PERFORMANCE EVALUATION OF OPEN GRADED FRICTION COURSE AND STONE MATRIX ASPHALT MIXES

Ph. D. THESIS

by

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ABSTRACT

Hot Mix Asphalt (HMA) is a bituminous mixture of coarse aggregate, fine aggregate, filler and binder, where all constituents are mixed, placed and compacted at high temperature. HMA can be dense graded mixes known as Bituminous Concrete (BC) and Dense Graded Bituminous Macadam (DBM), gap graded mix known as Stone Matrix Asphalt (SMA) or open graded mix known as Porous or Open Graded Friction course (OGFC).

The research work is laboratory evaluation of Stone Matrix Asphalt (SMA) and Open Graded Friction course (OGFC) mixes using modified binders and Warm Mix Asphalt (WMA), in comparison to convention asphalt for use as a surface course in India. SMA and OGFC mixes are new generation of asphalt pavement being designed for special purpose, used for surface courses only. SMA mix is for rut resistance and durable pavement. OGFC or Porous mixes are for storm or rain water management technique, which provide better surface friction quality, especially in wet weather. SMA and OGFC mixes have qualities of reducing splash & spray, noise reduction and provide high speed road network especially used at high traffic volume. Both the pavement mixtures may be beneficial for economic development of country by providing better road transportation.

In many countries SMA and OGFC mixes are successfully being constructed and performing very well. But in India, both type of mixtures are not in use and also not

having proper specifications for design and construction. In India, only trial stretches of SMA pavement were laid in some places whereas, rutting or permanent deformation is common distress on Indian roads. Porous pavement is very important when concern water scarcity or rain water runoff and evaporation problem in INDIA. But there is not any guideline, standards or specifications for implementation of these type of mixtures for Indian pavements.

This study is an effort to evaluate pavement performance of Stone Matrix Asphalt (SMA) and Open Graded Friction Course (OGFC) using nearby available construction materials to ensure satisfactory performance of these pavements in India. Engineering properties of OGFC and SMA mixtures with different asphalt binders were tested, through laboratory test developed for dense graded mixtures and standards and specifications of National Center of Asphalt Technology (NCAT), updates of the design procedure found in Federal Highway Administration Report (FHWA), National Asphalt Pavement Association (NAPA). During the research work Ministry of Road Transport and Highway (MoRTH, 2013) has also publish specifications for construction of SMA mixes, which were also incorporated.

For this research work five mix designs were done with five different binder types; one conventional bitumen (VG-30), two modified bitumen (PMB-40 and CRMB-55), two warm mix asphalt (produce by using dose of Evotherm and Zycotherm chemical additive in PMB-40 as a base binder). Which will assist in characterizing and understanding effect of using polymer modifier binder and warm mix asphalt technology in comparison to Plain bitumen of Viscosity Grade 30/ penetration grade 60/70 (VG-30). Selection of binder type was done as per climate condition (temperature condition) of Rajasthan.

Use of Crumb Rubber Modified Binder (CRMB), will help in solving the disposal problem of Low density Polythene (LDPE) and will also improve quality of mix.

Warm Mix Asphalt (WMA) is an energy-efficient and environmentally friendly product that significantly lowers mixing, production, placing and compaction temperatures of asphalt mixes up to 35 to 45°C. Such drastic reduction in temperature requirement of HMA, have the benefit of less fuel consumption and so, decreases production of greenhouse gases, CO_2 emissions and overall decrease in site temperature, also provide better working condition for labor and better compaction of mixes and increased paving season etc.

Pavement performance in terms of pavement stiffness, moisture susceptibility, elasticity property, permanent deformation and rut depth of mixtures is measured by the Indirect Tensile Strength(ITS), Tensile Strength Ratio (TSR), Resilient modulus of Elasticity (Mr), Dynamic Creep and Wheel Rut Depth tests.

Results showed that using polymer modified binders and WMA (even at lower mixing and compaction temperature) instead of unmodified asphalt/ plain bitumen improved the performance of the Stone Matrix Asphalt and Open-Graded Friction Course Mixture.

A final comparative study of both the type of mixtures is also done, which will help in selecting a design mix on the basis of purpose of road construction or particular demand of the area where road have to be planned.

KEY WORDS: open-graded friction course, stone matrix asphalt, mix design, polymer modified binder, warm mix asphalt, fiber, draindown, abrasion, moisture susceptibility, deformation and rutting.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transport Officials
ASTM	American Society for Testing and Materials
BC	Bituminous Concrete
CRMB-55	Crumb Rubber Modifier binder of penetration grade-55
DBM	Dense Bituminous Macadam
FHWA	Federal Highway Administration
Gmb	Bulk Specific Gravity of the Mix
Gsb	Bulk Specific Gravity of the Aggregate
Gmm	Specific Gravity of the Mix
HMA	Compacted Hot-Mix Asphalt
HWTD	Hamburg Wheel-Track Device
IRC	Indian Road Congress
IS	Indian Standards
ITS	Indirect Tensile Strength
M_R	Resilient Modulus
NAPA	National Asphalt Pavement Association

NCAT	National Center for Asphalt Technology
OBC	Optimum Binder Content
OGFC	Open-graded Friction Course
PMB-40	Polymer Modifier Binder of penetration grade-40
SMA	Stone Matrix Asphalt
TSR	Tensile Strength Ratio
VCA_{DRC}	Voids in coarse aggregate fraction only in dry-rodded condition
VCA_{MIX}	Voids in coarse aggregate skeleton
VFB	Voids Filled with Bitumen
VG-30	Plain bitumen of Viscosity Grade-30
VMA	Voids in Mineral Aggregates
VTM	Voids in Total Mix
WTD	Wheel Tracking Device
WMA	Warm Mix Asphalt

Note: The other symbols used in the text are explained as and when they are introduced

CHAPTER 1

INTRODUCTION

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1.1 General

The earliest traced modern roads were as far as 1500 B.C. in Rome. Between 300 B.C. and A.D.300, Romans built over 50,000 miles of well planned road network, some of which remains today. In 1599 classification of asphalt was done and efforts were started to find connection between asphalt and petroleum. In 1777, P.C. Lesage explain the theory of origin of asphalt. In 1802, first time rock asphalt was used for surfacing of bridge deck and sidewalk. John L. Mc. Adam started improvement of roadways by interlock and compaction of stone surface, in 1815. This "macadam " innovation lead to development of modern roads in Paris in 1858 and compacted asphalt pavement in London in 1869. This bitumen bound aggregates were started to use all over the word. In the late 1800's, development of the automobile, arose the need to provide safer and smoother road network for heavier vehicle.

Normally the performance of well, uniform, dense and close graded aggregates with plain bitumen and proper design and execution, under normal traffic and environmental condition is satisfactory. But due to the issue related to safety and comfort of road users being adversely affected by "Rutting" and permanent deformation with Dense Graded Mixture, a new more durable and stable gap, graded mixture i.e. Stone Matrix Asphalt (SMA) have to designed. And the matter of weather problems of higher incidences of skid related accidents crash during wet weather, raises need of development of open graded friction course i.e. porous pavement for providing users a roadway that is “reasonably” safe.

Both Open Graded Friction Course (OGFC) and Stone matrix Asphalt (SMA) are the New generation of Hot Mix Asphalt (HMA) mixes, used as surface mixtures only.

Porous pavement surface has been started to apply in United States in mid 1940s, as simple concrete "turfblocks" to address storm water flooding in the larger cities of the United States. (Mathew 2014). The concept of porous asphalt was proposed in 1960, so as to reduce storm water, raise water table and replenish aquifer. A design guide published at the Franklin Institute in Philadelphia, provided great initial reference for many porous pavement constructed since today (NAPA 2008). With proper design and construction material, no failure were shown. In porous pavement, maintenance is main warning, clogging of surface must be prevented.

Stone Mastic Asphalt (SMA) has been developed during 1960s in Germany to resist permanent deformation and shown better result in the United States as a stable and durable surface mixture. Gap graded structure of the mix with maximum coarse aggregate content, provide the mix stone-to-stone skeleton.

1.2 OPEN GRADED FRICTION COURSE

Open Graded Friction Course is a porous Hot Mix Asphalt (HMA) mix, used as surface course in permeable pavement. This mix is a new improve way to protect the environment by controlling wastage of precious "rain-water". OGFC pavement surface allow water to drain through permeable surfaces into a stone recharge bed and infiltrate into the soils below the pavement. For temporary storage of rain water, an aggregate sub base reservoir provides underneath the porous asphalt.

A porous asphalt pavement is a storm water management technique which differs from other asphalt pavement designs, as open gradation and structure of porous pavement make fluid to quickly pass through it thus reducing the amount of run-off from the adjacent area.

