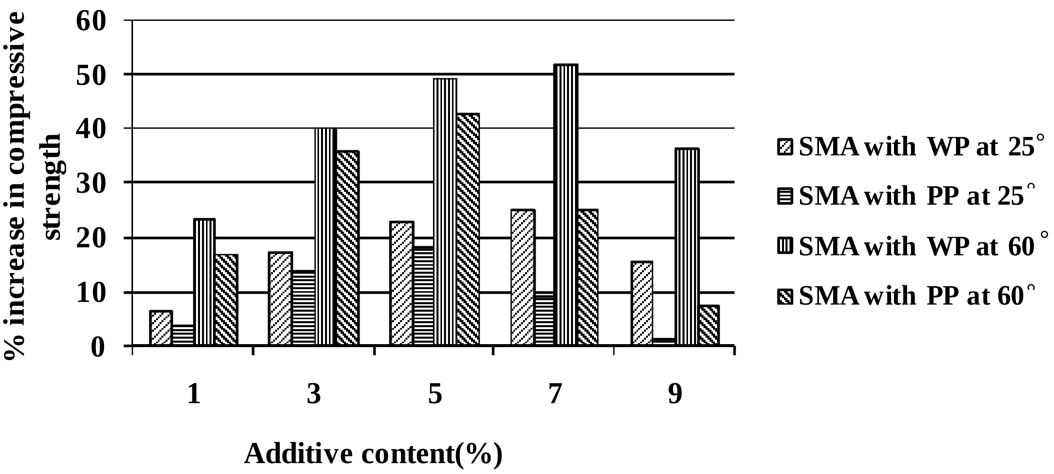

Fig. 6.7 Percentage increase in compressive strength with respect to the control mixture for WP and PP stabilized SMA

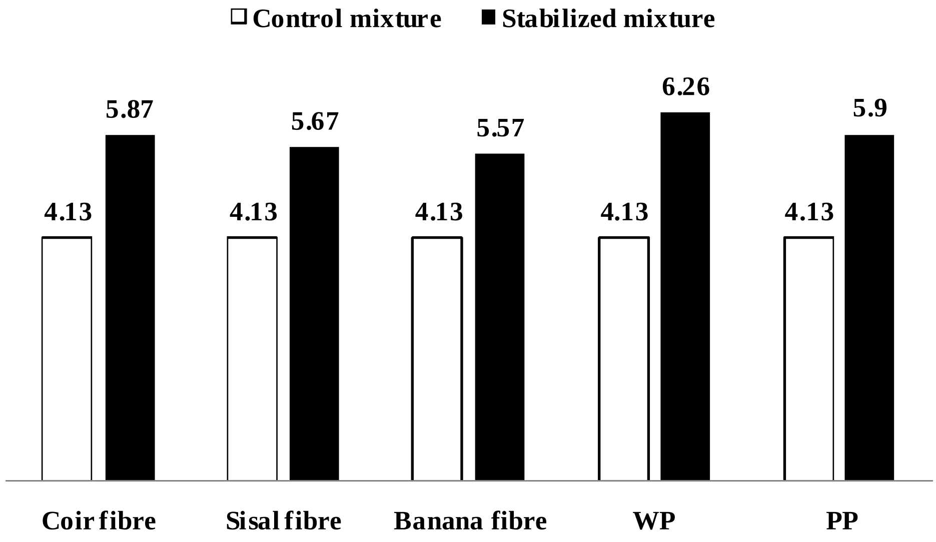

Fig. 6.8 Maximum compressive strength of SMA at 60°C with different additives

6.3.3 Effect of water

The loss of adhesion of aggregate with bitumen is studied by determining the percentage index of retained strength. Results reported in Table 6.3 and 6.4 show that the indices of retained strength (IRS) for all stabilized mixtures satisfy the limiting value of 75% as specified by ASTM D 1075. But for control mixture, it is only about 60%, showing the necessity of additives in SMA mixtures. Among the fibre stabilized SMA mixtures, coir fibre stabilized mixtures give the maximum value, while for mixtures stabilized with WP and PP; waste plastics stabilized SMA mixtures give the maximum retained strength. Considering the different SMA mixtures investigated, waste plastics stabilized SMA mixtures have the minimum water induced damage followed by polypropylene, coir, banana and sisal mixtures.

Table 6.3 Variation of index of retained strength of SMA mixtures with various fibre contents

%Fibre	**Index of retained strength (%) for SMA mixtures with**		
	Coir fibre	**Sisal fibre**	**Banana fibre**
0	**61.37**	**61.37**	**61.37**
0.1	82.23	80.00	80.18
0.2	92.31	90.70	90.72
0.3	**97.21**	**96.77**	**97.01**
0.4	96.42	95.76	95.74

Fig. 6.9 shows the index of retained strength (maximum) of SMA mixtures with various additives. Even though all the stabilized mixtures exhibit almost the same index of retained strength, SMA with waste plastics shows slightly higher value as compared to other mixtures. It can also be observed that the index of retained strength of the control SMA mixture was increased from about 60% to about 97% for fibre stabilized mixtures at 0.3% fibre content. For SMA with 7% WP and 5% PP, the index of retained strength is about 98%. The test results indicate that the adhesion between bitumen and aggregate can be improved significantly by the additives. The presence of additives in SMA mixture resulted in a mixture with superior water resistance property.

Table 6.4 Variation of index of retained strength with various WP and PP contents

% Additive	**Index of retained strength (%) for SMA mixtures with**	
	WP	**PP**
0	61.37	61.37
1	90.47	89.11
3	95.68	94.67
5	97.57	**97.84**
7	**98.38**	94.49
9	95.08	89.22

Fig. 6.10 shows the variation of compressive strength with soaking period. As the soaking period increases, more water is absorbed by the aggregates and this absorbed water weakens the cohesive bonds within the bitumen aggregate system. From the above results it is seen that prolonged soaking period reduces the strength of bituminous mixtures and the reduction is less in the case of plastic stabilized SMA mixture compared to fibre stabilized mixture due to the coating formed over the aggregate.

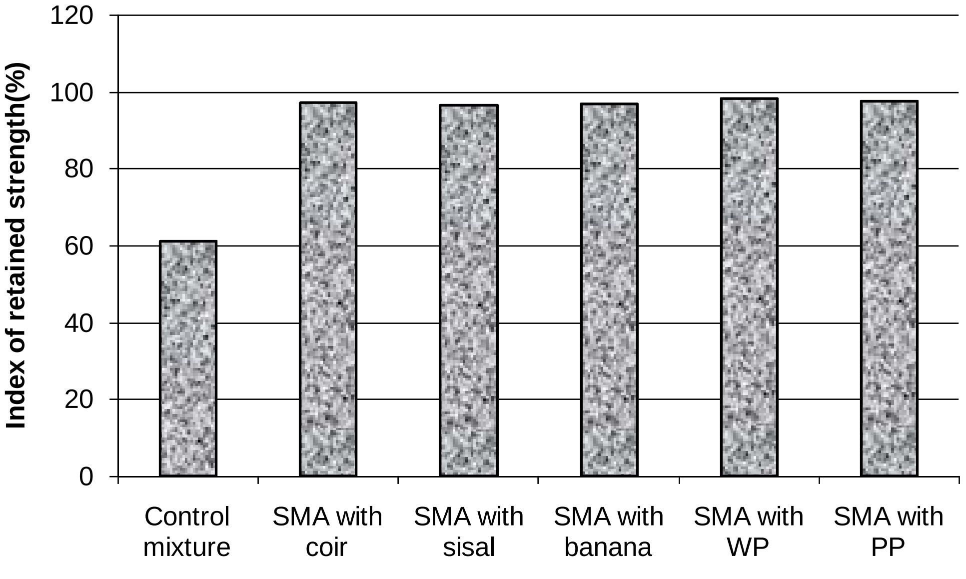

Fig. 6.9 Index of retained strength (maximum value) of SMA mixtures with various additive contents

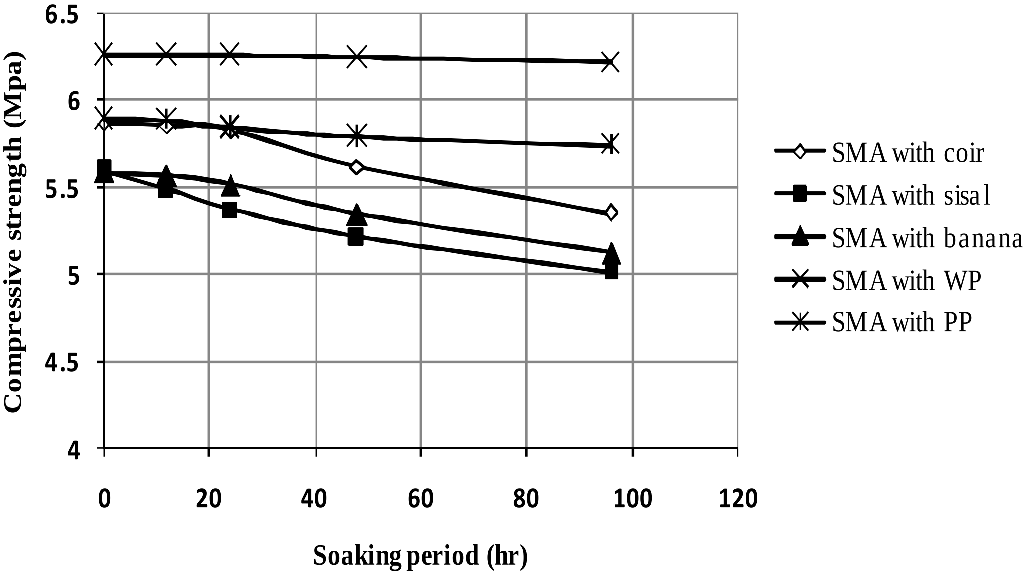

Fig. 6.10 Variation of compressive strength with soaking period

6.4 SUMMARY

Presence of additives in SMA mixture enhances the stone to stone contact of aggregates in the gap graded mixture by strengthening the bonding between them. These additives also enhance the adhesion between aggregate and bitumen, which results in less stripping of SMA mixture. All these give rise to a stiffer and tougher mix with considerable improvement in compressive strength.

Additives do not cause the SMA mixture to weaken when exposed to moisture. Actually they are enhancing the resistance to moisture susceptibility of the mixture. The indices of retained strength for all stabilized mixtures satisfy the limiting value of 75%. But for control mixture, it is only about 60%, which substantiate the necessity of additives in SMA mixtures. Although all the additives significantly improve the performance of the SMA mixtures in terms of compressive strength, waste plastics additive gives the best result.

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Chapter 7

SHEAR STRENGTH CHARACTERISTICS

7.1 INTRODUCTION

The usual volumetric components of field bituminous mixtures are aggregate, bitumen, water and air. Volume occupied by air may also be occupied by water. These components are analogous to soils, which are composed of soil particles, water and air. Because of the similarities, the triaxial test has been applied to bituminous mixtures also. A number of studies using the triaxial test for bituminous mixtures are conducted in the 1940s and 1950s. The strength of bituminous mixtures is due partly to the friction and interlocking of aggregates, which increases with increasing normal stress, and partly to cohesion or viscous resistance, which increases with increasing shear rate (Superpave, 1996). The Triaxial loading approach in determining material properties is useful for a variety of reasons. One of the most important reasons for this utility is the ability to properly handle the characterization of different types of materials, including those materials that do not stick together very well like bituminous mixtures at high temperature. According to Crockford et al.(2002) the characterizations attainable with the proper conduct of this testing approach are generally considered to be more closely associated with the true engineering properties than any other test.

The load-deformation response of bituminous materials is an important pavement design consideration. Both permanent and resilient deformation characteristics are important. The shear strength of bituminous mixture is also important, relative to the behaviour and performance of the material as a pavement layer. Since bituminous mixtures have little or no tensile strength, shearing resistance of the mix is used to develop a load-distributing quality that greatly reduces the stresses transmitted to the underlying layers. Some important factors influencing the shear strength of bituminous mixtures are gradation, moisture and density, maximum particle size, amount and plasticity of fines, particle geometric properties, and confining pressure. Thus shearing strength of road materials is the result of the resistance to movement at interparticle contacts, particle interlocking, physical bonds formed across the contact areas, chemical bonds due to cementation etc.. It is measured in terms of two parameters namely cohesion and angle of internal friction.

7.2 APPLICATIONS OF TRIAXIAL TEST DATA

The triaxial shear strength test has been recognized as the standard test for determining the strength of materials for over 50 years. The results from these tests provide a fundamental basis which can be used in analyzing the stability of bituminous mixes.

From different types of tests used to determine the shear strength parameters, triaxial test in principle effectively simulates the stress-deformation behaviour of road materials. This is supported by various stress-deformation tests reported by Rodriguez et al. (1988). Triaxial strength testing is attractive as a simple performance test for rut resistance. It is relatively quick, simple and inexpensive, and its simplicity should ensure good repeatability. Furthermore, triaxial strength testing provides information concerning mixture cohesion and internal friction both of which should contribute to mixture rut resistance (Christensen et al., 2000).

Marshall test is a kind of unconfined compressive strength test. Marshall stability is a good indication of the ideal binder content but fails to register the true shear strength of the mixture. The triaxial test, on the other hand, measures the shear strength of the test mix and its results gave better information for the prediction of mix field performance. This is because, the stresses acting on the laboratory specimen during the test simulate the state of stresses existing in the pavement. The mix stability in the form of shear strength obtained from the triaxial testing is considered as a fundamental material property that could be used in the mechanistic pavement design procedures.

McLeod (1951) used φ and c from triaxial tests to evaluate the maximum vertical load a pavement can carry. Worley (1951) showed that the triaxial test could be applied to flexible pavement design. Morris et al. (1974) evaluated various laboratory tests and concluded that triaxial tests can best be used to simulate the stress, temperature and strain conditions occurring in the field. Yoder and Witezak (1975) also suggested that the triaxial test offers a good means of evaluating pavement design.

7.3 PRINCIPLES OF TRIAXIAL TESTING

Triaxial test is defined by the Texas Department of Transport (TXDOT, 2002) as a test in which stresses are applied in three mutually perpendicular directions. The main principle behind a triaxial shear test is that the stress applied in the vertical direction (axial pressure equivalent to major principal stress) can be different from the stress applied in the horizontal directions (lateral pressure equivalent to minor principal stress) (Fig. 7.1). This produces a stress state, which induce shear stress. The shear strength of the material is obtained using a Mohr- Coulomb failure criterion represented by the following mathematical relationship:

$$\zeta_f = c + \sigma_n \tan \varphi \text{ -------------------- } (7.1)$$

Where,

ζ_f= shear strength

c = cohesion

σ_n= normal stress acting on failure plane

φ = angle of internal friction

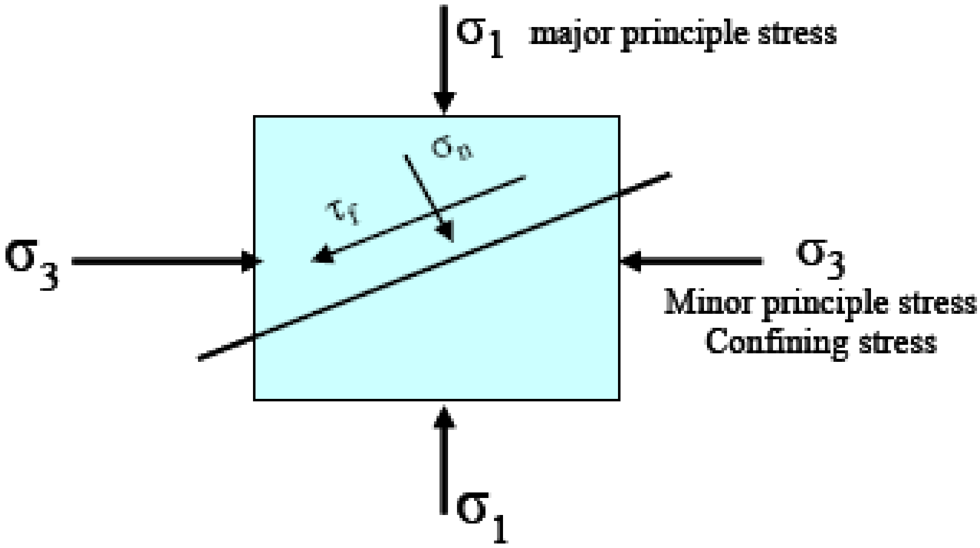

Fig. 7.1 Stress scenario at particle level

The shear parameters (cohesion c and angle of internal friction φ) of a material can be determined by conducting a series of triaxial tests on specimens with different confinement pressures. This requires at least three different specimens of the same material to be tested at different confining pressures in a triaxial cell. The stress conditions at which (shear) failure occurs can be represented by means of Mohr circles and the shear parameters, c and φ can be obtained from the failure envelope of Mohr's circle as shown in Fig. 7.2.

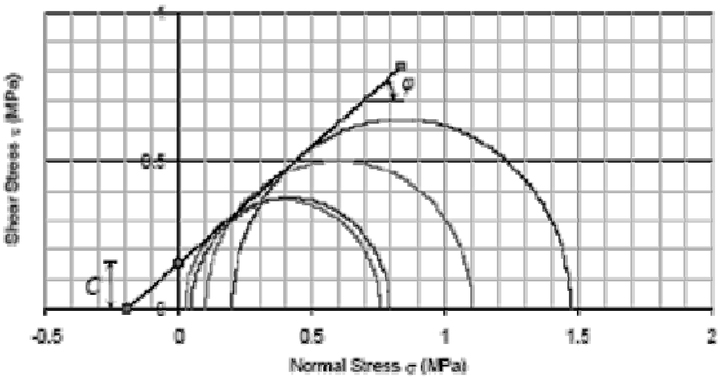

Fig. 7.2 Shear parameters from Mohr's Circle

Besides shear parameters of cohesion and angle of internal friction, other information like tangent and secant moduli and stress and strain at failure can be obtained from the stress-strain diagram. As shown in Fig. 7.3 below, the tangent modulus (E_{tan}) can be defined as the slope of the tangent at the linear part of the stress-strain curve. The tangent modulus therefore, provides an indication of the elastic stiffness modulus of the material. Ebels and Jenkins (2007) found that the tangent modulus has the potential to be a qualitative indicator of the stiffness of a bituminous mixture. The secant modulus (E_{sec}) is illustrated as the slope of the line drawn from the origin of the stress-strain diagram to the point on the curve where the maximum stress occurs while the strain-at-failure (ε_f) being the strain at which the maximum stress occurs.