Open Gradation of the mix is because of coarse texture surface and high and interconnected air void content throughout the mix. Uniformly graded aggregates with very little fines is used. 50-60 % of coarse aggregate is taken as of same particle size with less fines. Aggregate passing 2.36 mm sieve is kept less than 20% in the mix, which is very less fines in comparison to dense graded mixture.

Effective service life of porous pavement is 7 to 10 years, with the proper design and installation and maintenance practice these pavements provide attractive and cost effective pavement with a more than twenty years life span. OGFC surface course provide aesthetically attractive and safer pavement with storm water management systems that promote infiltration, improve water quality, and many times eliminate the need for detention basin. Environmental benefit and safety performance of these mixes makes them better than traditional HMA pavement. Economic benefit of these pavement are to reduce the need for traditional storm water infrastructure, reduces soil erosion, controls the amount of run-off from the surrounding area by allowing precipitation and run-off to flow through the structure.

Strength of a open gradation mixes depends on underlying structure. In case of low traffic pavement, parking lots, shoulders, sidewalks, pathways, drains, noise barriers area, tennis courts, patios, zoo areas, green house floors and swimming pool decks porous asphalt pavement solely can be used for pavements. For high traffic and heavy wheel loads porous asphalt pavement are constructed with underline sub-base and base structure.

They reduce splash and spray from tires in wet weather and typically result in a smoother surface than dense-graded HMA. OGFC mixtures should only be used on high speed and high traffic volume. Higher speed traffic reduced the clogging of pores due to debris.

Although, porous pavement are being used worldwide successfully due to its environmental benefit and better performance, these type of pavement are still not so much in practice in INDIA.

1.3 STONE MATRIX ASPHALT

Stone Matrix Asphalt (SMA) is a special type of mix, characterized by high quality coarse aggregates with rich proportion of binder and fiber additives. SMA is a gap graded hot mix asphalt mixture containing 70-80% coarse aggregate of total aggregate mass, 6-7% of binder, 8-12% of filler and about 0.3-0.5% of fiber or modifier. It consist of higher proportion of coarse aggregate & mineral filler and lower proportion of middle size aggregate as compared to dense graded mixtures. High concentration of coarse aggregate provides stone-to-stone contact to the mixture. This stone-on-stone skeleton provides strength to the mix and wear from studded tires, increased pavement performance with outstanding rutting resistance under heavy loads. Higher asphalt content makes the pavement more durable. Also reduce tire splash and tire noise. Higher binder content causes draindown during production, transportation and laying. Fiber or modifiers/ stabilizers are also added to mixture to prevent draindown.

The success in Europe has encouraged the other countries to adopt the use of SMA mixtures particularly on high volume roads such as interstates and urban intersections. However, this new methodology has to be evaluated using Indian materials to ensure satisfactory performance in India.

SMA is often considered a premium mix because of higher initial costs due to increased asphalt contents and the use of more durable aggregates. However, this higher initial cost may be offset by the improved performance of pavement for medium and high traffic loading situations. In addition to improved durability and rutting resistance, coarser surface texture of SMA pavement is also beneficial in tire noise reduction, fatigue resistance, improved wet weather friction. Reflecting cracks in SMA pavement are less than dense-graded mixtures.

1.4 WARM MIX ASPHALT

Warm mix Asphalt (WMA) is a relatively new technology of pavement construction, developed in 1990s. Construction of WMA pavements started in Europe in 1997. An additive is added to base binder which emulsify the binder. Emulsification of binder causes much less energy consumption and also results into less emissions during, construction. This condition provided better work condition and better paving condition.

WMA technology can reduce fuel consumption significantly and so, emissions during pavement construction process. The benefit of WMA is related to reduced handling temperature of mixing, placing and compaction. WMA technology provide longer possible haul distance, longer paving season and early opening the road to traffic as compared to traditional mixes. These benefit associates with less CO_2 emissions and other harmful byproducts. These attributes are beneficial for health of workers and environment. (Vaitkus et al. 2009).

Use of WMA with OGFC and SMA mixes will increase the market for each, as mitigation of problems associated with OGFC and SMA mixes and improvement in performance of mixes by taking in consideration of warm mix asphalt. Like SMA and OGFC requires higher binder content. High binder contents resulting in thick binder films.

In OGFC and SMA mixtures average binder film thickness requires is 8-11 micron, which is much higher than average film thickness of 4-6 micron in typical dense graded mixes. Film thickness is calculated based on effective asphalt content.. This thicker film of binder is essential for longevity. The heavy binder film on aggregate surface helps to resist stripping and oxidation of the asphalt cement (FHWA 1990).

This higher binder content causes drain down which can be corrected by lowering the mixing temperature. Higher temperature during mixing and compaction also cause the asphalt binder film to flow off from the aggregate surface. Which may results in some are having not enough asphalt and excessive binder in other part. WMA technology helps in lowering mixing and handling temperature.

Government of India, had also expressed serious concern over the environmental pollution being caused due to manufacturing and application of hot mixes. In order to find suitable solutions, WMA may be a better solution as producing less emissions and also improve performance of bituminous mixes and can be laid mechanically and at a faster rate in critical intersections.

In this research, Evotherm and Zycotherm two additives were used with PMB-40 as base binder to produce WMA. Both the additives work on one principal of improving binder properties at lower temperatures than hot mix asphalt binder.

Additives improve the quality of binder by improving chemical bonding between aggregate and asphalt. Also provide complete waterproofing to the mixture due to penetration and chemical bonding of asphaltic layer. And thus eliminates moisture induce damage of asphaltic layer. Also ensure uniform load transfer and provide dust control. Zycotherm/ Evotherm additives provide all this qualities to binders even at lower residual bitumen.

1.5 MODIFIED BINDER

Modified binder improve the performance of bituminous mixed used in the surfacing course of roads. The threat of disposal of rubber and plastic waste was also solved by this initial step. Modified binder also increases the life of bituminous mixes. In this research work two types of modified binders have been used i.e. Polymer Modified Binder (PMB) and Crumb Rubber Modified Binder (CRMB).

PMB - In this research work, Polymer modified bitumen which is thermoplastic in nature is used for improving the performance of the mixes. Polymer is a long chain or clusters of small molecules formed by chemically reacting many (poly) smaller molecules (monomers) to one another. Polymer used for this study is thermoplastic in nature. When heated, thermoplastic materials become soften like plastic but return to their hardened state upon cooling.

CRMB - Crumb Rubber Modified Bitumen is prepared by improving the quality of binder by the addition of crumb rubber and special types of additives like hydrocarbon materials, resins etc. These additions alter the physical properties of bitumen by making it more durable, resistant to temperature variations, and high traffic loads, weather and provide better adhesion between aggregate and binder which ensures longer life, strength and stability of the mix, reduced maintenance costs and excellent driving comfort.

1.6 NEED OF THE STUDY

India is a faster developing country, doing well in many field like, industrialization, education and fashion but there are still certain fields where country is lagging behind. Condition of the roads are still bad, not even in villages but also in metropolitans and cities. Hot mix asphalt pavements are facing serious distress problems everywhere. So much have to be done through research and innovations to improve quality of asphalt pavement. Tensile cracking and rutting along wheel path of vehicles are predominate on Indian roads, in comparison to other forms of distress.

Tropical countries like India (Rajasthan) with predominantly warm/hot climates, faces major problems of water scarcity (runoff and evaporation of rain water) and excessive rutting in flexible pavements with bituminous wearing courses. In order to provide skid resistance to pavement with lower run off, OGFC mix can be suggested. And further, Stone Matrix Asphalt (SMA) mixes, which are primarily gap graded mix, characterized by high coarse aggregates, high asphalt contents, less fines and fiber additives as stabilizers, may be a good solution as rut resistant wearing courses. High concentration of coarse aggregate maximizes stone–on–stone contact and interlocking in the mix which provides strength, and the rich binder provides durability

For economic growth of the country these new generation pavements should be constructed, but with any new technology drawback of unfamiliarity of industry and workers is associated. This research work mainly focused on to provide a basis through comparative study for implementation of new generation pavements in India.

SMA mixes can provide more durable pavement having great rutting resistance potential. Smooth and fast movement of vehicles due to better pavement condition with SMA mixes will also increase passenger comfort and will reduce traffic congestion and vehicle fuel consumption to some extent.

OGFC pavement can solve the wet weather difficulties and can also provide good friction characteristics for Indian pavement surfaces and can also solve water problem of most of Indian states to some extent by infiltration of rainwater thus reducing the amount of run-off from the adjacent area.

In many countries OGFC have been proposed to deal the serious safety problem during rainy season due to hydroplaning and loss of visibility resulting from excessive water splash from heavy traffic.

Open Grade Friction Course mix is used for safety purpose by immediate removal of water from pavement surface, but large void structure of the mix allows much more exposure of air and water and poor durability than traditional dense graded mixes. This additional exposure of the mix, increases moisture susceptibility of pavement. As a solution of these problems, performance of modified binder and warm mix asphalt were evaluated in this research.

1.7 OBJECTIVES OF THE STUDY

This research is a laboratory evaluation of OGFC and SMA mixes. The objectives of the research are as under :-

- To study the performance of OGFC and SMA mixes with the use of modified binders and warm mix binders in comparison to conventional asphat.
- Performance test on OGFC and SMA mixes and compares the result of OGFC and SMA mixes.

1.8 SCOPE OF THE RESEARCH

The primary objective of this research work is to evaluate effectiveness of various binders in producing high quality OGFC and SMA mixes. Specifically, this study is focused on improving performance of the mixes using modified binder over conventional asphalt. Also improving environmental condition and pavement quality using warm mix asphalt. In this study five different binders i.e. Plain bitumen of Viscosity Grade 30 (VG-30), PMB-40 (Polymer Modifier Binder of penetration grade-40), CRMB-55 (Crumb Rubber Modifier Binder of penetration grade-55), WMA-E and WMA-Z (Warm Mix Asphalt produce by adding Evotherm and Zycotherm additive in PMB-40 as a base binder) and one aggregate source, cellulose fiber (as stabilizer) and hydrated lime (as filler and anti-stripping agent) were used for OGFC and SMA mix designs. This will assist in characterizing and understanding the effect of using polymer modifier binder and warm mix asphalt technology in comparison to Plain bitumen. Mix designs for 19-mm nominal aggregate size OGFC mix were done according to the design procedure proposed by the National Center of Asphalt Technology (NCAT) for a range of 5.0–7.0 % asphalt binder. Mix designs for 13mm maximum aggregate size SMA (wearing course) were performed according to the specification and design procedure proposed by the Ministry of Road Transport and Highway, Highway Manual Specifications for Road and Bridge Works (MORTH, 2013) for a range of 5.0–7.0 % asphalt. The optimum binder content was determined as per design requirement of the mixes. The scope of the study is limited to following-

1. Conducted a detail review of the literature related to OGFC, SMA, Modified binder and WMA.

2. Prepare mix designs using one aggregate source, five different binders, one cellulose fiber, one filler for 19-mm nominal aggregate size OGFC mix and same for 13-mm nominal aggregate size (Wearing Course, Morth,2013) SMA mix.

3. Volumetric and mechanical properties of Marshall mixes were determined

4. Prepare specimen for 10 selected mix designs (5 OGFC+ 5 SMA) and evaluate Indirect Tensile strength (ITS), Tensile Strength Ratio (TSR), Resilient Modulus(Mr), Dynamic Creep, Rutting (Wheel Rut Depth) of each mix design.

5. Comparative study of both the mixes is also done.

6. Provide recommendations for use of modified binders and WMA technology in OGFC and SMA mixtures and future research.

1.9 STRUCTURE OF THESIS

The thesis has been divided into five chapters. **Chapter 1** deals with introduction and some background information about the topic as well as objectives and need of study. In the **chapter 2**, a comprehensive literature review is presented about the OGFC mixes, SMA mixes, modified binders and WMA technology including history, performance, use, benefits and drawbacks of OGFC and SMA pavements, and some of the latest research conducted using both technologies has been presented. In the **chapter 3,** certain experimental plan has been finalized on the basis of literature review. Within this chapter, characterization of all materials, the Design parameters and experimental methods for SMA and OGFC mixes have been presented and testing procedures used to realize the research objectives. **Chapter 4** deals with the analysis and discussion of results for the entire study. The conclusions from the study and recommendations for implementation and future research work have been presented in the final **Chapter 5**.

CHAPTER 2

REVIEW OF LITERATURE

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2.1 GENERAL

A detail review of literature has been made on the work related to OGFC and SMA mixes, Modified binder and Warm Mix Asphalt (WMA) technology is described in the following paragraphs. Not only in India, but all over the word majority of the roads are flexible type. Flexible pavement consists of a bituminous layer as surface course, granular layer as base and sub base course, over the subgrade.

Hot Mix Asphalt (HMA) is a most common type of bound layer of flexible pavement structure as the surface or wearing course. HMA is mixture of coarse aggregate, fine aggregate, filler and binder where, all the constituents are mixed, placed and compacted at higher temperature. HMA can be dense graded mixture known as Bituminous Concrete (BC) and Dense Graded Bituminous Macadam (DBM), gap graded mixture like Stone Matrix Asphalt (SMA) or open graded mix known as Porous or Open Graded Friction course (OGFC). The major difference between three type of mixes is in their structural skeleton as shown in **Fig. 2.1**

2.2 DIFFERENCE BETWEEN BC/ DBM, SMA AND OGFC MIXES

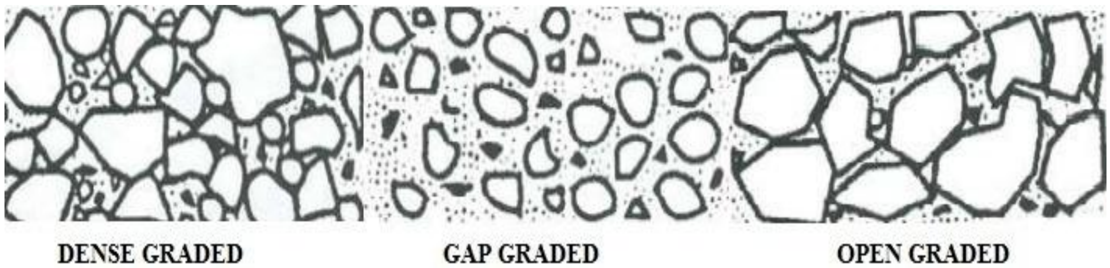

Fig. 2.1 Comparison of dense, gap and open gradation structure of HMA

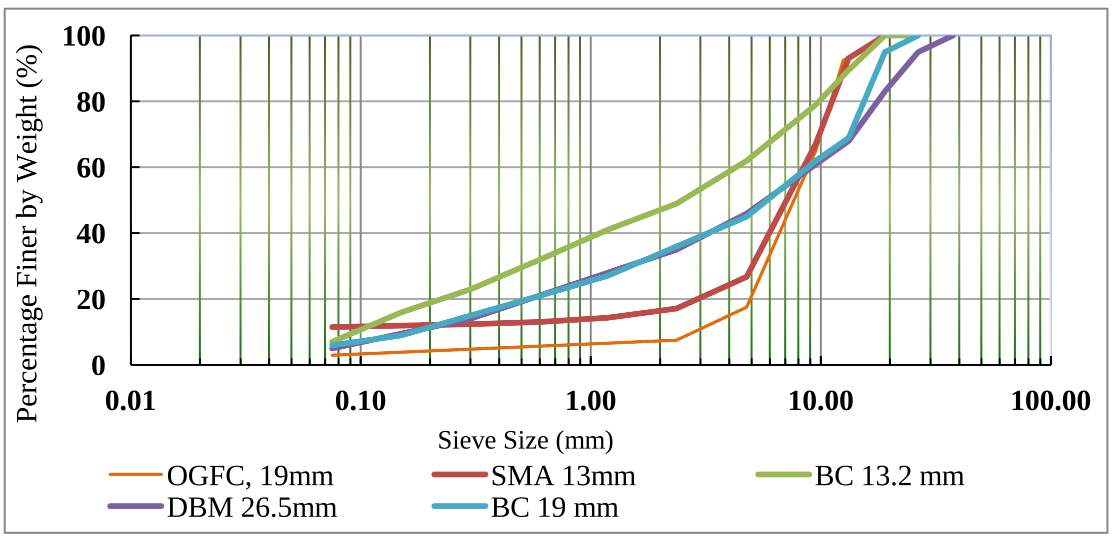

Fig. 2.2 Comparison graph of BC, DBM, SMA and OGFC gradation.

Conventional mixes like BC, DBM consist of 40-60 % coarse aggregates, SMA consists of 70-80 % of high quality coarse aggregates in the mix, where as OGFC consist of 50-60 % high quality coarse aggregates. Comparison graph of different HMA mixes gradation is shown in **Fig. 2.2** .

BC mixes consist of 40 to 50 % fines aggregates, SMA consist of 20-25 % fine aggregates and OGFC mixes have less than 20% fine particles of total aggregate weight (Coarse aggregate, Fine Aggregate and Filler).