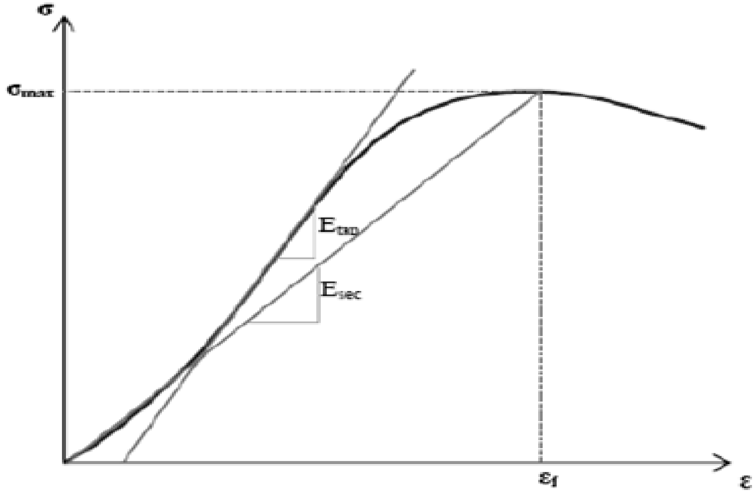

Fig.7.3 Schematic Stress-Strain diagram showing Tangent and Secant Modulus, Maximum Stress and Strain at Failure.

7.4 TRIAXIAL TEST

7.4.1 Effect of specimen size

Researchers conducting triaxial tests of bituminous mixtures have accepted a specimen height to diameter ratio of 1.5 to 1 (Pellinen et al., 2004). The specimen size of 100 mm in diameter and 150 mm in height is used for the present study.

7.4.2 Effect of temperature

The strength of bituminous mixtures is dependent on the viscosity of the binders, which in turn depends on the temperature of the mix. A test temperature of 60°C is used in this study, which is an acceptable temperature level by many researchers. (Smith, 1951; Low et al, 1995)

7.4.3 Effect of loading speed

Static truck loads represent the severest condition imposed on a bituminous pavement. Such loading can result in the accumulation of significant pavement deformation. Endersby (1951) found that in the triaxial test, the cohesion increases with increasing loading speed. Goetz and Chen (1957) reported that the angle of internal friction was not affected by the rate of strain, but the cohesion increases steadily as the rate of strain increases. A loading speed of 50.8 mm/min is selected for this study (Pellinen et al, 2004), which is same as the rate of loading given for Marshall test.

7.4.4 Specimen preparation and test conditions

The bitumen content for all the SMA mixtures are kept as 6.42% which is the optimum bitumen content for the control SMA mixture. Samples are compacted with Marshall compactor to get a cylindrical sample of 100 mm diameter and 150 mm height. The specimen is encased in a rubber membrane to allow for confinement pressure to be applied all around the specimen. Various types of confinement medium have been mentioned in literature including gases, water and oil (Lambe, 1951). In the present study water is used as the medium. Axial load is applied through a platen on the end of the cylindrical specimen, so as to get an unconsolidated undrained test condition. Test specimens are loaded beyond the peak load to understand the post peak behaviour. Four different confinement pressures of 0, 50, 75 and 100 kPa were used in the testing (Bueno et al., 2003; Ebels, 2008). For each confining pressure, three samples are tested and the average value is taken.

In the laboratory, confining stresses are applied to simulate stress due to the surrounding material in a pavement structure. This confinement increases with increasing depth in the pavement. Thus, varying the confining pressure in a laboratory test simulates the material at different depths in the pavement. The deviator stress in the laboratory represents applied wheel loads in the field that are transmitted through the bituminous layers to the underlying unbound layers. Increasing the deviator stresses in the laboratory simulates increasing the applied load magnitude in the field.

7.4.5 Test procedure

Fig. 7.4 shows the triaxial test up. The triaxial cell is a fluid-tight container with hydraulic connections at the base and a sliding load piston in the top. The cell can be readily opened to allow the positioning of specimens and cell accessories. The pedestal (base disc) on which the specimen sits is interchangeable with discs of different diameter provided that these are compatible with the cell itself. The cell must be able to safely withstand the confinement pressures required. The confining pressure around the specimen is furnished by pressurized water and the triaxial cell is connected to a system capable of providing the same. The internal dimension of the cell is large enough to accommodate the specimen to be tested. The specimen is enclosed in a latex membrane which is sealed with rubber O-rings on the base disc and top cap. One unconfined and three confined tests are conducted for the control and stabilized SMA mixtures with different additives. The specimens are loaded axially to failure at a strain rate of 50.8 mm/min. The confining pressures used are 0, 50, 75 and 100 kPa. The shape of the deformed specimen after testing is shown in Fig. 7.5.

Fig. 7.4 Triaxial test set up

Fig. 7.5 Deformed specimen

7.5 RESULTS AND DISCUSSIONS

7.5.1 Analysis using Mohr-Coulomb failure theory

Stone Matrix Asphalt (SMA) mixtures with different additives are investigated using triaxial shear strength testing. The cohesion and friction angle are obtained using the Mohr-Coulomb failure theory. The triaxial test results are tabulated in Table7.1.The table shows the measured deviator stress (σ_d) obtained at each confinement level (σ_3). Fig. 7.6 to 7.11 shows the plots of the Mohr-Coulomb failure envelope represented by the cohesion c and angle of internal friction φ for the tested mixtures (3samples for each confinement). Cohesion and friction are estimated using test results from different confinement levels to obtain at least three points in the failure line. The computed cohesion values for each additive for different percentages are shown in Fig. 7.12 and Fig.7.13.

Table 7.1 Triaxial shear strength test results

Type of additive	Confinement σ_3 (kPa)	Deviator stress σ_d (kPa)	C (kPa)/ φ (°)
No additive	0	418.57	109.06/35
	50	553.45	
	75	613.06	
	100	681.88	
Coir fibre	0	652.42	166.67/36
	50	801.39	
	75	870.05	
	100	944.39	
Sisal fibre	0	594.61	150.68/36
	50	732.54	
	75	811.89	
	100	878.51	
Banana fibre	0	578.93	146.59/36
	50	719.80	
	75	784.10	
	100	860.65	
Waste plastics	0	570.26	145.55/35.6
	50	707.66	
	75	776.03	
	100	845.78	
Polypropylene	0	553.25	139.52/35.6
	50	691.19	
	75	752.12	
	100	830.98	