BC mixes consist of 6 to 4 % mass of filler where as SMA mix consist much more as 8 to 12 % mass of filler and OGFC mixes consist of much less as 2 to 4 % filler content of total aggregate weight. (Bose et. al., 2006)

In dense graded mixes, pavement gain its strength from well-close-uniform designed gradation of mixture, in which fine aggregate, filler and binder matrix plays main role. In case of gap graded mixture, stone-to-stone contact of coarse aggregate provide strength. Gap-graded mix is more durable and rut resistant than dense graded mixtures because of its stone-on-stone skeleton. In case of open graded friction course, strength of mixture depend on underlying structure.

Designed BC mix at optimum binder content should consist of 3 to 6 % air void (as to maintain balance between elastic and stiffness property of mixes), while SMA mixes should have 2 to 4 % design air void (much less as to maintain stone-to-stone contact) and in case of OGFC mixes, it is much more as 17-25 %.(as to continue its open gradation)

The second main difference lies in binder content. Conventional mix consist of 5 to 6 % binder. Below this quantity, mix becomes unstable and above this quantity, mix lead to sudden drop of stability, because of filling all the voids and extra binder makes the aggregate to float in binder matrix. In the SMA and OGFC mixes, there is higher percentage (> 6.0 %) of binder, which accredited to filling more amount of voids present in it, due to high coarse aggregate skeleton. This high amount of binder contributes to the longevity of the pavement.

The third difference, use of stabilizing additives (fiber or polymer) in OGFC and SMA mixes, which attributed to reduce drain down due to higher bitumen content by filling up of large no of voids. On the contrary, there is no stabilizing agent in convention dense or uniformly graded mix, Since the binder content is moderate, which serve purpose of filling the moderate amount of voids and binding the aggregate.

In general, nominal layer thickness of BC layer in pavement surfacing is 30-65 mm, in case of SMA mixes, it is 25 to 75 mm while in case of OGFC mix it is much thinner as 19mm for normal or thin layer OGFC surfacing and maximum 38 mm for thick layer OGFC mix.

A primary difference between SMA and OGFC mixture is the air voids content as SMA mixtures content approximately 3 percent air void in the mix, whereas OGFC may have more than 20 percent air voids.

Too high air voids in HMA mixes increased rutting under traffic and binder aging. Besides increased permeability, higher air void causes aging, cracking, raveling, moisture damage to the mix and densification of pavement surface under traffic.

There has been reported a reduction of about 10% in pavement service life for each 1% increased in air voids over 7%. Low air voids may cause plastic flow of surface and shoving under traffic.

2.3 CURRENT SCEANARIO OF FLEXIBLE PAVEMENT

As per performance report of dense and well graded mixtures in recent year, premature rutting has been increasing in heavy duty pavement. High axle load and truck tires pressure causes premature deformation in pavement. Modification of pavement mixes by change in the gradation of binder and base course with the use of large size stone will minimize or control the rutting to a great extent (Kandhal et al. 1990)

The highway traffic in India is rising more rapidly rate with the increasing population and the road network has also expanded in different regions of India. This has led to an enhance in the number of heavy vehicles, as the travel time and vehicle operating costs have increased vastly. Apart from the increase in truck traffic, there is also a huge difference in the maximum and minimum temperatures of the country. The maximum air temperature can reach even 50°C in some parts of the country and the resulting pavement temperature can reach up to 60°C (Raghuram and Chowdary 2013).

With the increase in loading and temperatures, the pavements are subjected to various types of distresses. Rutting has been observed to be a major distress in flexible pavements and several studies were carried out across the globe to quantify the mechanisms of rutting and to reduce the effective rut depth along the wheel path. SMA mixes may prove a good solution of these pavement distresses problems, since they resists permanent deformation and has the potential for long term performance and durability.

Another major issue of road network is related to environmental. As most of the states of our country and also all over the world, there is serious issue of "water deficiency". Highways covers a major portion of the land. A number of studied are also being done to store valuable rain water which evaporates or runoff from large surface of highways. Furthermore, stagnate water on road surface also causes splash and spray, hydroplaning, potholes and stripping of bituminous mixes. Immediate removal of this rain water through drain will also reduce accidents/ problems related to skidding and slippery action of wet roads and reduce visibility especially during nights. Porous pavement or pavement with open graded friction course mixes are being constructed in many developed countries, as a solution of above mentioned issues along with a good surface quality road pavement.

One more important issue is related to environmental pollution during construction of road network. As per report of Government of India, increasing environmental pollution with increasing climatic temperature is a major concern. High temperature during construction process and Plastic/rubber scraps which takes billions of years to decompose are also some of the major reason of environmental pollution, these days. Using of binders which are modified with plastic and rubber waste will solve the problem of disposal of these waste, to a major extent. Further the implementation of warm mix asphalt technology will dropdown the temperature during construction processes and also reduce consumption of fuel and emission of harmful gases.

Detail literature on SMA, OGFC, modified binder and WMA are given in next sessions of this chapter.

2.4 OPEN GRADED FRICTION COURSE

Porous Asphalt friction course also known as a popcorn mix. Due to its safety and environmental benefit, this mix is popular in the United States, European countries and South Africa. These special-purpose porous friction-course mixtures suggested for new or old high-speed, high-volume roads and expressways to minimize hydroplaning, improve night visibility and surface frictional resistance, reduce splash and spray, and lower pavement noise levels (Watson et al. 2004; Decoene 1990)

These all qualities and benefit of porous mix is primarily due to immediate removing of water from pavement surface. In permeable mix, pavement surface are designed and constructed in such a way to have a minimum 20 % air-voids, through which water can be drain in to underlying structure. (Jimenez and Perez 1990; Shuler and Hanson 1990).

Desired higher percentage of air voids in a porous asphalt mixtures is obtain by using a uniform grading in aggregates mix design. (Huddleston et al.1993; Colwill 1993).

Higher binder content in porous mix also increase durability of the mixture (Kandhal and Mallick 1998; Decoene 1990; Jimenez and Perez 1990).

Uniform grading of the mix is designed by using mainly single aggregate i.e. 50-60% aggregate of same particle size with little amount of fines and fillers. Aggregate passing 2.36 mm sieve i.e. No. 8 sieve should be less than 20 % and filler should in between 2 to 5 %   (Nicholls 1997; Clifford et al. 1996).

Porous mix generally contains higher binder content as compare to traditional dense graded mixture. Higher binder content with the combination of low filler and uniform gradation causes draining of binder due to gravity during mixing, hauling and placement procedures (Watson et al. 2004). This phenomena of drainage of binder is called "Draindown".

Different stabilizers have different capacity to reduce draindown and hence provided different optimum binder contents in a same aggregate gradation mix at equal design air voids (Cooley et al. 2000).

Polymers and Cellulose fibers had a significant effect on the performance of the OGFC mixes. Polymer increases more resistance to raveling in the short term of the pavement life than cellulose fibers. Cellulose fibers had more significant effect on draindown properties of the OGFC mixes than the polymer. Lime has not shown any effect on the OGFC mix quality where as improves Tensile Strength Ration (TSR) value up to 82 % for the dense graded mix. (Hossam et al. 2005)

Mansour and Talat (2011) have done research on effect of aggregate gradation on open graded friction course mixtures. Ten different coarser to finer gradation of OGFC mixes were tested. All mixes showed good abrasion characteristics. Stabilizers in OGFC mix, improve the durability of mix by reducing the drain down of binder. When dry rodded unit weight of all mixes increases, strength of mixes increased and porosity and permeability of the OGFC mixture decreased. When dry rodded unit weight decreases, strength of mix decreased and so air void of the mixes increases and permeability of the mix increased. Dry rodded unit weight did not have significant effect on rutting. Therefore, an Open gradation of the mix can be modified according to required performance whether more permeability or more strength, by varying design air void ratio.

The National Asphalt Pavement Association [NAPA] recommends that the optimum asphalt content for porous asphalt be determined by asphalt content that meets the following requirements: air voids greater than 18 % and drain down less than 0.3 % (NAPA, 1994, 2003).

However the National Centre for Asphalt Technology (NCAT) recommends the optimum asphalt content for OGFC as air voids greater than 18 %, drain down less than 0.3% and in addition to these two, it introduces two more requirements to be met, namely: Cantabro Abrasion loss of un-aged specimens should be less than 20 % and Cantabro Abrasion loss of aged specimens should be less than 30 %. (Kandhal and Mallick 1999).

For design of open graded friction course, California Department of Transportation (2003), were using California Test 368 (CT 368), A Standard Method for Determining Optimum Bitumen Content (OBC) for Open Graded Asphalt Concrete. This method gives Optimum Binder content (OBC) on the basis of three criteria i.e. draindown, cantrabro test on aged and un aged specimen and air void, which provide an durable asphalt film thickness to aggregate mix and avoid excessive asphalt drainage. CT 368 method also have some limitation. As there is no verification of stone-on-stone contact, volumetric and mechanistic properties of compacted specimens also not determined and no performance testing for aging and moisture damage for the state's different climate regions .

Recently, staff members of the National Center of Asphalt Technology (NCAT) developed an improved design procedure for OGFC mixes. The methodology includes-materials selection, trial gradations, selection of an optimum design gradation, selection of an optimum binder content, and moisture susceptibility determination using the modified Lottman method in accordance with AASHTO T 283 with one freeze-thaw cycle. (UCPRC, 2012).

2.5 STONE MATRIX ASPHALT

SMA is a gap graded aggregate-asphalt hot mixture of maximizes binder content and coarse aggregate fraction. SMA mix contains 70-80 per cent coarse aggregate of the total stone content, 6-7 per cent of bituminous binder, 8-12 per cent of filer (cement/lime) and about 0.3 to 0.5 per cent of stabilizing additive (fiber) or other modifier. This enrich mixture provides a stable stone-on- stone skeleton that is held together by a rich mixture of asphalt cement, filler, and stabilizing additive. (Brown and Hemant 1993, MORTH 2013).

Increased traffic volume especially with heavy truck traffic, increased axle weight, and gross weight, increased tyre pressure and decreasing tyre- pavement contact area, have adversely affect the pavement performance. The amount of rutting or permanent deformation has also increased with dense graded asphalt pavement. (Scherocman, 1992).

By considering the factor contributing to rutting and type of bituminous mixes, in 1990 European Asphalt Researcher have research on old German asphalt mix technology, known as “splittmastixasphalt”. splittmastixasphalt is a premium mixture, have performed as long-lasting, rut-resistant asphalt surface mix. The English translation of “splittmastixasphalt” is “stone mastic asphalt”. The Americanized version of this mix technology is known as “stone matrix asphalt” (Prowell et al., 2002).

SMA was developed in Germany during the mid-1960s (Brown and Hemant, 1993). Since then, it is successfully being applied in Europe for its better performance. Earlier in the 1990s, become popular worldwide with increased rutting potential and resistance to wear due to studded tyre (Scherocman, 1991).

As per National Asphalt Paving Association (NAPA) and Washington state department of transportation (WSDOT, 2000) report, SMA is a more durable, tough, stable and rutting-resistant mixture. Gap graded structure of the mixture provide it aggregate to aggregate contact which provide it strength. Rich mortar binder provides it durability. SMA mixture consist of mineral aggregates, mineral filler, asphalt binder and stabilizing additives. SMA is designed to maximize rutting resistance and durability of the bituminous mixes. Mineral filler plays an significant role in air voids, voids in mineral aggregate and optimum binder content properties of SMA mixture.

Mogawer and Stuart (1996) suggested (i) minimum Tensile Strength Ratio (TSR) of 80 per cent and (ii) maximum allowable rut depths (by Hamburg wheel tracking device) of 4 mm at 10,000 passes and 10 mm at 20,000 passes for design of SMA mixture with desire rutting resistance and durability potential.

Brown and Mallick (1995) recommended use of dry-rodded unit weight apparatus (AASHTO T19) to conclude the extent of stone-on-stone contact existing in SMA mixture.

The gap-graded structure with higher amount of coarse aggregate provides, SMA mix a stone-on-stone contact of coarse aggregate's particles. This stone-to-stone skeleton provide strength to the mix. SMA mix also content higher binder content in mortar, which improves durability of mix (Brown et.al. 95,97).

Scherocman (1991) suggested 30-20-10 rule of SMA gradation design that the gradation should have 30 per cent aggregate passing 4.75 mm sieve, 20 per cent passing 2.36 mm sieve and 10 per cent passing 0.075 mm sieve.

The percent passing the 4.75 mm sieve is a critical factor in the formation of stone-on-stone contact in SMA (Brown and Mallick, 1994). As the percent passing 4.75 mm sieve decreases, the VMA remains nearly constant, and then begins to increase once the percent passing the 4.75 mm sieve reaches 30 to 40 percent. The point at which the VMA begins to increase defines the condition at which stone-on-stone contact begins to develop. Below 30 percent, a lowering of percent passing the 4.75 mm sieve tends to increase the VMA by opening up more space in the coarse aggregate structure. Hence, the percent passing the 4.75 mm sieve must be lowered below approximately 30 percent to ensure the formation of stone-on-stone contact (Brown et al., 1997).

Staurt et al 1992. stated that gap gradation and coarse aggregate content is control by the aggregates passing of sieve size 4.75 mm and 2.36 mm, while optimum binder content in the SMA mix is control by the, material which passing 0.075 mm sieve .

Higher binder content and gap-graded structure of mixture caused draining of binder during the high temperature of production and placement. This phenomena of draining of binder from mixture is called "Draindown". (Brown et al.1997a, Brown et al.1997b). The stabilizing additive holds bituminous binder in the mixture during placement, production and compaction of mixes, at the high temperature. These stabilizer act as a drain down reducer of binder. (Mogawer and Stuart, 1996). Cellulose fiber, polyester fiber, polymer modifier and mineral fiber stabilizer have been widely used in SMA. (Mallick et al. 2000; Putman and Amirkhanian 2004; Tayfur et al. 2007; Sharma V. and Goyal S., 2006). Commercial polymer is not economical in terms of usage (Mahrez, 2008) consequently using waste materials such as Crumb Rubber Modifier (CFM), in the asphalt mixture has been found to be more cost-effective and environment-friendly (Mashaan NS, 2013).

Vivek and Sowmya (2015) conducted a study on "Utilization of Fiber as a Strength Modifier in Stone Matrix Asphalt". Cellulose fiber used in SMA mixes are costly and not readily available. The researcher used low cost fiber i.e. plastic waste and coconut fiber. Use of low cost fiber i.e. plastic waste up to 8% by weight of total aggregate and coconut fiber up to 0.3% by weight of total aggregate, improved Marshall property of mixture. These fiber can also solve the problem of disposal of plastic waste. Coconut fiber contains some amount of cellulose fiber.

Fibers do not directly affect the strength or properties of mixes, they just act as absorber for excessive binder and thus increases durability of mixes. As Prowell et al. (2009) commented that there is no real purpose of fibers after the mix is compacted in-place. The main role of fibers in SMA mixes is to reduce the draindown of the binder rather than improving the mechanical properties of the SMA mixes.

The use of higher binder content enhances the durability of SMA. Because of its higher rut resistance property and higher durability, it is most preferred over the conventional dense graded asphalt mixes.

In dense graded asphalt mixes, the mortar (fine aggregate and asphalt cement) in the mix actually carries the traffic load. The coarse aggregate particles in dense asphalt mixes are not in close contact with each other and there will be considerable amount of space between the coarse aggregates which is filled with fine aggregate and asphalt cement. The gradation of the aggregate and optimum asphalt content for SMA are considerably different from dense graded asphalt mixes. The stone-on-stone contact is much higher in SMA and the loads are carried by the coarse aggregate particles instead of the mortar resulting in lower permanent deformation in SMA (Scherocman 1992).

The stone-on-stone contact in SMA mixture can be establish/ verify by two method. First method is based on the density of coarse aggregate. If density of the coarse aggregate only fraction is less than or equal to the density of coarse aggregate skeleton in the total SMA mixture sample, the SMA mixture has a stone-on-stone coarse aggregate skeleton (Brown et al., 1995). The second method is based on the relationship between Voids in Mineral Aggregate (VMA) and the percentage of fine aggregate (material passing 4.75 mm) in the SMA mixture. If the SMA coarse aggregate skeleton has VMA less than or equal to the coarse aggregate only fraction VMA, the SMA mixture is judged to have stone-on-stone contact (Brown et al., 1994). There are five different compaction methods are to determine VMA of the coarse aggregate only fraction: Marshall hammer, dry rodded method, vibrating table, Superpave gyratory compactor, and the British vibrating hammer. The Superpave gyratory compactor and dry rodded methods produced best results (Brown and Haddock 1997a; Brown and Haddock 1997b). Digital imaging were also being used to establish stone-on-stone contact. The advantage of digital imaging is that it can quantify the number of contacts between aggregate particles (Watson et al., 2004).