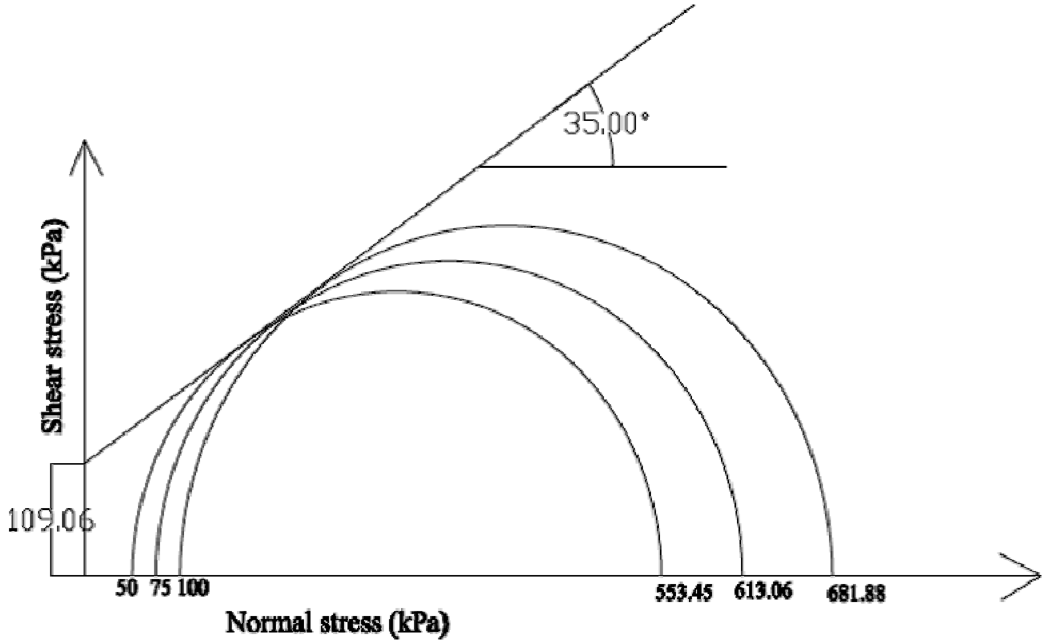

Fig. 7.6 Mohr's circle for control mixture

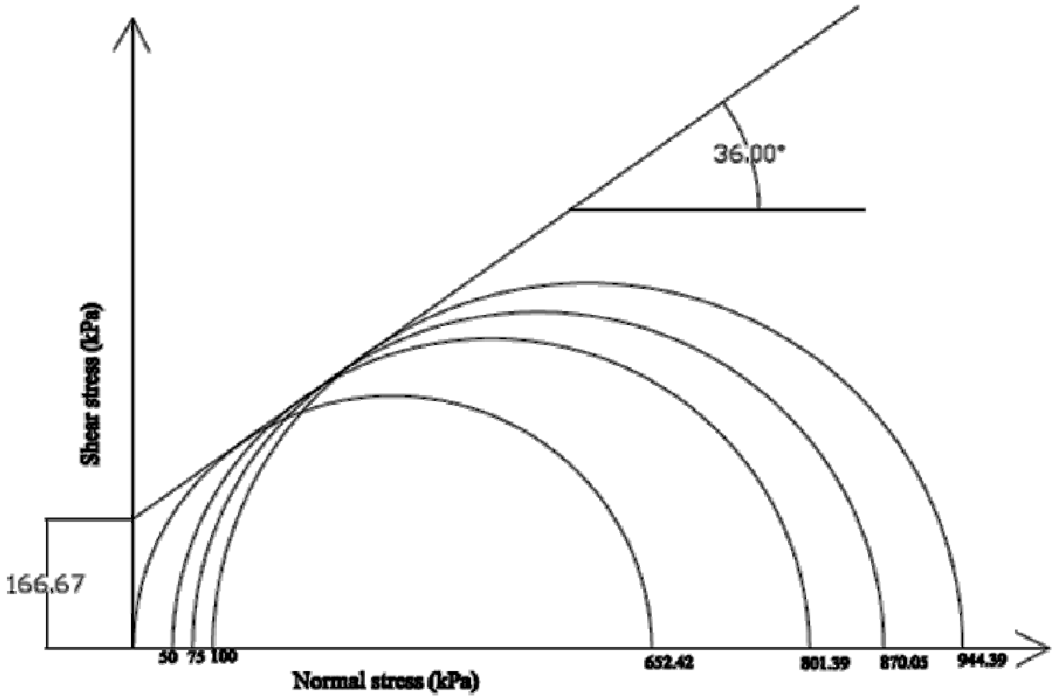

Fig. 7.7 Mohr's circle for coir fibre stabilized SMA

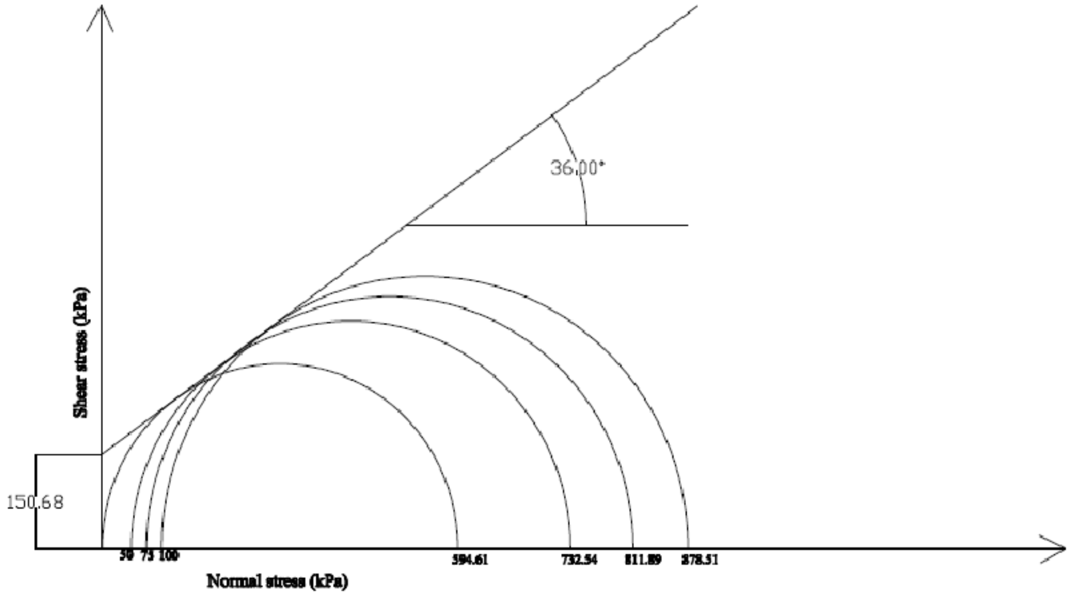

Fig. 7.8 Mohr's circle for sisal fibre stabilized SMA

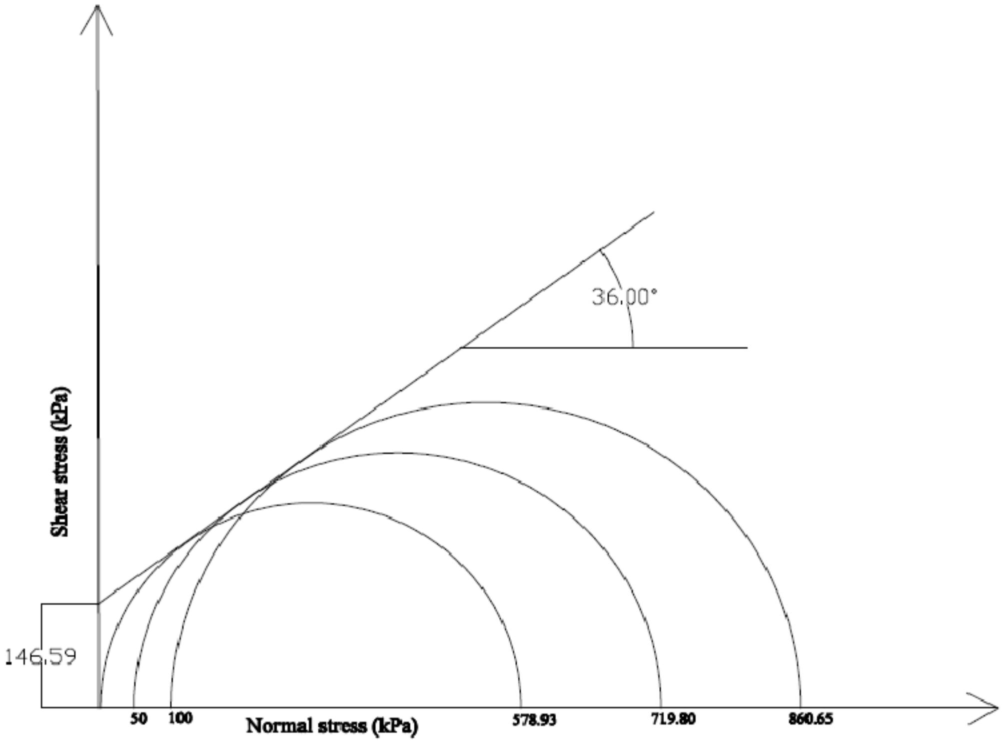

Fig. 7.9 Mohr's circle for banana fibre stabilized SMA

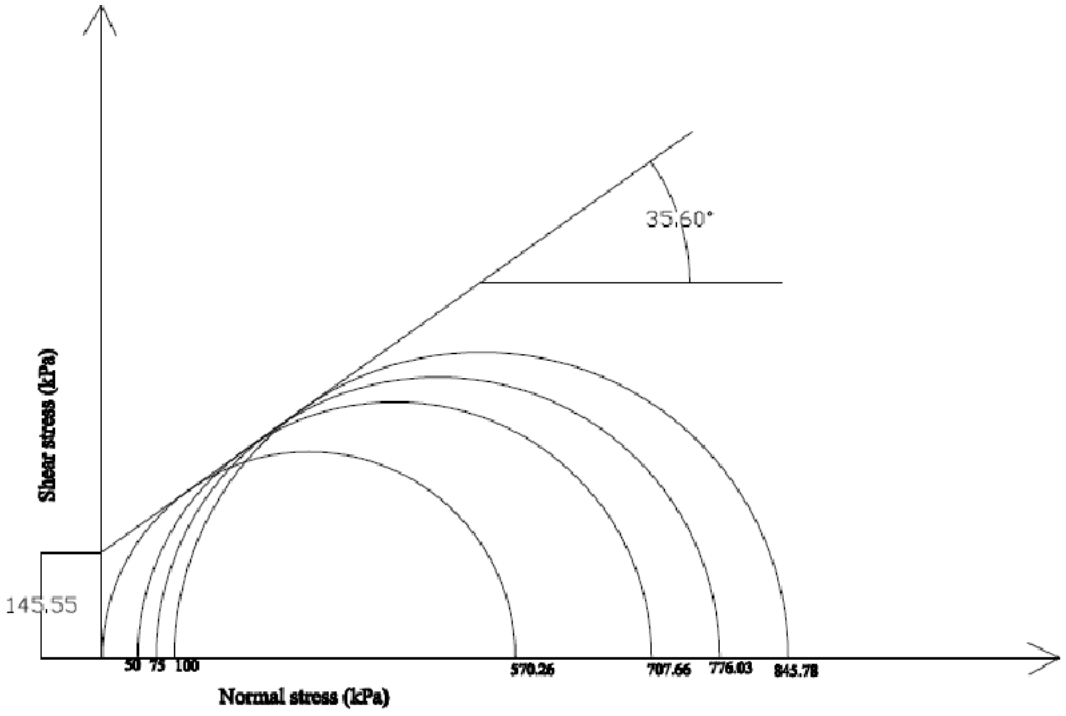

Fig. 7.10 Mohr's circle for waste plastics stabilized SMA

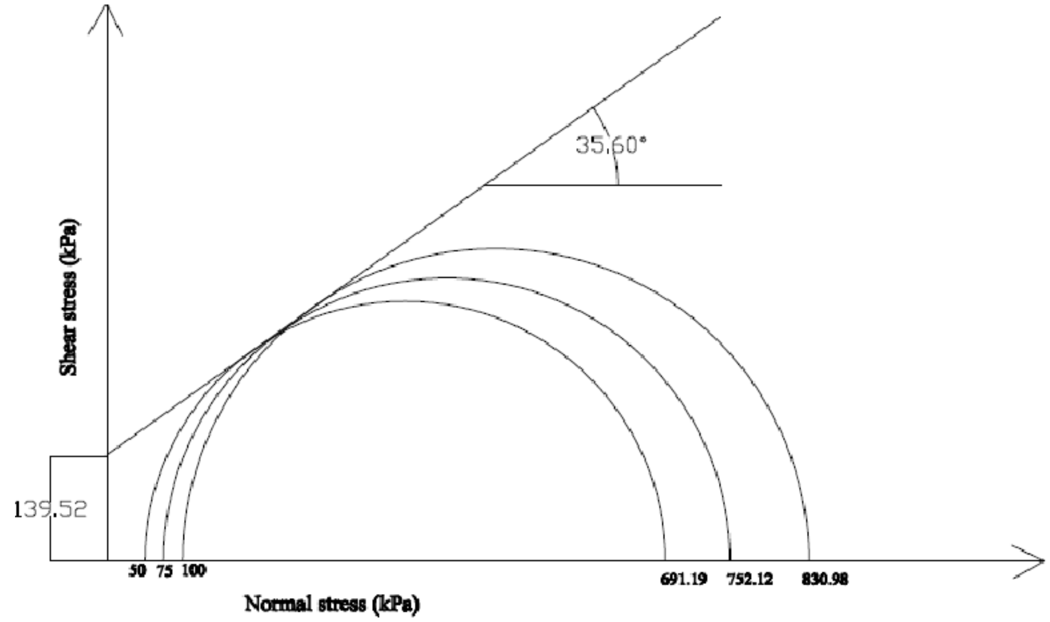

Fig. 7.11 Mohr's circle for polypropylene stabilized SMA

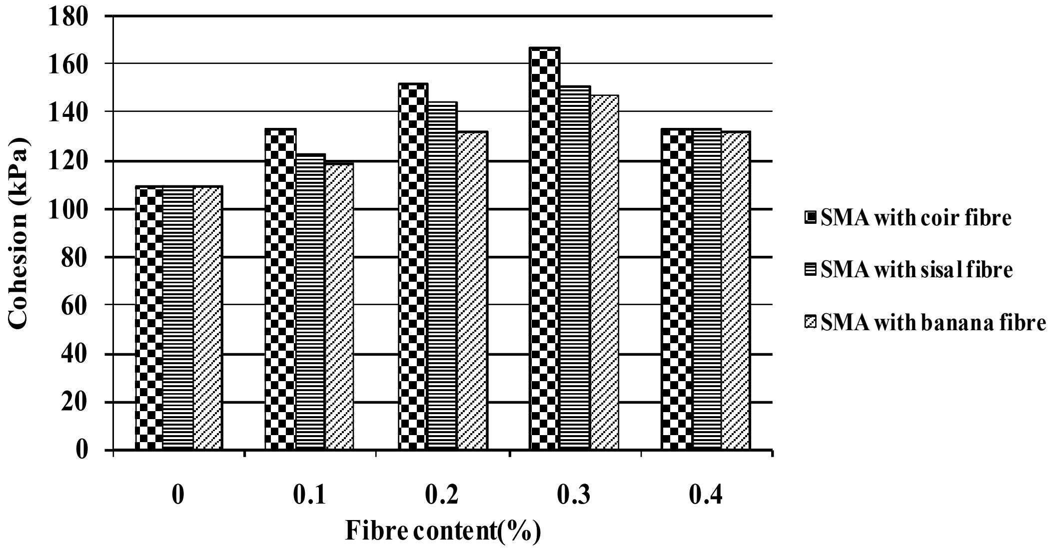

Fig. 7.12 Variation of cohesion with different fibres

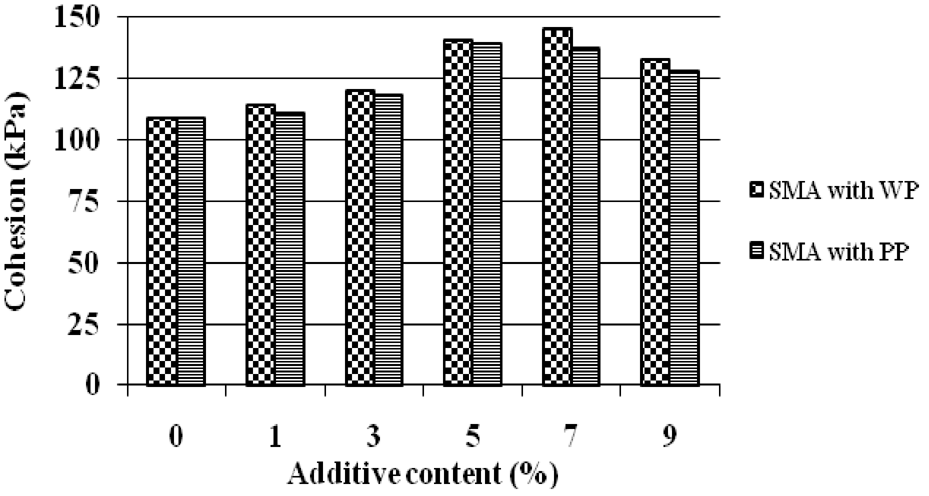

Fig. 7.13 Variation of cohesion with different WP and PP contents

7.5.1.1 Cohesion

Analysis of test data (Fig. 7.12 and 7.13) shows that the presence of additives has shown significant effect on cohesion, which increases approximately from 110kPa in control mixture to 170kPa in SMA mixtures with coir fibre and to about 145kPa in SMA mixtures with waste plastics. All the SMA mixtures give the highest cohesion at 0.3%fibre content, irrespective of the type of fibre and at 7% for waste plastics and at 5% for polypropylene. The cohesion values are found to be decreasing when additive contents are increased beyond this percentage. It is also evident from Fig. 7.12 that

SMA with coir fibre gives the maximum cohesion among the mixtures. Fig. 7.13 shows that waste plastics stabilized SMA mixtures show slightly higher cohesion value than the polypropylene stabilized mixtures. When compared to the control mixture the percentage increase in cohesion value is about 33% and 28% respectively for SMA mixture stabilized with WP (7%) and PP (5%). The larger the cohesion value, the higher the mix resistance to shearing stresses. This shows that all the stabilized mixtures have greater resistance to shearing stresses than the control mixtures. Variation of shear parameters with different additives in SMA mixture corresponding to 0.3% fibre content and 7% plastic content and 5% PP content are shown in Fig. 7.14. The fibre stabilized mixtures have the highest cohesion than the other stabilized mixtures. Among this, coir fibre stabilized mixtures gives the maximum cohesion and the percentage increase is about 53% with respect to the control mixture.

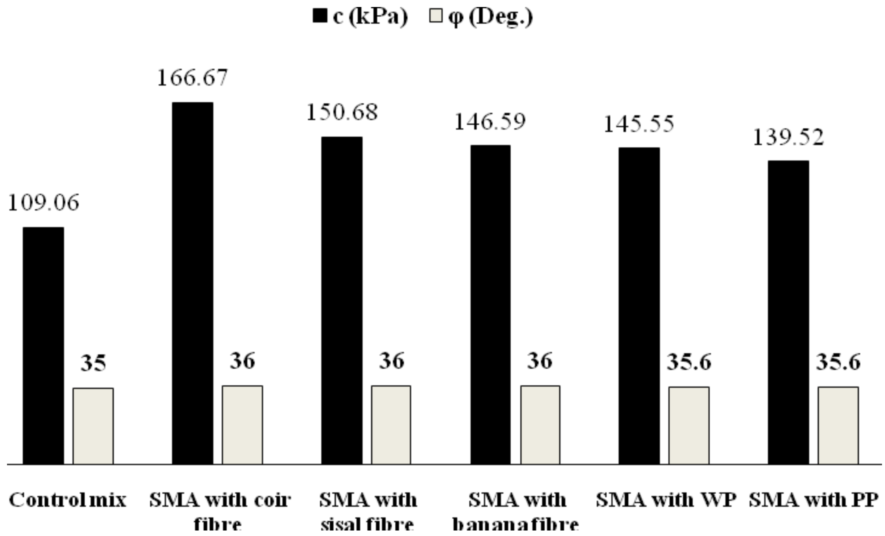

Fig. 7.14 Variation of shear parameters with different additives

7.5.1.2 Angle of internal friction

The variations of angle of internal friction of SMA mix with different percentages of additives are given in Fig. 7.15 and 7.16. It can be observed that the presence of additives in SMA mix will not result in considerable variation in the angle of internal friction of mix as compared to the control mixture. The value of φ is 36°for all fibre-stabilized mixes, 35.6° for WP and PP stabilized mixtures while 35° for the control mixture. The angle of internal friction value is an aggregate property, mostly dependent on aggregate properties such as grading and angularity of particles. Therefore no significant variation is expected since all mixtures have the same aggregate gradations.

A slight increase in angle of internal friction is occurred for the fibre stabilized mixtures at a fibre content of 0.3% and the percentage increase is only about 3 % with respect to the control mixture and for WP and PP mixtures, this increase is only about 1.7%. This slight increase in φ may be due to the influence of cohesion. The cohesion and friction angle are not entirely independent of each other since there is some sort of balancing effect as a result of the stabilisation of the mixture (Jenkins, 2000).

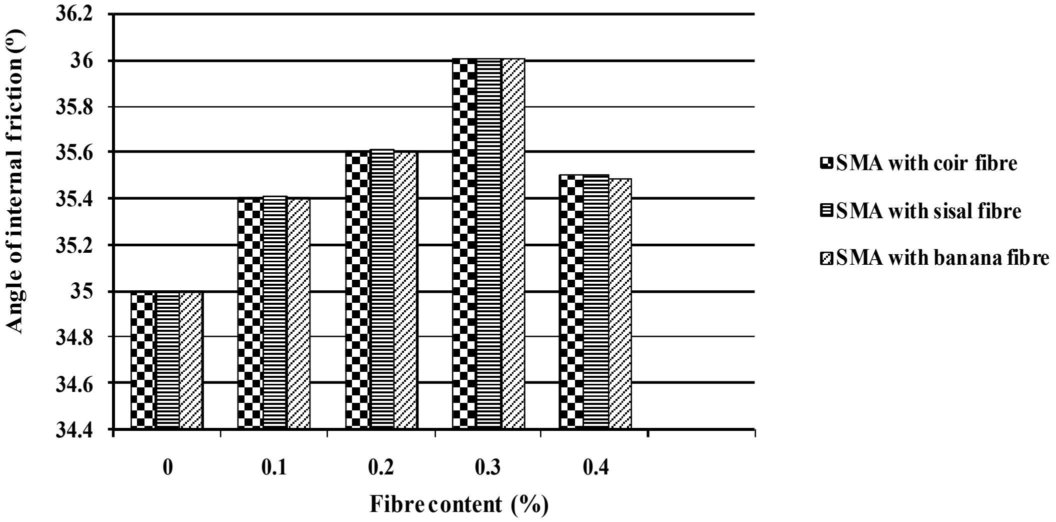

Fig. 7.15 Variation of angle of internal friction with different percentages of fibres

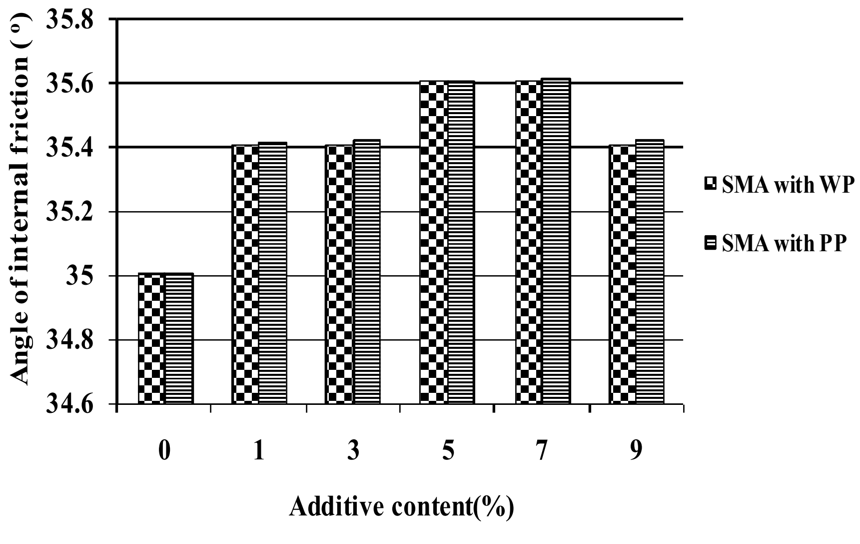

Fig. 7.16 Variation of angle of internal friction with different WP and PP contents

The parameters c and φ are the strength indicators of mixtures. The larger the c value, the higher the resistance to shearing stresses. In addition, the larger the φ value, the higher the capacity of the bituminous mixture to develop strength from the applied loads, and hence, the smaller the potential for permanent deformation. The cohesion values of all mixes with additives are higher than that of the control mixture, showing their higher resistance to shearing stresses.

7.5.1.3 Shear strength

The cohesion and angle of internal friction cannot be evaluated and compared in isolation. When comparing the performance of several mixes, the maximum shear stress that the mixture can withstand is of importance. This is dependent both on cohesion and angle of internal friction.

Shear strength is computed using Equation 7.1 at 300 kPa normal stresses which represents hypothetical pavement stress at the edge of the tyre at 75-mm deep in the pavement (Pellinen et al.,2004). The test results are shown in Table 7.2.

Table 7.2 Shear strength of various SMA mixtures

Type of mixture	**Shear strength (kPa)**
Control mixture	319.12
SMA with coir	384.63
SMA with sisal	368.64
SMA with banana	364.55
SMA with WP	363.51
SMA with PP	355.63

It can be seen that, with additives, SMA mixture retained higher shear strength. This suggests that the stabilized mixture is less prone to rutting by shear and densification compared to the control mixture. In order to densify mixtures by traffic the rearrangement of aggregate structure must take place by coupled action of volumetric and shear straining. Based on these findings the stabilized mixtures seem to be less prone to dilatation and shear compared to the control mixture. Coir stabilized SMA mixture shows the maximum shear strength of about 385 kPa. The percentage increase in strength is about 21% with respect to the control mixture, showing their much greater resistance to shearing stresses. The results indicate that the shear resistance is rising mostly from cohesion since the variation of φ is observed to be marginal. Also, sisal and banana fibre mixtures seem to deviate less from each other.

Mechanical behaviour of stabilized mixes depicted by Mohr– Coulomb shear strengths from conventional triaxial tests match with those given by Marshall's stability values. Both test results showed that stabilized mixes are stronger than the control mix. The presence of additives makes the mixes more flexible. Surface layer built with this stabilized SMA may not become rigid under traffic loading and, therefore, less susceptible to cracking.

7.5.2 Stress-Strain Curves for SMA Mixtures

Fig. 7.17.a to Fig. 7.17.e represents the variation of deviator stress with strain for all stabilized mixtures at 100kPa confinement level for different percentages of additives. The plots represent before and after peak stress development during the test. The peak stress was obtained by examining the graphs. For the stabilized mixture, it is observed that the peak stress developed and the time of its occurrence are higher when compared to those of the control mixture, a behaviour that was attributed to the influence of additives in the mix. The additives provide this additional reinforcement to bituminous mix in resisting permanent deformation and retard the occurrence of shear failure. In all tests, the stabilized mixtures showed higher maximum stress at failure than the control mixture.

SMA mixture with additives showed better resistance to shear deformation as shown by the triaxial shear strength test results. Notably, post peak failure for the additive reinforced bituminous mixtures showed gradual drop in strength, an effect that was attributed to the influence of additives in the mix.

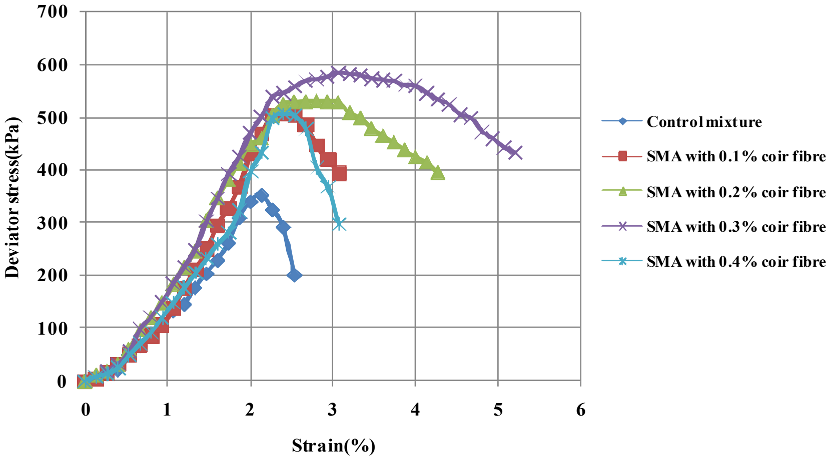

Fig. 7.17.a Variation of deviator stress with strain of SMA with different percentages of coir fibre.

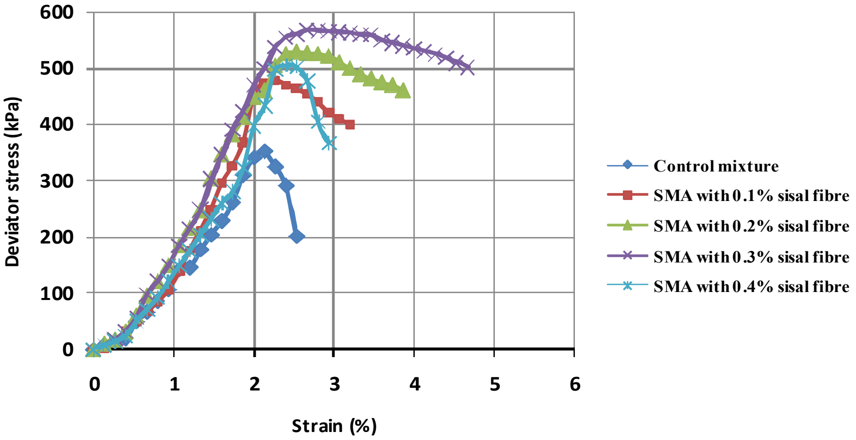

Fig. 7.17.b Variation of deviator stress with strain of SMA with different percentages of sisal fibre.

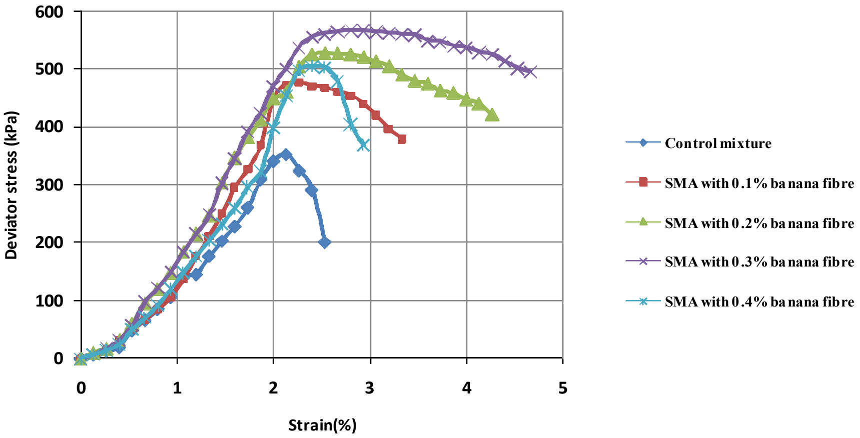

Fig. 7.17.c Variation of deviator stress with strain of SMA with different percentages of banana fibre

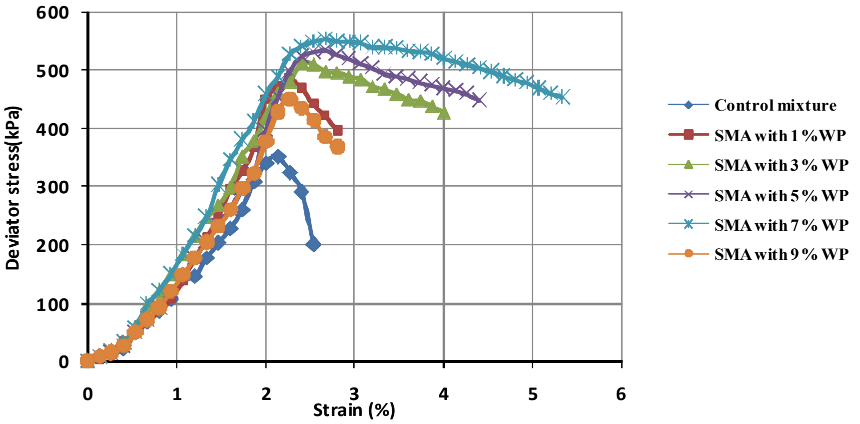

Fig. 7.17.d Variation of deviator stress with strain of SMA with different percentages of waste plastics

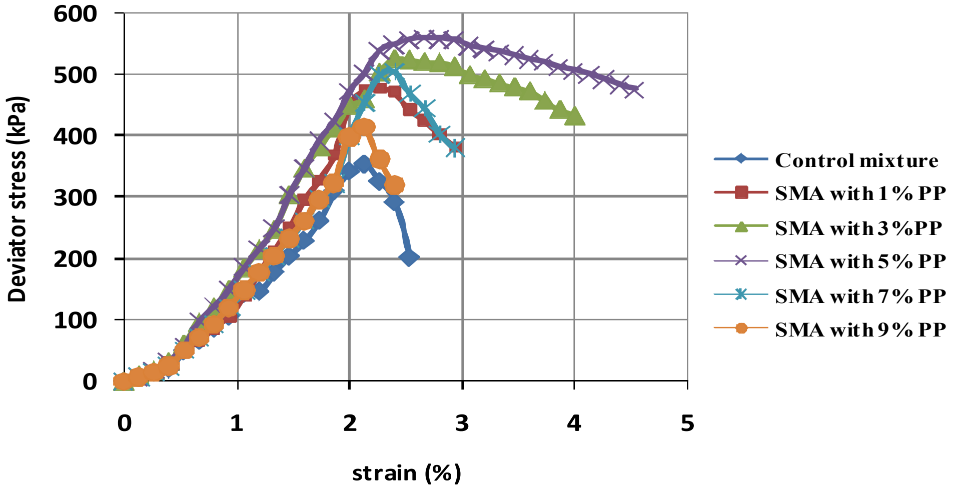

Fig. 7.17.e Variation of deviator stress with strain at different percentages of polypropylene.

By examining the stress-strain curves for the SMA mixtures, it can be inferred that in stabilized mixtures, the shape change of the stress-strain curves is more gradual with increase in additive content and brittle type failure does not seem to occur. Also, the failure strains are slightly higher. The following phenomena are observed during testing based on visual observations, inspection of stress-strain curves and failed specimens of SMA mixtures. For SMA mixtures, at around 0.5% axial strain aggregates started to slip initiating a structural transformation. This process continued until aggregate particle interlock was overcome and dilatation (volume increase) took place in the specimen.

7.5.2.1 Strain and stress at failure

Strain and stress at failure are parameters that could provide some additional insight into the material characterization. These values for stabilized SMA at various additive contents at 100 kPa confinement pressure are given in Table 7.3 and 7.4.The stress and strain values at failure increases due to the inclusion of additives up to 0.3% fibre content, 5% PP content and 7% WP content in SMA and after that it is found to be decreasing.

The variation of maximum failure strain and the corresponding stress for different confinement pressures for all SMA mixtures are summarized in Fig. 7.18 and 7.19.

Table 7.3 Strain and stress at failure for fibre stabilized SMA at various fibre contents. (100 kPa confinement pressure)

Fibre (%)	Coir fibre		Sisal fibre		Banana fibre	
	Strain at failure (%)	Stress at failure (kPa)	Strain at failure (%)	Stress at failure (kPa)	Strain at failure (%)	Stress at failure (kPa)
0	2.13	352.5	2.13	352.5	2.13	352.49
0.1	2.4	506.3	2.27	478.14	2.27	476.45
0.2	2.8	530.1	2.53	528.16	2.53	526.84
0.3	**3.07**	**584.2**	**2.67**	**568.15**	**2.8**	**567.49**
0.4	2.4	506.1	2.4	506.12	2.4	504.59

Table 7.4 Strain and stress at failure for stabilized SMA at different percentages of WP and PP (100 kPa confinement pressure).

.Additive (%)	Waste plastics		Polypropylene	
	Strain at failure (%)	Stress at failure(kPa)	Strain at failure (%)	Stress at failure (kPa)
0	2.13	352.5	2.13	352.5
1	2.27	486.45	2.27	476.45
3	2.4	512.45	2.4	524.68
5	2.53	542.58	**2.67**	**554.42**
7	**2.93**	**559.46**	2.4	504.587
9	2.27	454.85	2.13	414.568

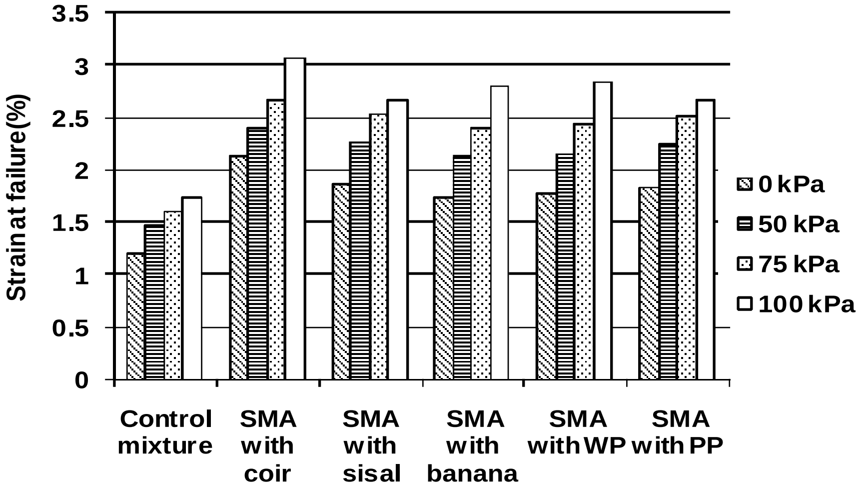

Fig. 7.18 Maximum strain at failure at different confinement pressures

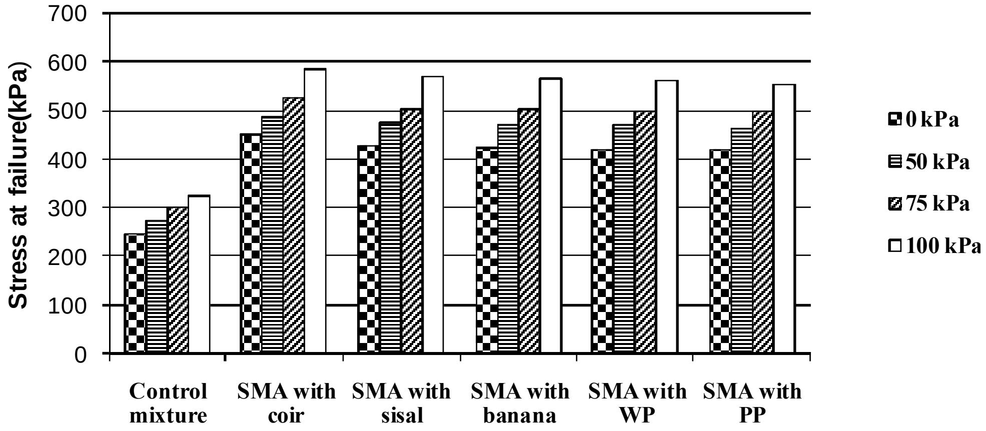

Fig. 7.19 Maximum stress at failure at different confinement pressures

7.5.2.2 Confinement Effect

Looking at the confinement pressure only (Fig. 7.18), there is a trend that strain at failure increases with increasing confinement pressure. This would indicate that strain at failure is a stress dependent behaviour. It can be seen that strain at failure ranges from 1.73 % for the control mixture to 3.07 % for coir fibre stabilized SMA at the highest confinement pressure.

Coir fibre stabilized mixtures show slightly higher stress at failure than the other stabilized mixtures (Fig.7.19). But when compared to the control mixture, all stabilized mixtures exhibit higher percentage increase in stress at failure. Fig. 7.20 summarizes the measured axial failure strains for the coir fibre stabilized SMA mixture at 0.3% fibre content for different confinement levels. By examining stress-strain curves, it can be observed that the strain at failure increases with increasing confinement pressure rendering it a stress dependent parameter. Similar trend was observed for other SMA mixtures.

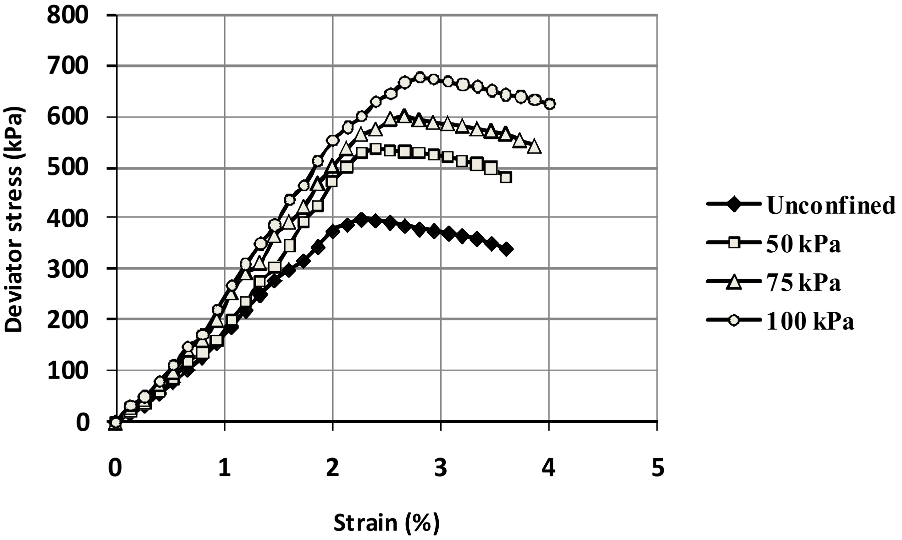

Fig. 7.20 Stress strain behaviour at various confinement pressures for coir fibre stabilized SMA.

7.5.2.3 Tangent modulus

Another material property that may be derived from the triaxial test is the tangent modulus. The maximum tangent modulus of all six mixtures including the control mixture at different confinement pressures are summarized in Fig.7.21. All stabilized mixes show high tangent modulus than the control mixture. As the confining pressure increases, the tangent modulus value increases. The tangent modulus exhibited a stress dependent behaviour. It can be seen that the tangent modulus generally varies between 1.2 kPa for control mixture to 2.3kPa for SMA with 0.3% coir fibre. As the tangent modulus is obtained from the linear part of the stress-strain diagram, it should provide an indication of the elastic stiffness of the material. It is evident that the presence of fibre in the mix enhances the elastic stiffness of the SMA mixture.

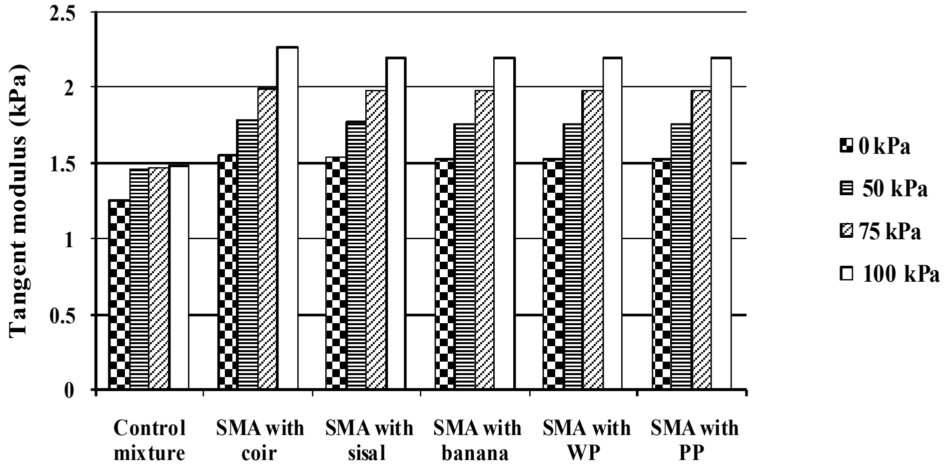

Fig.7.21 Tangent modulus at different confinement pressures

7.6 SUMMARY

The Stone Matrix Asphalt mixtures are investigated using triaxial shear strength testing at 50.8 mm/min ram rate loading at 60°C to investigate the effect of additive content on the mix strength properties by varying the type of additive and the percentage of additive. The test was conducted using 0, 50, 75 and 100kPa confinements. The Mohr-Coulomb failure theory was used to analyze the test data.

Analysis using Mohr-Coulomb failure theory shows that the SMA stabilized mixtures had highest cohesion and shear strength as compared to the control mixture. But all the mixes had almost similar angle of internal friction value, which is mostly dependent on aggregate properties such as grading and angularity of particles. Therefore no significant variation is observed, since all mixtures have the same aggregate gradations.

Data show that, all mix prepared with fibres, the higher values of stabilized mixture cohesion and shear strength can be associated to the fibre content of 0.3%, no matter the type of fibre. For waste plastics and polypropylene stabilized SMA mixtures, the highest cohesion and shear strength can be at 7% WP and 5% PP content respectively. Analysis however suggests that the high additive content beyond this percentage prevents the mixtures to develop aggregate interlock and therefore less cohesion and shear resistance. Among the stabilized SMA mixtures, the SMA mixes with coir fibre has the highest cohesion and shear strength. When compared with the control mixtures, these mixtures have 1.5 times higher cohesion and waste plastics stabilized mixtures has 1.3 times higher value. It is evident that cohesion is more influenced by the additive type.

By examining the stress-strain curves for the SMA mixture, it can be inferred that in the stabilized mixture, the peak stress developed and the time of its occurrence is higher when compared to those of the control mixture. For stabilized mixtures, it is observed that the shape change of the stress-strain curves is more gradual with increase in additive content and brittle type failure does not seem to occur as in the case of control mixture.

There is a trend that the strain at failure and tangent modulus increases with increasing confinement pressure, indicating their stress dependent behaviour. The increase in tangent modulus value of SMA mixture in presence of additives indicates the increased elastic stiffness of the stabilized SMA.

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Chapter 8

DRAIN DOWN CHARACTERISTICS

8.1 INTRODUCTION

Drain down is considered to be that portion of the mixture (fines and bitumen) that separates itself from the sample as a whole and flows downward through the mixture (NAPA, 1999). Drain down test is more significant for SMA mixtures than for conventional dense-graded mixtures. It can be used to determine whether the amount of drain down measured for a given bituminous mixture is within the specified acceptable levels. This test is primarily used for mixtures with high coarse aggregate content (the internal voids of the uncompacted mix are larger, resulting in more drain down) such as Stone Matrix asphalt and porous asphalt (open-graded friction course). Potential problems with SMA mixtures are drainage and bleeding. Storage and placement temperatures cannot be lowered to control these problems due to the difficulty in obtaining the required compaction. Therefore, stabilizing additives has been added to stiffen the mastic and thereby reducing the drainage of the mixture at high temperatures and to obtain even higher binder contents for increased durability (FHA, 1992).

SMA mixtures exhibited a very high bitumen binder film thickness (6-7% by weight of mix). This high binder content and the filler content (as compared to that of dense-graded HMA) lead to higher susceptibility for the bitumen binder to drain off the aggregate skeleton (i.e., drain down) in SMA mixtures. Irregular distribution of bitumen binder due to its drain down can lead to raveling of zones with low bitumen binder content and reduction of permeability in zones with accumulation of bitumen binder (Watson and Jared, 1995, Mallick et al.,2000). Fat spots as shown in Fig. 8.1 are formed.