Aggregate gradation is a fundamental aspect in the development of stone-on-stone contact in SMA mixes, the SMA gradations adopted in various countries are reviewed in **Table 2.1**. Recently, “Ministry of Road Transport and Highways Manual for Construction and Supervision of Bituminous Works (MORTH, 2013)” have publish mix design standard for SMA design suitable for Indian conditions. Previous to this MORTH, 2013 publication, Indian Roads Congress (IRC) introduced a tentative specifications for SMA mix design, (IRC:SP:79, 2008) where the aggregate gradation closely matches with NCHRP specifications. And Previous to this IRC publication, SMA mixes were designed in India using the MORTH 2001, where the aggregate gradation closely matches with German specifications. The percentage material passing the 4.75 mm sieve size is less than 30% for all the standards reported in **Table 2.1** except the German specifications, and MORTH (2013) specifications. It is worthwhile to highlight here that, according to Brown et al. (1997a, 1997b), “the percent passing the 4.75 mm sieve must be lowered below

Table 2. 1: SMA Gradations Developed in Various Countries

Organization	MORTH -2013 And IRC:SP:79,2008		NAPA, Kandal	NCHRP 425 (Brown & Cooley,	German Specification
Country	**INDIA**		**USA**		**Germany**
Nominal maximum aggregate size, mm	**13 Wearing Course**	**19 Binder (Intermediate) course**	**12.5**	**19**	**12.5**
Sieve Size,	**Cumulative percent by weight of total aggregate passing**				
26.5	-	100	-	-	-
25	-	-	-	100	-
19	100	90-100	100	90-100	100
16	-	-	-	-	-
13.2	90-100	45-70	-	-	-
12.5	-	-	85-95	50-74	90-100
9.5	50-75	25-60	75	25-60	34-75
4.75	20-28	20-28	20-28	20-28	23-41
2.36	16-24	16-24	16-24	16-24	18-30
1.18	13-21	13-21	-	13-21	15-24
0.600	12-18	12-18	12-16	12-18	12-20
0.300	10-20	10-20	12-15	12-15	10-17
0.150	-	-	-	-	9-14
0.075	8-12	8-12	8-10	8-10	8-13
0.020	-	-	3 Max.	-	-

approximately 30 percent to ensure the formation of stone-on-stone contact". Some of the studies on SMA mixes carried out in India (Punith et al., 2004;Kamaraj et al., 2006) followed the MORTH (2001) gradation. However, Kamaraj et al. (2006) ensured stone-on-stone contact using the method developed by Brown and Mallick (1995).

Stone Matrix Asphalt is superior type of pavement, should be used in heavily trafficked highways. Choice of SMA can be a good investment in terms of 5 to 10 year increase service life and other additional advantages mentioned above in this chapter. For gaining maximum benefit, SMA mixture should be well designed with high standard production and laying method. Improvement in the mix design of the SMA can be done as per requirement and environment condition. In wet and cold region of India, mix design should take in to account lower air void and higher binder content while in most of drier and warmer regions, a stiffer binder with higher air void and lower binder content should take into consideration.

2.6 MODIFIED BINDER

Performance of dense graded asphalt pavement improve with the modified asphalt binder. Structural properties and the durability of the mixes increases with the modification of binder with different type of additive. (Punith and Veeraragavan 2010; Suresha et al. 2009).

With the addition of modifier or fibers, binder content in the mixture can be increase and thus durability of mixtures increases due to increase film thickness

(NCHRP,2000). Consequently, modified binders also can be beneficial in new generation mixtures like porous or stone matrix asphalt pavement. Structural properties of the mix dependent on the deformation and fatigue resistance of the mixture. Durability of these mixes also depend on the higher binder content, which increases stone retention without draining of binder during construction. (Kandhal and Mallick 1998).

Modified binder controls running off the binder from aggregate surface and maintain a thicker binder film and also delay oxidation and thus reduces raveling of the aggregate particles. (Ruiz et al. 1990; Perez, Jimenez and Gordillo J 1990; Alvarez et al. 2006, 2008).

A number of effort were made to modify asphalt mixes performance. One of them is using discarded tires of vehicles i.e. crumb rubber. Using of tire wastes also solved the problem of disposal, which is a serious environmental issue. (Saiton 1990).

Use of Crumb Rubber Modified Binders (CRMB) in bituminous mixes is increasing due to its improved properties. Rejected vehicle tires mechanical sheared and grind off to small particles to make recycle rubber or Crumb (Krutz and Gardiner 1992)

Crumb Rubber Modified Binders (CRMBS) have increased the performance of the bituminous mixes during various field and laboratory tests. Polythene carry bag is being used everywhere, now a days for domestic or transport good etc. These polybags are made from Low-density polyethylene (LDPE). Even only in India, more than 10 million metric tons per year of LDPE are being produced and from which, less than 20% of are being recycled because of limited recycling option. Remaining LDPE are send to landfill, which is not a good solution as these polythene are not readily biodegradable and remains in environment for billions of years in a more or less unchanged state. Use of these domestic LDPE by recycling is a very good idea. In asphalt industry, efforts are also being done to use reclaimed polyethylene (RPE) carry bags in bituminous mixtures. (Punith and Veeraragavan 2007).

Pavement construction requires large quantity of construction materials. Even use of a small percentage of reclaimed polyethylene, will solve the problem of disposal of huge quantity polythene material. Utilization of these LDPE, not only solve the environmental problem to some extent but also modify the properties of asphalt mixtures.

Mahsaan et. al. (2014) have done comparative study on fatigue life of conventional SMA and Crumb Rubber Modified (CRM) reinforced SMA. Life of SMA mixture was significantly increased with the use of Crumb Rubber. Also studied relation of fatigue stiffness with resilient modulus and life dynamic. Resilient modulus has shown higher correlation coefficient with fatigue life than permanent strain. Thus resilient modulus prove to be a more reliable indicator for evaluating the fatigue life of bituminous mixture. Although fatigue test is considered a destructive test, it correlate better with resilient modulus test which is nondestructive test as compared to the creep test which is destructive test.

2.7 WARM MIX ASPHALT

Rising energy costs and environmental awareness have encouraged to developed alternate paving materials which lowers production temperatures but also hold similar field performance to hot-mix asphalt (HMA).

The Warm Mix Asphalts (WMA) is modified form of Hot Mix Asphalt (HMA) technology, in which bituminous mixture is produced, laid and compacted in temperature lower than conventional HMA. HMA is mixed and compacted at temperatures of approximately165°C, and 135°C, respectively The WMA is produced by mixing chemical additives to the conventional binder to improve the pavement performance of bituminous mixture.

Warm-mix asphalt (WMA) have same engineering property, as hot-mix asphalt (HMA). Major difference between HMA and WMA is that WMA is produced at lower plant temperatures than conventional HMA. Key benefits of the reduced temperature have the benefit of reduce fuel consumption and emissions (Hurley and Prowell 2005, 2006; Prowell 2007, 2008; Proewll et al. 2012, Kristjansdottir et al. 2007).

Warm Mix Asphalt (WMA) is a new innovative technology which work as " Adhesion Promoter". WMA make it possible to prepare PMB-40 mixes at 120ºC temperature when compared to traditional Hot Mix Asphalt (HMA) mixed at 150 to 160° C. Thus it reduces the fuel consumption and greenhouse gases (Rohith and Ranjitha 2013)

Warm-mix asphalt (WMA), which originated in Europe in the mid 1990s, appears to be a promising paving material that addresses following mentioned issues. WMA is an asphalt mixture that can be mixed and compacted at temperatures lower than the required temperatures for conventional HMA. It has been proven that WMA techniques can provide a number of benefits, including reduction of fuel consumption and emission, extension of construction seasons, improved compaction.

Warm mix Asphalt has been developed to reduce the mixing and compaction temperature of hot mix asphalt without sacrificing the quality of the resulting pavement. With the use of WMA technologies in asphalt paving, the energy consumption can be cut by 40%, subsequently reducing emissions (Vaitkus et al. 2009).

A considerable amount of energy is needed for preparing HMA mixes. For energy efficiency and sustainability, it is significant to reduce the energy consumed by the mixing and compaction processes. Sasobit, Aspha-min, and zeolite additives have recently developed. Theses chemical or additive reduces viscosity of the binder and thus ultimately reducing the mixing and compaction temperatures of asphalt binders and mixtures. (FHWA 2016).

In 1968, Csanyi prepared Warm Mix Asphalt by foamed asphalt technology where steam is injected into hot bitumen to reduce viscosity (Marek 2014). The environmental friendliness and energy effectiveness of warm asphalt was stated in the 1990s (Jenkins et al. 1999).