Fig. 8.1 Fat spots

8.2 DRAIN DOWN TEST

The test developed by AASHTO T305 is anticipated to simulate conditions that the mixture is likely to encounter as it is produced, stored, transported, and placed. The test provides an evaluation of the drain down potential of a bituminous mixture during mixture design and/or during field production. This test method covers the determination of the amount of drain down in an uncompacted bituminous mixture when the sample is held at elevated temperatures comparable to those encountered during the production, storage, transport, and placement of the mixture.

Drain down test is conducted on loose mixtures at the optimum binder content to ensure that the draining property of the SMA mixtures is within the acceptable levels. The samples of the SMA loose mixtures are placed in a wire basket fabricated using standard 6.3mm sieve cloth. Wire basket and its dimensions are given in Fig. 8.2 and 8.3. The basket is positioned on a pre-weighted plate or pan which is placed in an oven for three hours at an anticipated mix production temperature. At the end of three hours, the basket containing the sample is removed from the oven along with the pan and the pan is weighted. The mass of any binder that drain down from the mixture to the pan is measured. This mass is then expressed as a percentage by weight of the total mixture. The drain down of SMA mixtures should not exceed 0.3% by weight of the mixture (AASHTO T305).

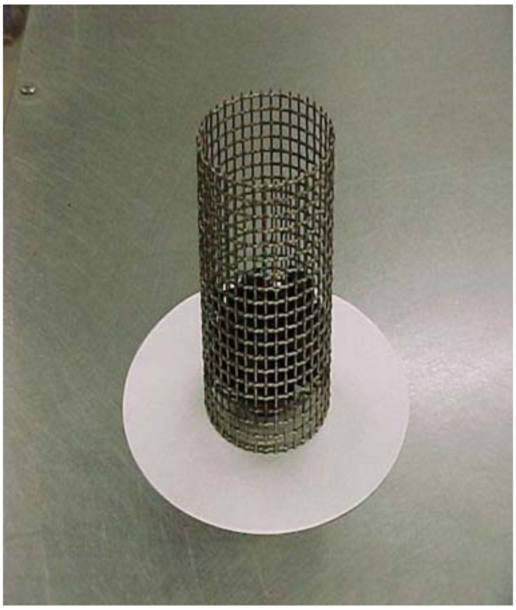

Fig. 8.2 Drain down test apparatus

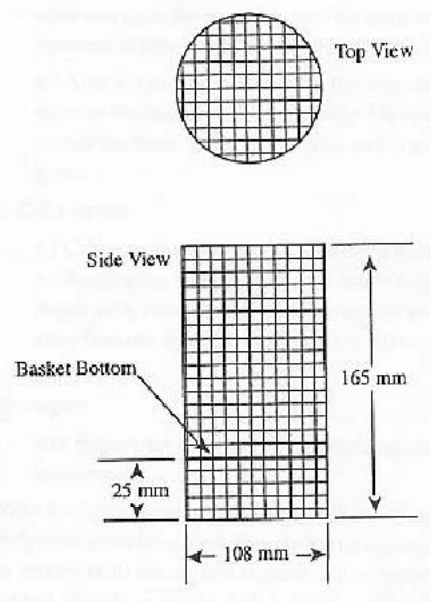

Fig. 8.3 Dimensions of wire basket

8.2.1 Test procedure

In this study, the SMA mixtures obtained at optimum binder content are checked for drain down. A total of twenty two loose SMA samples are tested with triplicate samples for each design mix of SMA, stabilized with each additive and also without additive.

The mass of loose SMA mixture sample and the initial mass of the pan is determined to the nearest 0.1 g. The loose SMA sample is then transferred and placed into the wire basket without consolidating or disturbing it. The basket is placed on the pan and the assembly afterward is placed in the oven (175˚ C) for 1hour. After the sample has been in the oven for 1 hour, the basket and the pan is removed and the final mass of the pan is determined and recorded to the nearest 0.1 g. The Drain down of the mixture can be calculated as follows,

$$Drain\ down\ (\%) = \left(\frac{C-B}{A}\right)100$$

A = Mass of initial total sample (g), B = Mass of initial pan (g) and C = Mass of final pan (g)

The drain down at the optimum bitumen content for each percentage of additive content are determined.

8.4 RESULTS AND DISCUSSIONS

Results of drain down at various percentages of additive contents are given in Table 8.1 & 8.2 and Fig. 8.4 & 8.5. From Table 8.1 and 8.2, it can be observed that all additives provide significant stabilization to the mixture as compared to the control mixture. Drain down of the control mixture is 6.5% which is beyond the specified limits as per AASHTO T305 (not to exceed 0.3% by weight of mix). It is evident that in all stabilized SMA mixtures, the values of drain down decreases considerably with increase in additive content and reaches the acceptable limit at 0.2 % fibre content and 5% WP and PP content. This indicates that in all mixtures, each additive is performing its function as a stabilizing additive. The potential effects of the inclusion of additives in SMA mixtures are therefore beneficial in preventing the bleeding phenomenon of the mixtures and the drain down of this gap graded SMA mix having rich binder content. Either fibre or polymer additive can be effectively utilized as the stabilizing agent. Fibre stabilizers are found to be more effective in reducing the drain down than polymer stabilizers due to the absorptive nature of fibres. Among the fibre stabilized mixtures, Coir fibre reaches the 0% drain down at 0.3% fibre content.

Table 8.1 Drain down values for different fibre percentages

% Fibre	**Drain down (%)**		
	Coir	**Sisal**	**Banana**
0	6.497	6.497	6.497
0.1	1.887	2.347	2.584
0.2	0.083	0.114	0.116
0.3	0	0.012	0.014
0.4	0	0	0.003

Table 8.2 Drain down values for different percentages of PP and WP

% Additive	**Drain down (%)**	
	Polypropylene	**Waste plastics**
0	6.497	6.497
1	2.402	2.61
3	1.497	1.489
5	**0.146**	0.128
7	0.018	**0.017**
9	0.004	0.002

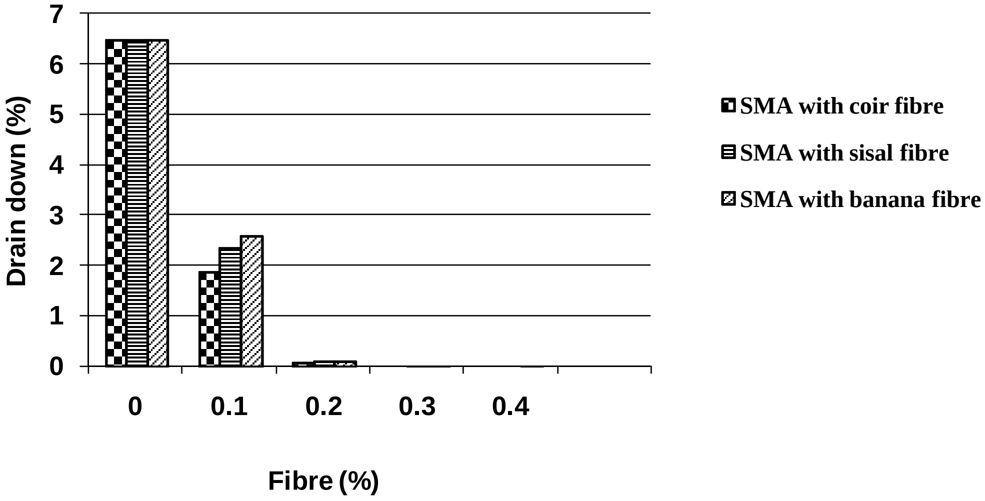

Fig. 8.4 Variation of drain down with different fibre percentages

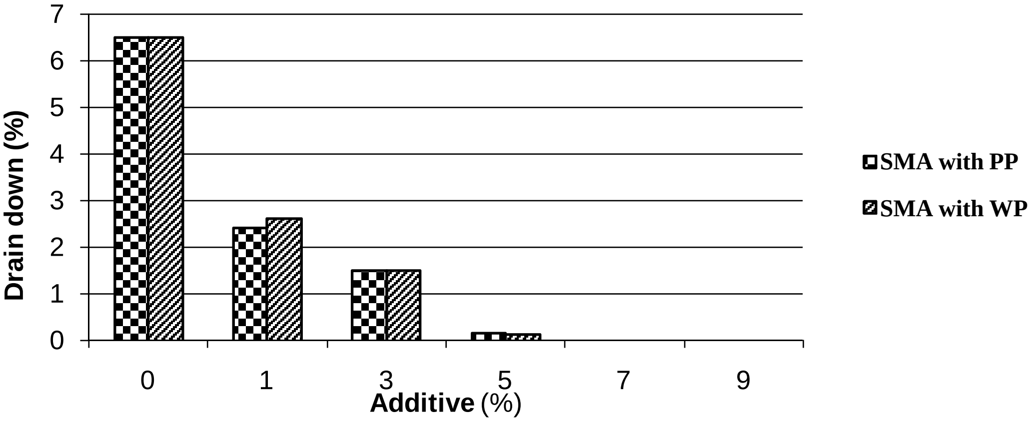

Fig. 8.5 Variation of drain down with different percentages of WP and PP

8.4.1 Stabilizing capacities of different additives

There are some differences in the performance of each additive at binder contents greater than the optimum binder content. Drain down is also tested at binder contents exceeding the optimum binder content to determine the stabilizing capacity of each additive. Binder contents of each SMA mixes are varied from 6.5% (by weight of mixture) at an increment of 1.0% until a drain down of 0.3% is observed. The stabilizing capacity of each additive is determined as the binder content at which the drain down reached 0.3%. The drain down results at varying binder contents are given in Fig. 8.6 and the stabilizing capacities of various additives are given in Table 8.3. It is evident that the fibre stabilized mixtures have higher stabilizing capacity than the mixes with WP and PP. All the additives exceeded 10% binder content before reaching 0.3% drain down. The coir fibre had the highest stabilizing capacity of 16%. The fibres have a much higher stabilizing effect, which can be attributed to the absorptive nature of the fibres compared to the polymers. The fibers firmly bind the aggregate particles inside the matrix and prevent them of movement, which makes the mix stiffer. Waste plastics reached the drain down limit at 11% binder content. The waste plastics and polypropylene have almost similar stabilizing capacities.

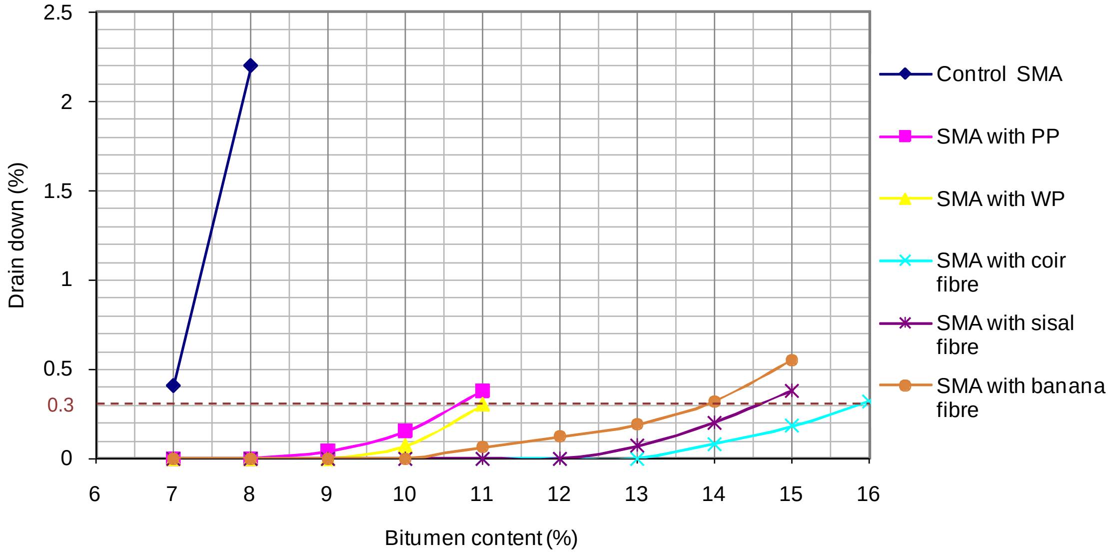

Fig. 8.6 Drain down results at varying binder contents

Table 8.3 Stabilizing capacities of various additives

Additive	Stabilizing Capacity (%)
Coir	15.9
Sisal	14.7
Banana	14
Polypropylene	10.8
Waste plastic	11

8.5 SUMMARY

From the drain down study of the SMA mixtures, it can be concluded that all the five additives used in the stone matrix asphalt for the present investigation act as effective stabilizing agents. The role of additive is to stiffen the mastic and thereby reducing the drainage of the mixture at high temperatures during storage, transportation, placement and compaction of SMA mixtures. Due to the gap graded gradation and rich binder content in SMA, the control mixture is subjected to heavy drain down. This strongly supports the need of the additive in SMA mixtures. All the additives bring down the drain down of the mixture to the specified level. The coir fibre which has a higher stabilizing capacity as compared to other additives is found to be more effective than the others.

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Chapter 9

STATISTICAL ANALYSIS OF THE TEST RESULTS

9.1 INTRODUCTION

Statistical analysis of the test results are performed to quantify significant differences across the various mix types considered in this research. Analysis of variance (ANOVA) is used to identify the main interaction effects of the independent variables on the dependent variables. If significant interaction is found through ANOVA, Tukey’s Homogeneous Groups comparison is selected to perform more detailed analysis, through pair wise comparison across the multiple dependent variables. This approach compares the mean of each population against the mean of each of the other populations, creating separate groups for results that are statistically different, based on a level of significance of 0.05.

SPSS statistical analysis program V.16 is used to prepare an optimization table based on the performance measures conducted. Results of the Marshall stability, indirect tensile strength, compressive strength, triaxial shear tests and drain down study are statistically analyzed with 5% level of significance.

In order to test the significance of difference in the various properties of SMA stabilized with various additives, at various percentages of additives, analysis of variance (ANOVA) has been carried out. For fibres, the contents are 0.1% to 0.4% by weight of mixture at an increment of 0.1% and for waste plastics and polypropylene, these are 1% to 9% by weight of mixture, at an increment of 2%. In the single-factor tests of ANOVA, the additive content was chosen as factor, the stability, bulk specific gravity, indirect tensile strength, compressive strength, cohesion, shear strength and the percentage drain down are taken as responses. Wherever ANOVA shows, significant difference in the properties among the different stabilized mixtures with varied additive contents, Tukey’s post hoc multiple comparison test is used to identify homogeneous groups.

The significance of difference in mean values of various characteristics of polypropylene and waste plastics stabilized SMA are tested using independent sample t-test. Then a comparison between the best among this and the best fibre stabilized SMA are carried out using t-test for independent samples.

9.2 RESULTS AND DISCUSSIONS

The results of ANOVA analysis for the various characteristics of Stone Matrix Asphalt mixtures stabilized with different percentages of additives are summarized. The Homogeneous groups are identified by the Tukey's post hoc multiple comparison test and the optimum value of additive contents are obtained. Comparison between SMA mixtures with fibres at optimum levels are carried out. By independent sample t-test, the significance of difference in mean values of stability, strength and drain down characteristics of SMA stabilized with waste plastics and polypropylene is carried out and a comparison between the best among this and the fibre stabilized mixture is also obtained.

9.2.1 Optimum content of fibre in SMA mixtures

The Homogeneous groups are identified by Tukey's post hoc multiple comparison test and the optimum value of additive contents are obtained and the results are tabulated for various stabilized SMA mixtures.

9.2.1.1 Coir fibre stabilized SMA

Tables for ANOVA analysis and Tukey's test for different characteristics of Stone Matrix Asphalt stabilized with various coir fibre contents are given in Table 9.1 to Table 9.10.

Table 9.1 Stability of coir fibre stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	53.929	4	13.482	884.937	.000
Within Groups	.152	10	.015		
Total	54.081	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0	3	7.4157			
0.4	3		7.9360		
0.1	3		8.1923		
0.2	3			10.0733	
0.3	3				12.5800
Sig.		1.000	.156	1.000	1.000

Table9.2 Bulk specific gravity of coir fibre stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.002	4	.001	144.458	.000
Within Groups	.000	10	6.9E-6		
Total	.002	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0.4	3	2.298			
0.3	3	2.308			
0.2	3		2.315		
0.1	3			2.318	
0	3				2.3203
Sig.		.239	1.000	1.000	1.000

Table 9.3 Indirect tensile strength of coir fibre stabilized SMA

ANOVA table (Unconditioned)

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.266	4	.066	826.247	.000
Within Groups	.001	10	7.9E-5		
Total	.266	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0	3	.8143			
0.1	3		.8510		
0.4	3			1.0831	
0.2	3			1.0983	
0.3	3				1.1242
Sig.		1.000	1.000	.302	1.000

Table 9.4 Indirect tensile strength of coir fibre stabilized SMA

ANOVA table (conditioned)

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.011	4	.253	1.100E5	.000
Within Groups	.000	10	2.3E-6		
Total	1.011	14			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	2	3	4	5
0	3	.4253				
0.1	3		.7090			
0.2	3			1.0590		
0.4	3				1.0521	
0.3	3					1.1048
Sig.		1.000	1.000	1.000	1.000	1.000

Table 9.5 Percentage TSR of coir fibre stabilized SMA

ANOVA

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4421.944	4	1105.486	2.662E3	.000
Within Groups	4.153	10	.415		
Total	4426.097	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0	3	52.2284			
0.1	3		83.3106		
0.2	3			93.6902	
0.4	3				97.1378
0.3	3				96.42
Sig.		1.000	1.000	1.000	.267

Table 9.6 Compressive strength of coir fibre stabilized SMA at 25^{0}C

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2.074	4	.519	444.168	.000
Within Groups	.012	10	.001		
Total	2.086	14			

Tukey's test

%	N	Subset for alpha = 0.05		
		1	2	3
0	3	5.0997		
0.1	3	5.1879		
0.2	3		5.7084	
0.4	3			5.9601
0.3	3			5.9622
Sig.		.061	1.000	1.000

Table 9.7 Compressive strength of coir fibre stabilized SMA at 60^{0}C

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	8.482	4	2.120	1.270E3	.000
Within Groups	.017	10	.002		
Total	8.498	14			

Tukey's test

%	N	**Subset for alpha = 0.05**			
		1	**2**	**3**	**4**
0	3	4.1323			
0.1	3		4.2526		
0.2	3			5.2243	
0.4	3				5.8467
0.3	3				5.8680
Sig.		1.000	1.000	1.000	.965

Table 9.8 Percentage Drain down of coir fibre stabilized SMA

ANOVA

Source	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	87.642	4	21.911	6.547E5	.000
Within Groups	.000	10	4.4E-5		
Total	87.643	14			

Tukey's test

%	N	**Subset for alpha = 0.05**			
		1	**2**	**3**	**4**
0.4	3	0			
0.3	3	0			
0.2	3		0.083		
0.1	3			1.887	
0	3				6.4967
Sig.		.213	1.000	1.000	1.000

Table 9.9 Cohesion of coir fibre stabilized SMA

ANOVA

Source	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	5370.515	4	1342.629	1.057E4	.000
Within Groups	1.270	10	.127		
Total	5371.785	14			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	2	3	4	5
0	3	109.06				
0.1	3		132.87			
0.4	3			132.09		
0.2	3				151.62	
0.3	3					166.70
Sig.		1.000	1.000	1.000	1.000	1.000

Table 9.10 Shear strength of coir fibre stabilized SMA

ANOVA

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	5370.515	4	1342.629	1.057E4	.000
Within Groups	1.270	10	.127		
Total	5371.785	14			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	2	3	4	5
0	3	319.12				
0.1	3		354.55			
0.4	3			379.42		
0.2	3				382.54	
0.3	3					384.63
Sig.		1.000	1.000	1.000	1.000	1.000

ANOVA shows that there is significant difference in stability, strength and drain down characteristics of SMA for different percentages of coir fibre at 1% level of significance (sig < 0.01). Homogeneous groups are identified by Tukey's post hoc multiple comparison test and this clearly shows that all the characteristics of coir fibre stabilized SMA changed significantly at each percentage of fibre content and **the optimum value obtained at 0.3 % fibre content (by weight of mixture) for coir fibre stabilized SMA**, which differs significantly from the control mixture and other fibre mixtures.

9.2.1.2 Sisal fibre stabilized SMA

Tables for ANOVA analysis and Tukey's test for the different characteristics of Stone Matrix Asphalt stabilized with various sisal fibre contents are given in Table 9.11 to Table 9.20.

Table 9.11 Stability of sisal fibre stabilized SMA

ANOVA table

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	37.137	4	9.284	1.564E4	.000
Within Groups	.006	10	.001		
Total	37.143	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0	3	7.4157			
0.1	3		7.7433		
0.2	3			8.7010	
0.4	3			8.7417	
0.3	3				11.8620
Sig.		1.000	1.000	.313	1.000

Table 9.12 Bulk specific gravity of sisal fibre stabilized SMA

ANOVA table

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.003	4	.001	241.840	.000
Within Groups	.000	10	3.13E-6		
Total	.003	14			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	2	3	4	5
0.4	3	2.278				
0.3	3		2.291			
0.2	3			2.3		
0.1	3				2.31	
0	3					2.32
Sig.		1.000	1.000	1.000	1.000	1.000

Table 9.13 Indirect tensile strength of sisal fibre stabilized SMA

ANOVA table (unconditioned)

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.232	4	.058	699.539	.000
Within Groups	.001	10	8.3E-5		
Total	.233	14			

Tukey's test

%	N	Subset for alpha = 0.05		
		1	2	3
0	3	.8143		
0.1	3	.8313		
0.4	3		1.0538	
0.2	3		1.0619	
0.3	3			1.1057
Sig.		.223	.810	1.000

Table 9.14 Indirect tensile strength of sisal fibre stabilized SMA

ANOVA table (conditioned)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.930	4	.232	8.688E4	.000
Within Groups	.000	10	2.7E-6		
Total	.930	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0	3	.4253			
0.1	3		.6915		
0.2	3			1.0114	
0.4	3			1.0153	
0.3	3				1.0766
Sig.		1.000	1.000	.085	1.000

Table 9.15 Tensile strength ratio of sisal fibre stabilized SMA

ANOVA table

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4385.992	4	1096.498	2.356E3	.000
Within Groups	4.655	10	.465		
Total	4390.647	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0	3	52.2284			
0.1	3		83.1836		
0.2	3			95.2448	
0.4	3				96.3466
0.3	3				97.3715
Sig.		1.000	1.000	.341	.404

Table 9.16 Compressive strength of sisal fibre stabilized SMA at 25^0C

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.214	4	.303	1.701E3	.000
Within Groups	.002	10	1.8E-4		
Total	1.216	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0	3	5.0997			
0.1	3		5.1603		
0.2	3			5.5814	
0.4	3				5.7954
0.3	3				5.7996
Sig.		1.000	1.000	1.000	.653

Table 9.17 Compressive strength of sisal fibre stabilized SMA at 60^{0}C

ANOVA table

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	6.207	4	1.552	503.452	.000
Within Groups	.031	10	.003		
Total	6.238	14			

Tukey's test

		Subset for alpha = 0.05		
%	N	1	2	3
0	3	4.1323		
0.1	3	4.2202		
0.2	3		5.1456	
0.4	3			5.6623
0.3	3			5.6666
Sig.		.465	1.000	.938

Table 9.18 Percentage Drain down of sisal fibre stabilized SMA

ANOVA table

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	89.440	4	22.360	1.111E6	.000
Within Groups	.000	10	2.0E-5		
Total	89.440	14			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	**2**	**3**	**4**	**5**
0.4	3	0				
0.3	3		.012			
0.2	3			0.114		
0.1	3				2.347	
0	3					6.4967
Sig.		1.000	1.000	1.000	1.000	1.000

Table 9.19 Cohesion of sisal fibre stabilized SMA

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1836.149	4	459.037	3.235E3	.000
Within Groups	1.419	10	.142		
Total	1837.567	14			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	**2**	**3**	**4**	**5**
0	3	109.06				
0.1	3		121.64			
0.4	3			132.42		
0.2	3				144.12	
0.3	3					150.68
Sig.		1.000	1.000	1.000	1.000	1.000

Table 9.20 Shear strength of sisal fibre stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.841E7	4	4601355.395	3.238E3	.000
Within Groups	14209.473	10	1420.947		
Total	1.842E7	14			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	2	3	4	5
0	3	319.12				
0.1	3		324.58			
0.4	3			341.24		
0.2	3				356.65	
0.3	3					368.64
Sig.		1.000	1.000	1.000	1.000	1.000

ANOVA shows that there is significant difference in the stability, strength and drain down characteristics for the different percentages of sisal fibre in the mixture at 1% level of significance (sig < 0.01). Homogeneous groups are identified by Tukey's post hoc multiple comparison test and this clearly shows that all the characteristics of sisal fibre stabilized SMA changed significantly at each percentages of fibre content and **the optimum value obtained at 0.3 % fibre content (by weight of mixture) for SMA with sisal fibre**, which differs significantly from the control mixture .

9.2.1.3 Banana fibre stabilized SMA

Tables for ANOVA analysis and Tukey's test for the different characteristics of Stone Matrix Asphalt stabilized with various banana fibre contents are given in Table 9.21 to Table 9.30.

Table 9.21 Stability of banana fibre stabilized SMA

ANOVA table

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	37.208	4	9.302	1.667E4	.000
Within Groups	.006	10	.001		
Total	37.214	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	**2**	**3**	**4**
0	3	7.4157			
0.1	3		7.7323		
0.2	3			8.643	
0.4	3			8.703	
0.3	3				11.8540
Sig.		1.000	1.000	.070	1.000

Table 9.22 Bulk sp.gravity of banana fibre stabilized SMA

ANOVA table

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.003	4	.001	241.820	.000
Within Groups	.000	10	3.13E-6		
Total	.003	14			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	**2**	**3**	**4**	**5**
0.4	3	2.275				
0.3	3		2.286			
0.2	3			2.296		
0.1	3				2.308	
0	3					2.32
Sig.		1.000	1.000	1.000	1.000	1.000

Table 9.23 Indirect tensile strength of banana fibre stabilized SMA

ANOVA table (unconditioned)

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.234	4	.059	732.119	.000
Within Groups	.001	10	8.1E-5		
Total	.235	14			

Tukey's test

%	N	**Subset for alpha = 0.05**		
		1	**2**	**3**
0	3	.8143		
0.1	3	.8272		
0.4	3		1.0540	
0.2	3		1.0650	
0.3	3			1.1018
Sig.		.441	.578	1.000

Table 9.24 Indirect tensile strength of banana fibre stabilized SMA

ANOVA table (conditioned)

Spurce	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	.926	4	.232	3.084E5	.000
Within Groups	.000	10	7.5E-7		
Total	.926	14			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	2	3	4	5
0	3	.4253				
0.1	3		.6941			
0.2	3			1.0107		
0.4	3				1.0150	
0.3	3					1.0762
Sig.		1.000	1.000	1.000	1.000	1.000

Table 9.25 Tensile strength ratio of banana fibre stabilized SMA

ANOVA table

	Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	4378.400	4	1094.600	2.616E3	.000
Within Groups	4.185	10	.418		
Total	4382.585	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0	3	52.2284			
0.1	3		83.9092		
0.2	3			94.9014	
0.4	3				96.2997
0.3	3				97.6705
Sig.		1.000	1.000	.134	.145

Table 9.26 Compressive strength of banana fibre stabilized SMA at 25^{0}C

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.215	4	.304	1.703E3	.000
Within Groups	.002	10	1.8E-4		
Total	1.216	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0	3	5.0997			
0.1	3		5.1494		
0.2	3			5.5402	
0.4	3				5.7496
0.3	3				5.7572
Sig.		1.000	1.000	1.000	.953

Table 9.27 Compressive strength of banana fibre stabilized SMA at 60^{0}C

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	6.120	4	1.530	3.562E3	.000
Within Groups	.004	10	4.3E-4		
Total	6.124	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0	3	4.1323			
0.1	3		4.2011		
0.2	3			5.0068	
0.4	3				5.5421
0.3	3				5.5683
Sig.		1.000	1.000	1.000	.557

Table 9.28 Percentage Drain down of banana fibre stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	89.419	4	22.355	6.693E5	.000
Within Groups	.000	10	3.3E-5		
Total	89.419	14			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0.4	3	.003			
0.3	3	.014			
0.2	3		0.116		
0.1	3			2.584	
0	3				6.4967
Sig.		.074	1.000	1.000	1.000

Table 9.29 Cohesion of banana fibre stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1845.480	4	461.370	1.147E4	.000
Within Groups	.402	10	.040		
Total	1845.882	14			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	2	3	4	5
0	3	109.06				
0.1	3		118.47			
0.4	3			131.25		
0.2	3				138.55	
0.3	3					146.59
Sig.		1.000	1.000	1.000	1.000	1.000

Table 9.30 Shear strength of banana fibre stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.850E7	4	4624721.811	1.147E4	.000
Within Groups	4031.558	10	403.156		
Total	1.850E7	14			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	2	3	4	5
0	3	319.12				
0.1	3		328.25			
0.4	3			341.44		
0.2	3				358.86	
0.3	3					364.55
Sig.		1.000	1.000	1.000	1.000	1.000

ANOVA shows that there is significant difference in the stability, strength and drain down characteristics for different percentages of banana fibre in the mixture at 1% level of significance. (sig < 0.01). Homogeneous groups are identified by Tukey's post hoc multiple comparison test and this clearly shows that all the characteristics of banana fibre stabilized SMA changed significantly at each percentage of fibre content and **the**

optimum value obtained at 0.3 % fibre content (by weight of mixture) for the banana fibre stabilized SMA, which differs significantly from the control mixture.

9.2.2 Optimum content of waste plastics and polypropylene in SMA mixtures

ANOVA analysis are carried out to find the influence of waste plastics and polypropylene in the characteristics of SMA and to identify the homogeneous groups, Tukey's post hoc multiple comparison test is carried out and arrived at the optimum additive content.

9.2.2.1 Waste plastics stabilized SMA

The results of the ANOVA analysis and Tukey's test for the WP stabilized SMA mixtures are given in Table 9.31 to 9.40. The optimum waste plastics content is obtained based on the results.

Table 9.31 Stability of waste plastics stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	74.791	5	14.958	367.452	.000
Within Groups	.488	12	.041		
Total	75.279	17			

Tukey's test

%	N	Subset for alpha = 0.05					
		1	2	3	4	5	6
0	3	7.42					
1	3		8.72				
3	3			11.18			
9	3				10.60		
5	3					13.12	
7	3						13.70
Sig.		1.00	1.00	1.00	1.00	1.00	1.00

Table 9.32 Bulk specific gravity of waste plastics stabilized SMA

ANOVA table

ANOVA					
Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.006	5	0.001	106.797	.000
Within Groups	1.373E-4	12	1.144E-5		
Total	0.006	17			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	2	3	4	5
9	3	2.356				
7	3		2.346			
5	3		2.336			
3	3			2.33		
1	3				2.326	
0	3					2.32
Sig.		1.00	1.00	1.00	1.00	1.00

Table 9.33 Indirect tensile strength of waste plastics stabilized SMA (unconditioned)

ANOVA table

Source	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	.416	5	.083	1004.27	.000
Within Groups	.001	12	.000		
Total	.417	17			

Tukey's test

%	N	Subset for alpha = 0.05			
		1	2	3	4
0	3	.8143			
1	3		1.0228		
3	3			1.1913	
5	3			1.2141	
9	3			1.2149	
7	3				1.2420
Sig.		1.000	1.000	.069	1.000

Table 9.34 Indirect tensile strength of waste plastics stabilized SMA (conditioned) ANOVA table

Source	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	1.443	5	.289	7292.07	.000
Within Groups	.000	12	.000		
Total	1.444	17			

Tukey's test

%	N	**Subset for alpha = 0.05**				
		1	**2**	**3**	**4**	**5**
0	3	.4253				
1	3		.8992			
3	3			1.1469		
9	3				1.1642	
5	3				1.1824	
7	3					1.2287
Sig.		1.000	1.000	1.000	.612	1.000

Table 9.35 Tensile strength ratio of waste plastics stabilized SMA

ANOVA table

Source	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	5055.071	5	1011.014	771.055	.000
Within Groups	15.735	12	1.311		
Total	5070.806	17			

Tukey's test

%	N	**Subset for alpha = 0.05**		
		1	**2**	**3**
0	3	52.23		
1	3		87.9210	
3	3			96.2679
9	3			95.8327
5	3			97.3917
7	3			98.93
Sig.		1.000	1.000	.380

Table 9.36 Compressive strength of waste plastics stabilized SMA at 25^{0}C

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3.308	5	.662	3286	.000
Within Groups	.002	12	.000		
Total	3.310	17			

Tukey's test

%	N	Subset for alpha = 0.05					
		1	2	3	4	5	6
0	3	5.0997					
1	3		5.4256				
9	3			5.8777			
3	3				5.9642		
5	3					6.2516	
7	3						6.3601
Sig.		1.000	1.000	1.000	1.000	1.000	1.000

Table 9.37 Compressive strength of waste plastics stabilized SMA at 60^{0}C

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	9.850	5	1.970	1946.85	.000
Within Groups	.012	12	.001		
Total	9.863	17			

Tukey's test

%	N	Subset for alpha = 0.05					
		1	2	3	4	5	6
0	3	4.1323					
1	3		5.0908				
9	3			5.6232			
3	3				5.7899		
5	3					6.1495	
7	3						6.2606
Sig.		1.000	1.000	1.000	1.000	1.000	1.000

Table 9.38 Drain down (%) of waste plastics stabilized SMA at 60^0C

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	101.413	5	20.283	453523.89	.000
Within Groups	.001	12	4.475E-5		
Total	101.414	17			

Tukey's test

%	**N**	**Subset for alpha = 0.05**			
		1	**2**	**3**	**4**
9	3	0.002			
7	3	0.017			
5	3	0.128			
3	3		1.489		
1	3			2.61	
0	3				6.50
Sig.		0.09	1.00	1.00	1.00

Table 9.39 Cohesion of waste plastics stabilized SMA

ANOVA table

Source	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	1569.293	5	313.859	9.936E3	.000
Within Groups	.379	12	.032		
Total	1569.672	17			

Tukey's test

%	**N**	**Subset for alpha = 0.05**				
		1	**2**	**3**	**4**	**5**
0	3	109.06				
1	3		122.34			
3	3			128.55		
5	3				140.82	
9	3				140.90	
7	3					145.55
Sig.		1.000	1.000	1.000	.994	1.000

Table 9.40 Shear strength of waste plastics stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.572E7	5	3144209.526	1.004E4	.000
Within Groups	3759.285	12	313.274		
Total	1.572E7	17			

Tukey's test

%	N	Subset for alpha = 0.05				
		1	2	3	4	5
0	3	319.12				
1	3		328.85			
3	3			342.54		
5	3				351.18	
9	3				351.78	
7	3					363.51
Sig.		1.000	1.000	1.000	.995	1.000

From the ANOVA analysis, it is evident that there is significant difference in various characteristics of waste plastics stabilized SMA for different percentages of WP at 1% level of significance (Sig. <0.01). Homogeneous groups are identified by Tukey's post hoc multiple comparison test. The results show that the various characteristics changed significantly at each percentage of waste plastics and the **optimal characteristics are obtained at 7% waste plastics content by weight of mixture.**

9.2.2.2 Polypropylene stabilized SMA

The results of the ANOVA analysis and Tukey's test for the PP stabilized SMA mixtures are given in Table 9.41 to 9.50. The optimum polypropylene content is obtained based on the results.