In this study an attempt has been made to compare performance of Warm Mix Asphalt for OGFC and SMA mixtures produced with the chemical additive (1) Evotherm and (2) ZycoTherm in comparison to Hot Mix Asphalt for OGFC and SMA produced with plain and modified bitumen. These Evotherm And Zycotherm additive were added to PMB-40 binder. PMB-40 was chosen as a base binder, so as to provide benefit of modified binder also along with warm asphalt.

2.7.1. ZycoTherm

ZycoTherm chemical used in this study, is a WMA additive and is added in PMB-40 binder. This is an odor free, chemical warm mix additive that has been engineered to provide significantly improved benefits over current WMA technologies by offering lower production and compaction temperatures, while simultaneously enhancing the moisture resistance of pavements by serving as an anti-striping agent. Mixes that have ZycoTherm modified binder, can be produced at 120°C - 135°C and also be compacted at 90°C - 120°C. Overall, ZycoTherm offers temperature reductions depending on the properties of the mix. ZycoTherm has built in antistrip mechanism that allows it to dually function as an antistrip as well as a warm mix additive. The additive is universally compatible with all types of modified as well as unmodified binders. This included Polymer Modified Bitumen binders. It does not affect binder grading or change any other binder properties.

2.7.2. Evotherm

A reduction in mixing temperatures results in reduced CO_2 emissions, increased sustainability, improved working conditions for construction and maintenance crews, extended paving season and financial benefits derived through lower production costs. Hence Warm Mix is the Future of Asphalt Mixtures. Evotherm technology enables contractors to reduce production temperatures by 35 to 55°C compared to typical HMA temperatures. This reduction in temperature reduces oxidation of the binder, which leads to a variety of benefits, particularly crack resistance of mixes. Several studies conducted with plant prepared mixes were tested for cracking resistance using different methods, and showed that the Evotherm mixes generally performed better in comparison than the HMA.

The reduced binder oxidation is a result of lower mixing and compaction temperatures, and the other is that the binder absorption in the Evotherm mixes is significantly less compared to the HMA. This reduced absorption leads to a higher effective binder content in the matrix, especially in absorptive aggregate

A study was carried out by Wurst (2011) for warm mix open graded friction course mixes. A chemical package (Evotherm TM) and a water -injection method (foaming) warm mix asphalt technology was used for study. Polymer and fiber stabilizing additives were replaced by the warm mix asphalt technology. As compared to traditional OGFC mix, warm mix OGFC has shown better result. WMA technology has improved the mix abrasion resistance and permeability of the mix and reduce the potential for moisture susceptibility and drain-down. The results indicate that the Evotherm mixes compacted at 115°C exhibit significantly higher resistance to cracking than the similarly formulated hot mix samples compacted at 152°C.

Research on Sasobit and Aspha-min gained prominence in June 2005, as WMA had reduced energy consumption by about 30% and also raised the longevity of the mixing plant. Sasobit is a synthetic wax and Aspha-min is a synthetic zeolite. (Cervarich M.B. 2003, Hurley and Prowell 2005a, 2005b,). Comparative research on Sasobit and Evotherm were has shown that Evotherm is better than Sasobit for improved stiffness and viscosity reduction of the recycled binder. As well, Sasobit is better for the normal binder WMA process than for the recycle WMA process (Doh et al. 2010).

A Warm Mix Asphalt (WMA) containing Evotherm® can be quickly opened to traffic. Overall, Evotherm® appears to be a viable tool for reducing mixing and compaction temperatures that can be readily added to hot mix asphalt. Reductions in mixing and compaction temperatures are expected to reduce fuel costs, reduce emissions, and widen the winter paving window.

CHAPTER 3

CHARACTERIZATION OF MATERIAL AND METHODS

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3.1 INTRODUCTION

In this research work, study have been done regarding performance of OGFC and SMA mixes. These mixes have been used worldwide, in very large scale especially in European countries. Research regarding design procedure, gradation, material and construction technique as per climatic condition of particular state, being done since many years. But in India, these type of pavements are not so much in practice. In this report an effort has been made to evaluate the performance of SMA and OGFC mixes, with the use of modified and warm asphalt binders in comparison to plain bitumen with nearby available materials (aggregates, filler, fiber and binder). Efforts were also made to make pavement construction environment friendly by using WMA, SMA and OGFC techniques. WMA technique reduces fuel consumption, OGFC reduces water runoff and SMA is a sustainable pavement. CRMB also solves the problem of disposing rubber waste. This chapter describe the laboratory works carried out in this investigation.

This chapter is divided into four parts. First part deals with the experiments carried out on the materials, Second part deals with the OGFC mix design method, third part deals with mix design of SMA Mix and the forth part deals with the various performance tests carried out on both OGFC and SMA mixes at optimum binder content.

3.2 METHODOLOGY

In the present study, two type of bituminous mixes i.e. Stone Mastic Asphalt (SMA) as per MORTH specification and Open Graded Friction Course (OGFC) as per NCAT specification were investigated. The materials such as coarse aggregates (size 10mm and 6 mm), fine aggregate (stone dust) and bituminous binder (VG-30, PMB-40 and CRMB-55) were tested as per relevant Indian Standard (IS). Physical properties of aggregates such as gradation, water absorption, specific gravity, impact value, crushing strength, Los Angeles abrasion value and flakiness & elongation index (shape test) were determined. The properties of bitumen binders such as specific gravity, penetration, softening point, viscosity and ductility were evaluated in the laboratory. Good design of bituminous mixture should be strong, durable, resistive to moisture damage and permanent deformation, environment friendly and economic.

In general, optimum binder content for conventional bituminous mixes is determined on the three basic factors, that is Maximum Marshall Stability, maximum unit weight, and 4 % design air voids. But mixes used in this study are different in structure and function than conventional mixes. As SMA is a gap graded mix, strength of the pavement depends on the stone-on-stone skeleton and OGFC mix are open graded, strength of this type pavement depends on underlying structure and function of these pavements also differ. Design requirements for each mix is discussed separately, in this chapter. Same material were used, so as to make comparison of both mixes more reliable and simple. A number of mixes were prepared and tested for each binder type for both the bituminous mixes, to achieve the all requirements. Drain down, abrasion loss and voids in the mixes were determined to find out OBC. Performance tests related to stability and strength of the pavement, stiffness and elastic property, moisture susceptibility, permanent deformation and rut depth were done on designed mixes at Optimum Binder Content (OBC).

Bituminous mix designs were done for following :-

1. OGFC Mix Design
2. SMA Mix Design

Flow Chart of the experimental work carried out in this chapter, is given in **Fig. : 3.1**