Table 9.41 Stability of PP stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	66.169	5	13.234	1.454E4	.000
Within Groups	.011	12	.001		
Total	66.180	17			

Tukey's test

% PP	N	Subset for alpha = 0.05					
		1	2	3	4	5	6
0	3	7.416					
1	3		8.252				
3	3			10.213			
9	3				10.52		
7	3					11.25	
5	3						12.8433
Sig.		1.000	1.000	1.000	1.000	1.000	1.000

Table 9.42 Bulk specific gravity of PP stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.005	5	.001	113.055	.000
Within Groups	.000	12	8.1E-6		
Total	.005	17			

Tukey's test

% PP	N	Subset for alpha = 0.05		
		1	2	3
0	3	2.320		
1	3	2.328		
3	3	2.338		
5	3		2.346	
6	3		2.355	
7	3			2.368
Sig.		.705	1.000	1.000

Table 9.43 Indirect tensile strength of PP stabilized SMA (unconditioned)

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.453	5	.091	162.959	.000
Within Groups	.007	12	.001		
Total	.460	17			

Tukey's test

% PP	N	Subset for alpha = 0.05			
		1	2	3	
0	3	.8143			
1	3		1.0076		
9				1.1245	
3	3				1.1337
7	3				1.1672
5	3				1.1693
Sig.		.835	1.000	1.000	.502

Table 9.44 Indirect tensile strength of PP stabilized SMA (conditioned)

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.747	5	.349	758.674	.000
Within Groups	.006	12	4.6E-4		
Total	1.752	17			

Tukey's test

% PP	N	Subset for alpha = 0.05			
		1	2	3	4
0	3	.4253			
1	3		.8619		
3	3			1.0555	
9	3			1.0400	
7	3				1.1300
5	3				1.1400
Sig.		.737	1.000	1.000	1.000

Table 9.45 Tensile strength ratio of PP stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	7210.570	5	1442.114	635.887	.000
Within Groups	27.215	12	2.268		
Total	7237.784	17			

Tukey's test

% PP	N	Subset for alpha = 0.05			
		1	2	3	
0	3	52.2584			
1	3		85.5489		
9	3			92.49	
3	3				93.1012
7	3				96.8129
5	3				97.4900
Sig.		.794	1.000	1.000	.058

Table 9.46 Compressive strength of PP stabilized SMA at 25^{0}C

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2.638	5	.528	288.899	.000
Within Groups	.022	12	.002		
Total	2.660	17			

Tukey's test

% PP	N	Subset for alpha = 0.05				
		1	2	3	4	5
0	3	5.0997				
9	3	5.1525				
1	3		5.2982			
7	3			5.5674		
3	3				5.8083	
5	3					6.0276
Sig.		1.000	1.000	1.000	1.000	1.000

Table 9.47 Compressive strength of PP stabilized SMA at 60^0C

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	9.950	5	1.990	1.125E3	.000
Within Groups	.021	12	.002		
Total	9.971	17			

Tukey's test

% PP	N	Subset for alpha = 0.05					
		1	2	3	4	5	6
0	3	4.1323					
9	3		4.4264				
1	3			4.8265			
7	3				5.1701		
3	3					5. 6018	
5	3						5.8954
Sig.		1.000	1.000	1.000	1.000	1.000	1.000

Table 9.48 Drain down (%) of PP stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	100.631	5	20.126	2.999E5	.000
Within Groups	.001	12	6.7E-7		
Total	100.631	17			

Tukey's test

% PP	N	Subset for alpha = 0.05			
		1	2	3	4
9	3	.004			
7	3	.0180			
5	3	.146			
3	3		1.497		
1	3			2.402	
0	3				6.4967
Sig.		.952	1.000	1.000	1.000

Table 9.49 Cohesion of PP stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	688.918	5	137.784	2.476E3	.000
Within Groups	.668	12	.056		
Total	689.586	17			

Tukey's test

% PP	N	Subset for alpha = 0.05				
		1	2	3	4	5
0	3	109.06				
1	3		122.85			
3	3			128.82		
9	3			128.825		
7	3				132.68	
5	3					139.52
Sig.		1.000	1.000	.271	1.000	1.000

Table 9.50 Shear strength of PP stabilized SMA

ANOVA table

Source	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	6908180.812	5	1381636.162	2.501E3	.000
Within Groups	6630.049	12	552.504		
Total	6914810.861	17			

Tukey's test

% PP	**N**	**Subset for alpha = 0.05**				
		1	**2**	**3**	**4**	**5**
0	3	319.12				
1	3		324.44			
3	3			338.24		
9	3			338.25		
7	3				342.45	
5	3					355.63
Sig.		1.000	1.000	.276	1.000	1.000

ANOVA analysis shows that there is significant difference in various characteristics of polypropylene stabilized SMA for different percentages of polypropylene at 1% level of significance (Sig. <0.01). Homogeneous groups are identified by Tukey's post hoc multiple comparison test. The tables show that the various characteristics changed significantly at each percentage of polypropylene, showing the influence of additives on the characteristics of SMA and **the optimal characteristics are obtained at 5% polypropylene content by weight of mixture.**

9.2.3 Comparison of fibre stabilized SMA

Comparison between fibre stabilized mixtures at optimum fibre content of 0.3% is carried out and the test results are given in Table 9.51 to 9. 61.

Table 9.51 Group Statistics

Parameters	fibre	N	Mean	Std. Deviation
Stability(kN)	Coir	3	12.5800	.22539
	Sisal	3	11.8620	.01510
	Banana	3	11.8540	.00200
Bulk sp.gravity	Coir	3	2.308	.00265
	Sisal	3	2.291	.00115
	Banana	3	2.286	.00153
ITS(unconditioned)	Coir	3	1.1242	.00053
	Sisal	3	1.1057	.00323
	Banana	3	1.1018	.00012
ITS(conditioned)	Coir	3	1.1048	.00060
	Sisal	3	1.0766	.00121
	Banana	3	1.0762	.00087
%TSR	Coir	3	96.42	.09515
	Sisal	3	97.37	.18682
	Banana	3	97.68	.06955
CS25^0 C	Coir	3	5.9622	.00552
	Sisal	3	5.7954	.00068
	Banana	3	5.7572	.00035
CS60^0 C	Coir	3	5.8680	.05616
	Sisal	3	5.6666	.00191
	Banana	3	5.5683	.00031
% Drain down	Coir	3	0	.00058
	Sisal	3	0.012	.00058
	Banana	3	0.014	.00000
Cohesion	Coir	3	166.67	.55537
	Sisal	3	150.68	.42852
	Banana	3	146.59	.26211
Shear strength(kPa)	Coir	3	384.63	55.58041
	Sisal	3	368.64	42.90922
	Banana	3	364.55	26.26376

Table 9.52 ANOVA table

		Sum of Squares	df	Mean Square	F	Sig.
Stability(kN)	Between Groups	1.043	2	0.521	30.647	.001**
	Within Groups	0.102	6	0.017		
	Total	1.145	8			
Bulk sp.gravity	Between Groups	2.667E-6	2	1.333E-6	26.375	.000**
	Within Groups	2.133E-5	6	3.556E-6		
	Total	2.400E-5	8			
ITS25	Between Groups	8.584E-4	2	4.292E-4	119.932	.000**
	Within Groups	2.147E-5	6	3.579E-6		
	Total	8.799E-4	8			
ITS60	Between Groups	0.002	2	8.095E-4	935.288	.000**
	Within Groups	5.193E-6	6	8.656E-7		
	Total	0.002	8			
%TSR	Between Groups	1.278	2	0.639	39.296	.000**
	Within Groups	0.098	6	0.016		
	Total	1.376	8			
CS25	Between Groups	0.081	2	0.040	3.892E3	.000**
	Within Groups	6.206E-5	6	1.034E-5		
	Total	0.081	8			
CS60	Between Groups	0.152	2	0.076	72.169	.000**
	Within Groups	0.006	6	0.001		
	Total	0.158	8			
% Drain down	Between Groups	8.956E-5	2	4.478E-5	201.500	.000**
	Within Groups	1.333E-6	6	2.222E-7		
	Total	9.089E-5	8			
Cohesion	Between Groups	493.925	2	246.963	1.321E3	.000**
	Within Groups	1.122	6	0.187		
	Total	495.047	8			
Shear strength(kPa)	Between Groups	4.938E6	2	2.469E6	1.318E3	.000**
	Within Groups	11,240.336	6	1,873.389		
	Total	4.949E6	8			

** significantly different at 1% level of significance

Table 9.53 Stability of fibre stabilized SMA Tukey's test

[

Fibre	N	Subset for alpha = 0.05	
		1	2
Banana	3	11.8540	
Sisal	3	11.8620	
Coir	3		12.5800
Sig.		.997	1.000

Table 9.54 Percentage drain down of fibre stabilized SMA Tukey's test

Fibre	N	Subset for alpha = 0.05	
		1	2
Banana	3	0.014	
Sisal	3	0.012	
Coir	3		0.000
Sig.		1.000	1.000

Table 9.55 Indirect tensile strength of fibre stabilized SMA

Tukey's test (unconditioned)

Fibre	N	Subset for alpha = 0.05	
		1	2
Banana	3	1.1018	
Sisal	3	1.1057	
Coir	3		1.1242
Sig.		.104	1.000

Tukey's test (conditioned)

Fibre	N	Subset for alpha = 0.05	
		1	2
Banana	3	1.0762	
Sisal	3	1.0766	
Coir	3		1.1048
Sig.		.840	1.000

Table 9.56 Percentage TSR of fibre stabilized SMA Tukey's test

Fibre	N	Subset for alpha = 0.05	
		1	2
Sisal	3	97.3682	
Banana	3	97.6765	
Coir	3		98.2743
Sig.		.064	1.000

Table 9.57 Compressive strength of fibre stabilized SMA

Tukey's test(25 ⁰C)

Fibre	N	Subset for alpha = 0.05		
		1	2	3
Banana	3	5.7572		
Sisal	3		5.7954	
Coir	3			5.9622
Sig.		1.000	1.000	1.000

*Tukey's test(60*⁰ C)

Fibre	N	Subset for alpha = 0.05	
		1	2
Banana	3	5.5683	
Sisal	3	5.5666	
Coir	3		5.8680
Sig.		.949	1.000

Table 9.58 Cohesion of fibre stabilized SMA

Tukey's test

Fibre	N	Subset for alpha = 0.05		
		1	2	3
Sisal	3	150.68		
Banana	3		146.59	
Coir	3			166.67
Sig.		1.000	1.000	1.000

Table 9.59 Shear strength of fibre tabilized SMA

Tukey's test

Fibre	N	Subset for alpha = 0.05	
		1	2
Banana	3	364.55	
Sisal	3	368.64	
Coir	3		384.63
Sig.		.992	1.000

The test results show that coir fibre stabilized SMA shows significantly highest compressive strength, indirect tensile strength, tensile strength ratio, stability, bulk specific gravity and least drain down compared to the other fibre stabilized mixtures with sisal and banana fibre. ANOVA analysis shows that there is significant difference in the characteristics of SMA mixture for different fibres (at an optimum fibre content of 0.3% by weight of mixture) at 1% level of significance (Sig. <0.01) showing the influence of additives on the characteristics of SMA. Homogeneous groups as identified by Tukey's post hoc multiple comparison tests reveal that SMA stabilized with sisal and banana fibre can be grouped into the same group. It is evident that **among the fibre stabilized mixtures, SMA mixture with 0.3% coir fibre by weight of mixture is the best.**

9.2.4 Comparison of waste plastics and polypropylene stabilized SMA mixtures

Comparison between WP and PP stabilized mixtures at optimum additive content (7% for waste plastics and 5% for polypropylene) are carried out using independent sample t-test to identify which SMA mixture gives the highest optimum value.

Table 9.60 Group Statistics

Parameters	cat	N	Mean	Std. Deviation
CS25^{0}C	Poly Propylene	3	6.028	0.041
	Waste plastics	3	6.360	0.007
CS60^{0}C	Poly Propylene	3	5.895	0.057
	Waste plastics	3	6.261	0.008
ITS(unconditioned)	Poly Propylene	3	1.169	0.001
	Waste plastics	3	1.242	0.004
ITS(conditioned)	Poly Propylene	3	1.135	0.000
	Waste plastics	3	1.2287	0.005
%TSR	Poly Propylene	3	97.49	0.109
	Waste plastics	3	98.93	0.368
Stability(kN)	Poly Propylene	3	12.843	0.025
	Waste plastics	3	13.700	0.020
% Drain down	Poly Propylene	3	0.146	0.001
	Waste plastics	3	0.017	0.001
Bulk sp.gravity	Poly Propylene	3	2.346	0.004
	Waste plastics	3	2.346	0.001
Cohesion	Poly Propylene	3	139.52	0.030
	Waste plastics	3	145.55	0.344
Shear strength(kPa)	Poly Propylene	3	355.63	0.810
	Waste plastics	3	363.51	0.356

Table 9.61 Independent Samples t-Test

	Levene's Test for Equality of Variances		t-test for Equality of Means		
	F	Sig.	t	df	Sig.
CS25^{0}C	3.332	.142	-13.959	4	.000**
CS60^{0}C	3.044	.156	-9.123	4	.001**
ITS(unconditioned)	2.458	.192	-30.862	4	.000**
ITS(conditioned)	5.987	.071	-29.797	4	.000**
%TSR	5.952	.071	-4.692	4	.009**
Stability(kN)	.203	.676	-35.382	4	.000**
% drain down	3.200	.148	20.125	4	.000**
Bulk sp.gravity	3.028	.157	2.747	4	.052
Cohesion	13.341	.022*	-42.824	2	.000**
Shear strength(kPa)	13.495	.021*	-42.838	2	.000**

* significant at 5% level of significance

** significant at 1% level of significance

The t-test shows that there is no significant difference in bulk specific gravity. In all other parameters, waste plastics have significantly higher values than polypropylene.

9.2.5 Comparison of SMA mixtures with waste plastics and coir fibre

It is identified that SMA stabilized with WP is better than that with PP and SMA stabilized with Coir fibre is better among the fibre stabilized mixtures. A comparison between SMA stabilized with WP and Coir fibre with respect to various parameters are carried out using t-test for independent samples and the results are given below.

Table 9.62 Comparison between WP and coir fibre stabilized SMA

Parameter	Fibre	Mean	Std. Deviation	t-value	p-value
CS25^{0}C	Waste plastics	6.3601	.00746	74.257	0.000*
	Coir	5.9622	.00552		
CS60^{0}C	Waste plastics	6.2606	.00792	11.991	0.000*
	Coir	5.8680	.05616		
ITS(Unconditioned)	Waste plastics	1.2420	.00386	52.334	0.000*
	Coir	1.1242	.00053		
ITS(Conditioned)	Waste plastics	1.2287	.00490	40.108	0.000*
	Coir	1.1048	.00060		
%TSR	Waste plastics	98.93	.36807	6.502	0.002*
	Coir	98.27	.09515		
Stability(kN)	Waste plastics	13.7000	.02000	7.042	0.002*
	Coir	12.5800	.22539		
% drain down	Waste plastics	.017	.00115	-33.541	.000*
	Coir	0	.00058		
Bulk sp.gravity	Waste plastics	2.346	.00115	7.400	.002*
	Coir	2.308	.00265		
Cohesion	Waste plastics	145.55	.34356	-54.946	.000*
	Coir	166.67	.55537		
Shear strength(kPa)	Waste plastics	363.51	34.35598	-54.953	.000*
	Coir	384.63	55.58041		

*Significantly different at 1% level of significance

The mean values of stability, bulk specific gravity, compressive strength and tensile strength values of waste plastics stabilized Stone Matrix Asphalt is optimal. The t-test reveals that the values of the above properties for waste plastics stabilized SMA is significantly higher than that of coir fibre stabilized SMA at 1% level of significance (p-value<0.01). Cohesion and shear strength are significantly higher for coir fibre stabilized SMA compared to waste plastics stabilized SMA.

9.3 SUMMARY

Statistical Analysis has been done by using SPSS package Ver.16. The optimum additive contents of every mix are determined with respect to different parameters like stability, bulk specific gravity, tensile strength, compressive strength, cohesion, shear strength and drain down characteristics of the SMA mix. The significance of differences in mean values of parameters at various levels of additive contents are tested by ANOVA. Comparison of different additive stabilized mixtures at these optimum contents are carried out to arrive at the best fibre additive from the fibre stabilized mixtures by ANOVA and also the best additive among the waste plastics and polypropylene stabilized mixtures by paired t- test. A pair wise comparison is made between the best among these stabilized mixtures by t-test for independent samples to suggest the best Stone Matrix Asphalt mixture.

ANOVA analysis shows that there is significant difference in the properties of SMA at different percentages of additive at 1% level of significance indicating the influence of additives on the strength, stability and drain down characteristics of stabilized SMA. From the Tukey’s multiple comparison tests, homogeneous groups are identified and arrived at the optimum fibre content as 0.3% by weight of mixture for fibre stabilized SMA mixtures and 7% by weight of mix for waste plastics and 5% by weight of mix for polypropylene stabilized SMA mixtures.

Homogeneous groups as identified by Tukey’s post hoc multiple comparison tests reveal that SMA stabilized with sisal and banana fibre can be grouped into the same group. It is evident that among the fibre stabilized mixtures, SMA mixture with 0.3% coir fibre by weight of mixture is the best.

The t-test shows that there is no significant difference in bulk specific gravity for SMA with waste plastics and polypropylene. In all other properties, waste plastics stabilized SMA is having significantly higher values than polypropylene stabilized SMA.

The mean values of stability, bulk specific gravity, compressive strength and tensile strength values of waste plastics stabilized Stone Matrix Asphalt is optimal. The t-test reveals that the value of the above properties for WP stabilized SMA is significantly higher than that of coir fibre stabilized SMA at 1% level of significance (p-value<0.01). It can be concluded that waste plastics stabilized Stone Matrix Asphalt mixture is the best among the mixtures investigated.

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Chapter 10

SUMMARY AND CONCLUSIONS

10.1 INTRODUCTION

Annual increase in maintenance expenditures demands the urgent need for building durable and efficient roads. Severe climatic conditions, growing traffic volume and insufficient drainage conditions results in faster deterioration of the pavements in Kerala. Stone matrix Asphalt (SMA) has proved to be the right choice to handle such situations. This research is an attempt to study the influence of additives in improving the characteristics of SMA mixtures and to propose a durable surface course.

This chapter presents summary and conclusion of this study based on the various objectives addressed.

10.2 SUMMARY

Additives are added to improve the characteristics of SMA, which is a gap graded mixture with rich binder content. The influence of additives, both natural fibres and polymers on the characteristics of SMA is studied. The natural fibres like coconut fibre, sisal fibre, banana fibre and a polymer, polypropylene are used as additives. Moreover, the use of waste plastics as an additive to SMA is also explored. The SMA mixture without any additive is taken as the control mixture. The volumetric and stability characteristics are studied by Marshall tests and the strength characteristics by indirect tensile strength tests, compressive strength tests and triaxial strength tests. The drain down sensitivity of the mixture is also studied by a drain down apparatus. Statistical Analysis is conducted to test the significance of various mix types considered in this research. Major conclusions of this research are discussed in the succeeding sections.

10.3 CONCLUSIONS

The major conclusions deduced from this study are presented in five different sections - influence of additives in SMA, comparison of fibre stabilized mixtures, comparison of mixtures with polypropylene and waste plastics, comparison of various stabilized mixtures and statistical analysis of the test results.

10.3.1 Influence of additives in SMA

Additives influences the characteristics of SMA mixtures by showing an enhancement in strength and stability, reduction in water induced damages and drain down, while maintaining the specified volumetric characteristics.

10.3.1.1 Volumetric and stability characteristics

Marshall Stability test results show that:

- The air voids of stone matrix asphalt mixtures increase after adding fibres into the mixture due to the net working effect of the fibres within the mix. Owing to the filling property offered by the additives waste plastics and polypropylene resulted in less air voids in the mixture as compared to the control mixture. However, the air voids of all mixtures are located within the required specification range of 3 to 5% (AASHTO T 312) which support the use of these additives.
- Increasing the fibre additive content in the SMA mixture resulted in an increase in the voids in mineral aggregate (VMA) and a reduction in voids filled with bitumen (VFB) values. But the values of VMA decreases and VFB increases by the addition of waste plastics and polypropylene additives to the SMA mixtures. But VMA values are within the required specification range of 17% minimum, which also supports the use of these additives.
- The bulk specific gravity of SMA mixtures slightly decreases with the addition of fibre additives and increases with waste plastics and polypropylene additives. This is due to the variations in air voids in the mixture as compared to the control mixture.

- With the increase in the percentage of additives in the SMA mixture, Marshall stability and Marshall quotient values increase with respect to the control mixture showing its better resistance against permanent deformations. The maximum values for these properties are obtained at 0.3% fibre content irrespective of the type of fibre, 5% polypropylene content and 7% waste plastics content by weight of mix. Beyond this percentage of additives, the results show a decreasing trend.
- Flow value of SMA mixtures decreases due to the addition of fibres. The mixes become less flexible resulting in a low flow value. By adding waste plastics and polypropylene to SMA mixtures, flow value of mixtures decreases initially (up to 7% WP and 5% PP) and after that there is an increase due to the decrease in the stone to stone contact of mixtures. However, flow values are located within the required specification range of 2 to 4mm (AASHTO T 245) supporting the use of additives in SMA mixtures.

10.3.1.2 Strength characteristics

Based on the indirect tensile strength test, compressive strength test and triaxial strength test, the following conclusions can be drawn.

- The mixtures containing additives have higher values of indirect tensile strength at failure under static loading as compared to the control mix, indicating the improved cracking potential of SMA mix.
- The effect of additive in increasing the indirect tensile strength value of SMA mix is more influential in the conditioned state due to the improved adhesion property.
- Presence of additives strengthen the bonding between the aggregates provided by the binder and thereby enhancing the stone to stone contact which will result in increasing the resistance to crushing. This gives rise to a stiffer and tougher mix with considerable improvement in compressive strength.
- It is also observed that with respect to the control mixture, the compressive strength of stabilized mixtures decreases with increase in temperature. But the

percentage decrease in strength is less with the increase in additive content up to a certain level.

- SMA stabilized mixtures has the highest cohesion and shear strength as compared to the control mixture, proving its rutting resistance against shear. This result is in agreement with the higher peak stress and the extended duration of its occurrence, which can be attributed to the role of additives as an additional reinforcement to the bituminous mixtures in resisting permanent deformation and retarding the occurrence of shear failure.
- The influence of additives on the value of angle of internal friction of SMA mixture is very less.
- Due to the presence of additives in SMA mixture tangent modulus of the mix increases with increasing confinement pressure, indicating their stress dependent behaviour and its improved elastic stiffness.
- For stabilized mixtures, it is also observed that the shape change of the stress-strain curves is more gradual with increase in additive content and brittle type failure does not seem to occur as in the case of control mixture.

10.3.1.3 Moisture susceptibility

The retained stability value, tensile strength ratio and index of retained strength which are the indicators of the 'extent of moisture induced damage' shows that all stabilized SMA mixtures exhibits higher values against the lower values of control mixture. This support the influence of additives in significantly reducing the water induced damages of the SMA mixture. In addition, it also indicates that additives do not cause the mixture to weaken when exposed to moisture.

- The values of retained stability, tensile strength ratio and index of retained strength for the control mixture is less than the required minimum values of 70% (LS 283), 70% (AASHTO T 283) and 75% (ASTM D 1075) respectively. When additives are added, these values are enhanced to above 90%.

10.3.1.4 Drain down sensitivity

The potential effects of the inclusion of additives in SMA mixtures are beneficial in preventing the bleeding phenomenon of the mixtures and the drain down of SMA mix. The role of additive is to stiffen the mastic and thereby reducing the drainage of the mixture at high temperatures during storage, transportation, placement and compaction of SMA mixture.

- All the five additives used in the SMA mixture for the present investigation act as an effective stabilizing agent and provide significant stabilization to the mixture as compared to the control mixture.
- Due to the gap graded gradation and rich binder content in SMA, the control mixture is subjected to heavy drain down of 6.5% which is beyond the specified limits of 0.3% by weight of mix. The presence of additives in the SMA mix bring down the drain down of the mixture to the specified level. This again supports the need of the additive in SMA mixtures.

10.3.2 Fibre stabilized SMA

Optimum fibre content of fibre stabilized mixtures and the best fibre additive is arrived by analysing the volumetric, mechanical, moisture susceptibility and drain down characteristics of the SMA mixture with various fibre additives such as coir, sisal and banana fibre. In this research, fibre length is kept as constant (6 mm) and the content is varied from 0.1% to 0.4% at an increment of 0.1% by weight of mixture.

10.3.2.1 Stability and volumetric characteristics

- Irrespective of the type of fibre, the maximum values of stability, Marshall Quotient and bulk specific gravity of SMA mixtures are obtained at 0.3% fibre content.
- Comparing different types of fibre stabilized SMA mixtures, mixtures with coir fibre have the highest stability (12.58 kN), indicating their higher rutting resistance and better performance than mixtures with other fibres. The percentage increase in stability with respect to the control mixture is about 70% for SMA with coir fibre and about 60% for SMA with other fibres.

- Flow value of SMA mixtures decreases after adding fibres. Owing to the stiffness of fibres in the mixture, the mixes become less flexible resulting in a low flow value. However, flow values of all SMA mixtures are located within the required specification range of 2 to 4 mm.

- The Marshall quotient of coir fibre stabilized SMA mixture at 0.3 % fibre content is almost doubled with respect to the control mixture, indicating its better resistance against permanent deformations and also indicates that these mixtures can be used in pavements where stiff bituminous mixture is required.

- Coir fibre stabilized SMA has the highest bulk specific gravity when compared to mixes with other fibres. Since higher specific gravity results in better design mixes, the coir fibre stabilized mixtures perform better than other stabilized mixtures considered.

- Considering the volumetric characteristics, at 0.3% fibre content, air void increases by 11.5%, VMA increases by 2.2%, while VFB decreases by 2.4% for coir fibre stabilized mixtures. The percentage changes are respectively 9.25% increase for air void, 5.4% increase for VMA and 1% decrease for VFB in sisal fibre stabilized mixtures. Whereas 8.5% increase in air voids, 5.9% increase in VMA and 1% decrease in VFB are observed in banana fibre stabilized mixtures. But all the volumetric characteristics are within the required specification range which also supports the use of these fibre additives.

10.3.2.2 Strength characteristics

- All the fibre stabilized SMA mixtures has the maximum tensile strength at 0.3% fibre content. The coir fibre stabilized SMA exhibits the highest tensile strength showing its higher cracking resistance as compared to the other fibre stabilized mixtures. The percentage increase in strength with respect to the control mixture is 38% for unconditioned and 160% for conditioned samples for the coir fibre stabilized mixture, whereas around 35% and 153% for both sisal and banana fibre stabilized mixtures respectively.

- Fibre reinforcing effect increases initially with increasing fibre content in SMA, but at high fibre content (more than 0.3%) induce coagulation and thus reduce its reinforcing effect, resulting in less stiff mixture with lower strength values.
- From the compressive strength test results, all fibre stabilized mixtures show the maximum value of compressive strength at 0.3% fibre content. SMA with coir fibre exhibits higher compressive strength as compared to the other fibre stabilized mixtures indicating its higher crushing resistance.
- It can be observed that the percentage increase in compressive strength with respect to the control mixture at 0.3% fibre content for coir fibre stabilized mixes at 25˚C and 60˚C are 17% and 42% respectively. Similarly, the percentage increase in strength is about 14% and 37% at 25˚C and 60˚C respectively for SMA with sisal fibre and is about 13% and 35% at 25˚C and 60˚C when banana fibre is added.
- All the stabilized mixtures give the highest cohesion at 0.3% fibre content, irrespective of the type of fibre. The cohesion values are found to be decreasing when additive contents increased beyond this percentage.
- All fibre-stabilized mixes has the same angle of internal friction. The cohesion value increases approximately from 100 kPa in control mixture to 170 kPa in SMA mixtures with coir fibre, showing a percentage increase of about 53% exhibiting their higher resistance to shearing stresses than the other fibre stabilized mixtures, which shows 38% and 26% respectively for sisal and banana fibre.
- Coir stabilized SMA mixture shows the maximum shear strength of about 385kPa at 300 kPa normal stress. The percentage increase in strength of this mixture is about 21% with respect to the control mixture, showing their much greater resistance to shearing stresses. Sisal and banana fibre mixtures seem to deviate less from each other.
- The percentage increase in stress at failure is about 67% and strain at failure is 44% at 100kPa confinement pressure for coir fibre stabilized SMA with respect to the control mixture.

- The presence of fibre in the mix enhances the elastic stiffness of the SMA mixture, showing a substantial increase in tangent modulus with respect to the control mixture for the coir fibre mix.

  The test results converge to the conclusion that the best performance of the Stone Matrix Asphalt mixture is at 0.3% fibre content and with coir fibre.

10.3.2.3 Moisture susceptibility

- The presence of fibres in SMA mixtures gives the higher retained stability, tensile strength ratio and index of retained strength at 0.3 % fibre content by weight of mix and the best performance is exhibited by SMA with coir fibre indicating its higher resistance to moisture induced damages.

10.3.2.4 Drain down sensitivity

Fibres have a much higher stabilizing effect than the other additives, as they firmly bind the aggregate particles inside the matrix and prevent them of movement and make the mix stiffer.

- Due to the absorptive nature of fibres, fibre stabilizers are found to be effective in reducing the drain down of the SMA mixtures. Among the fibre stabilized mixtures, coir fibre reaches the 0% drain down at 0.3% fibre content.
- The coir fibre had the highest stabilizing capacity of 16% followed by sisal and banana fibre.

Based on the volumetric, mechanical and drain down characteristics of the various fibre stabilized mixtures it can be concluded that ***the optimum fibre content of the fibre stabilized Stone Matrix Asphalt mixture is 0.3% by weight of mixture and the coir fibre additive is the best among the fibres investigated.***

10.3.3 Polypropylene and waste plastics stabilized SMA

A polymer, polypropylene and a waste material, waste plastics are also tried as additives in SMA mixture. The additive content is varied from 1% to 9% at an increment of 2% by weight of mixture. Optimum additive content of the stabilized mixtures and the best additive among this is arrived from the volumetric, mechanical, moisture susceptibility and drain down characteristics of the SMA mixture with these additives at different proportions.

10.3.3.1 Volumetric and stability characteristics

- Owing to the filling property offered by the waste plastics and polypropylene additives, the stabilized mixtures resulted in a less air void as compared to the control mixture and other fibre stabilized mixtures. But the results are within the specified limit of 3 -5%. But VMA values of these mixtures shows a decreasing trend but VFB values, an increasing trend, which is opposite to the trend shown by fibre stabilized mixtures. But all the results are within the specification range.
- The addition of 5% polypropylene raises the Marshall stability of control mix by 73% and that of 7% waste plastics by 82% and at these additive contents, a reduction in flow value (within the specified limit of 2 to 4 mm) is observed due to the enhanced interlocking of aggregates in the mixture. Beyond this percentage of additive content, the stability value decreases. The mixtures with waste plastics have higher stability (13.7 kN) than mixtures with polypropylene and fibres, indicating their higher rutting resistance. The reduction in flow value increases its resistance to plastic flow.
- The Marshall quotient of SMA mixture is almost doubled with respect to the control mixture at 5% PP content and 7% WP content and slightly higher with the additive, waste plastics, showing its better resistance against permanent deformations.
- Bulk specific gravity increases with an increase in waste plastics and polypropylene content in SMA. Both additive contents show almost the same trend and the values are greater than the fibre stabilized mixtures.

10.3.3.2 Strength characteristics

- The maximum values of indirect tensile strength, compressive strength and shear strength are obtained for the SMA mixtures with 5% PP content and 7% WP content and the strength decreases beyond this additive content.

- SMA mixture stabilized with waste plastics exhibit higher indirect tensile strength than polypropylene stabilized mixtures showing its capability to withstand slightly larger tensile strains prior to cracking.
- Waste plastics stabilized SMA mixtures shows the highest compressive strength than the polypropylene stabilized mixtures indicating its higher resistance to crushing.
- Waste plastics stabilized SMA mixtures show slightly higher cohesion value than the polypropylene stabilized mixtures, showing its greater resistance to shearing stresses. The values of the angle of internal friction of both mixtures are the same.
- Strain and stress at failure for waste plastics stabilized SMA is slightly higher than that of polypropylene stabilized mixtures. The values of tangent modulus for both mixtures are almost the same indicating the same elastic stiffness.

10.3.3.3 Moisture susceptibility

- The retained stability of the mixture increases with increasing additive content up to 7% for waste plastics and 5% for polypropylene and after that it is found to be decreasing.
- Waste plastics stabilized SMA mixture exhibits the maximum retained stability and index of retained strength of about 98% and a tensile strength ratio of about 99% showing its higher protection against water damage.

10.3.3.4 Drain down sensitivity

- At 5% PP and 7% WP content, the drain down of the mixes is within the required specified limits, indicating the effects of these additives in SMA mixtures to prevent the bleeding and the drain down of mixtures.
- The waste plastics and polypropylene have almost similar stabilizing capacities, but less than that of fibre stabilized mixtures.

Based on the volumetric, mechanical and drain down characteristics of these mixtures it can be concluded that, the optimum additive content for SMA mix with waste plastics is 7% and for polypropylene, it is 5%. Waste Plastics, which is the best additive among this, showing better resistance to rutting, cracking, crushing, shearing and stripping off and also the superior water resistance property, can replace the expensive polymers in SMA mixtures.

10.3.4 Comparison of various stabilized mixtures

- Test results have illustrated that, the type of additive and its content play significant roles in the volumetric and mechanical properties of bituminous mixtures. Results show that different additives have different reinforcing effects.
- Regarding the volumetric characteristics, fibre stabilized mixtures show higher air voids and voids in mineral aggregates than the other mixtures, but the voids filled with bitumen is more in waste plastics stabilized mixtures. But in all stabilized mixtures, the results are within the specification range.
- It is observed that SMA mixes with 7% waste plastics has the highest Marshall stability, Marshall quotient, bulk specific gravity, indirect tensile strength and compressive strength showing its better resistance against permanent deformations, cracking and crushing as compared to other stabilized mixtures.
- The flow values of fibre stabilized mixtures are slightly more than that of waste plastics stabilized mixture.
- All the stabilized SMA mixtures show higher retained stability, tensile strength ratio and index of retained strength. The addition of 7% waste plastics in the SMA mixture gives the best result and exhibit superior water resistance property.
- When compared with the control mixtures, coir fibre stabilized mixtures has 1.5 times higher cohesion and waste plastics stabilized mixtures has 1.3 times higher value. Coir stabilized mixtures has the maximum shear strength when compared to other mixtures.
- In all stabilized SMA mixtures, due to the absorptive nature of fibres, fibre stabilizers are found to be more effective in reducing the drain down than the waste plastics and polypropylene additives. But all SMA mixes with additives at optimum bitumen content satisfy the specified drain down values.

- The effective utilization of the waste plastics for SMA mixtures will result in substantial increase in the scrap value for this otherwise undesirable waste material, which are getting littered all over the area. This will also lead to an ecofriendly sustainable construction method.

10.3.5 Statistical Analysis of the test results

Statistical Analysis using SPSS package Ver.16 verified the precision of the results of various experimental programmes.

- ANOVA analysis shows that there is significant difference between different percentages of additives in SMA at 1% level of significance indicating the influence of additives on the strength, stability and drain down characteristics of SMA mixtures.
- From the Tukey's multiple comparison tests, homogeneous groups are identified and arrived at the optimum additive content for SMA mixtures as 0.3%, 5% and 7% by weight of mix with fibres, polypropylene and waste plastics respectively.
- A comparison of different fibre stabilized mixtures at optimum contents are carried out by ANOVA and arrived at the best fibre additive as coir fibre.
- The t-test show that waste plastics stabilized SMA is having significantly higher values than polypropylene stabilized SMA for all properties except in bulk specific gravity.
- The t-test reveals that the mean values of stability, bulk specific gravity, compressive strength and tensile strength for waste plastics stabilized SMA is significantly higher than that of coir fibre stabilized SMA at 1% level of significance (p-value < 0.01). But the values of cohesion and shear strength are significantly higher for coir fibre stabilized SMA as compared to waste plastics stabilized SMA.
- A pair wise comparison between the best among these stabilized mixtures (coir fibre stabilized and waste plastics stabilized) by t-test for independent samples shows that waste plastics stabilized SMA mixture is the best.

The results of this research clearly establish the influence of additives in the performance of SMA. Among the additives investigated, waste plastics have great promise as an environmental friendly sustainable material. The comprehensive evaluation of this waste plastics stabilized Stone Matrix Asphalt mixture strengthens the confidence level in the field application of this material as an ideal surface course.

10.4 SCOPE FOR FURTHER RESEARCH

Further research is recommended on the following aspects:-

Long term Performance Evaluation - This research was mainly concentrating on the laboratory investigations. Hence the results of this research are to be ascertained in the field by constructing experimental test tracks, monitoring and conducting long term performance evaluation under varying traffic and environmental conditions.

Fatigue failure resistance & Rutting Characteristics - Repeated load testing can give us an idea about the fatigue failure resistance of the bituminous mixtures. This can be recommended for further research to assess the effect of additives on fatigue behavior. Hamburg wheel tracking Test can be recommended for the further study of rutting characteristics, which are already arrived in this research by Marshal stability test and Triaxial test.

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