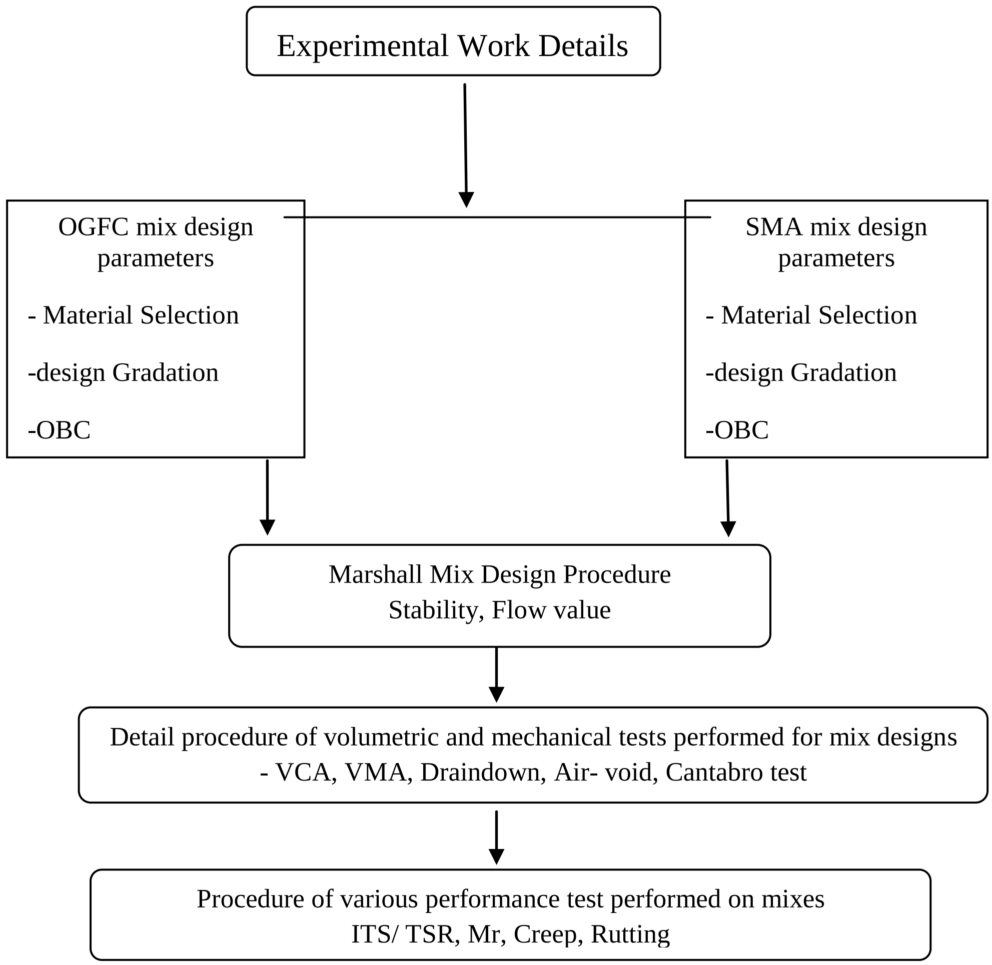

Fig.3.1: Flow diagram structure of Chapter3

3.3 OGFC MIX DESIGN

OGFC is a new generation of pavement, applying successfully worldwide but still in India, there is not any pavement construction using OGFC surface mixtures. And further there is not any technical guidance or standards provided by Indian Road Congress (IRC) or MORTH for OGFC mixture preparation. Therefore, mix design of OGFC is done as per standards and guideline of National Centre for Asphalt Technology (NCAT), updates of Federal Highway Administration (FHWA) and technical reports of University of California Pavement Research Centre (UCPRC). Mix design of OGFC is less structured than for dense-graded mixtures. The five basic steps in the mixture design procedure are-

1) Material selection
2) Selection of design gradation
3) Determination of Optimum Binder Content (OBC)
4) Marshall specimen prepared at desired gradation and OBC

3.3.1 MATERIAL SELECTION

OGFC mixes are designed to be permeable, which differentiates them from dense-graded (BC) and gap graded (SMA) mixes, which are relatively impermeable. Mix design requirement of OGFC is given in **Table:3.1.** Crushed granite stone and crushed gravel with a small percentage of stone dust is used for design of OGFC mixes.

Table 3.1 : OGFC mix design requirement

Material	Specification
Nominal Maximum Aggregate Size	19 mm
Coarse Aggregate in the mix	50 -60 % particle of same size
Binder	> 6.0 % (6.0-7.5)
Filler	3% by dry mass of aggregate
Fiber	0.2 to 0.4% by weight of the total mix

3.3.1.1 AGGREGATE

High quality aggregates with maximum size not exceeding 19 mm were selected for OGFC mix design. The entire aggregate were procured from a single quarry from Bassi near Jaipur city. The crushed stone was sieved into various fractions after washing and drying. Aggregates used in the present study were tested to ensure good quality aggregates. Physical properties of aggregates used for mix design are shown in **Table. 3.2.**

Aggregate hardness as measured by the Los Angeles abrasion test showed good correlation with aggregate breakdown. An increase in abrasion loss resulted in an increase in aggregate breakdown for mixtures compacted with Marshall hammer. Therefore, a limit on abrasion loss is justified to help minimize aggregate breakdown.

3.3.1.2 FIBER

OGFC mixes contains generally 6% binder of total aggregate weight which is much higher as compared to dense graded mixtures. This excessive binder content causes draindown of mixes during mixing and compaction. Cellulose fiber was used as stabilizer to control drain down. Cellulose fibers were added in powder form, at a dosage rate of 0.2 to 0.4% by weight of the total mix (aggregate and asphalt binder) and mixed with the aggregate before the asphalt binder was introduced. Test properties of cellulose fiber used in the mix design, is shown in **Table. 3.3** and close view of fiber is shown in **Fig 3.2(a) & (b)**.

The standards developed in abroad specify the dosage rate of cellulose fibers as minimum 0.3% by weight of total mix. In this study, the fiber dosage rate is fixed as 0.3% by the weight of total mix. Although, draindown test was performed to ensure optimum fiber content and accordingly doses were increased, so as to control draining of binder.

Table 3.2: Physical properties of aggregates used

Property	Test Performed	Test Result	MORTH, 2013, IRC:SP:79, 2008 Specification	Test Methods
Cleanliness	Grain Size Analysis	0 %	< 2% passing 0.075 mm sieve	IS: 2386 (Part-I)-1963
Particle Shape	Combined Flakiness Index & Elongation Index	23%	< 30%	IS: 2386 (Part I)-1963
Strength	Aggregate Impact Value-Toughness	13.56%	< 18%	IS: 2386 (Part IV)-1963
	Los Angel Abrasion Value- Hardness	21.4%	< 25%	IS: 2386 (Part IV)-1963
	Aggregate Crushing Value	14.6%	< 30%	IS: 2386 (Part IV)-1963
Durability	Soundness with Sodium Sulphate (5cycle)	8.47	<12%	IS: 2386 (Part V)-1963
	Soundness with Magnesium Sulphate (5cycle)	12.14	<18%	
Water Absorption	Water Absorption of C.A. (10mm)	0.80%	< 2%	IS: 2386 (Part III)-1963
	Water Absorption of C.A. (6mm)	0.93%		
	Water Absorption of C.A. (Stone Dust)	1.38%		
Stripping	Coating and stripping of bitumen aggregate mixtures	98%	Retained coating > 95%	IS 6241-1971
Liquid Limit	Fine aggregate	21 %	25 % Max	AASHTO T 89
Specific Gravity	Sp. Gr. of C.A. (10mm)	2.83%	2.5 -3.2	IS: 2386 (Part III)
	Sp. Gr. of C.A. (6mm)	2.82%		
	Sp. Gr. of F.A. (Stone Dust)	2.81%		
	Sp. Gr. of Lime Filler	2.9%		

Table 3.3: Properties of Cellulose Fiber used

Mesh Screen Analysis	**Passing**
850 µm (No. 20) Sieve	73 %
425 µm (No. 40) Sieve	52 %
106 µm (No. 140) Sieve	15 %
Test Performed	**Result**
Fiber Length/ thickness/ diameter	5-6 mm
Specific Gravity	1.45
Bulk density	1557gm/ cc
Ash content, 2-3 gm, 595°C, 2hour	20 %
PH value, 100 ml distilled water added, 30 minutes	8.5
Oil Absorption test, 5gm shaken on a wrist action, 10 minutes	2.8 %
Moisture Content, 10 gm, 121°C, forced air oven for 2 hours	3.5 %
Temperature Resistant	Up to 200 °C
Solubility	Insoluble in water and organic solvents.

Fig. 3.2: (a) Cellulose Fiber Close View (b) Grounded Cellulose Fiber

3.3.1.3 FILLER

Hydrated lime ($CaCO_3$), in dry powder form was added in the OGFC mixture at a rate of 3.0 % by dry mass of aggregate to fill the requirement of filler. Lime also fulfilled the purpose of an anti-stripping agent. Properties of lime used is given in **Table 3.4.**

Table 3.4: Properties of Hydrated Lime (Filler) used

Mesh Screen Analysis	**Passing**
150 µm Sieve No. 100	100.0%
75 µm Sieve (No. 200)	99 %
45 µm Sieve (No. 325)	95%
TEST PERFORMED	**RESULT**
Plasticity Index (PI)	4 Max
Specific Gravity	2.43
Apparent Dry Bulk Density (Loose)	0.35 gm/ cm3
Percent passing 0.02 mm	< 20 %

3.3.1.4 BINDER

Five binders were selected on the basis of climatic condition of locality, for study the performance of mixtures. List of binders used is given in **Table: 3.5.** These binders were collected from local depot., of the Jaipur city. Some normal physical test were performed to determine properties of these binders and results are given in **Table : 3.6.** and various tests are shown in **Fig. :3.4.**

Table 3.5: Binder type used in this study

Binder Type	Specification	
VG-30	Plain Bitumen	Viscosity grade 30
PMB-40	Polymer Modified Bitumen	penetration grade-40
CRMB-55	Crumb rubber modified Bitumen	penetration grade-55
WMA-E	Warm mix Asphalt	Evotherm additive with PMB-40 as a base binder
WMA-Z	Warm mix Asphalt	Zycotherm additive with PMB-40 as a base binder

WMA is a newest technology, developed to reduce the mixing and compaction temperature of hot mix asphalt without sacrificing the quality of the resulting pavement. Additon of WMA additive make it possible to prepare PMB-40 mix at

120°C. "Evotherm" is a product of Mead Westvaco's Asphalt Division and "Zycotherm" is produced by Zydex Industries. WMA may lower the optimum asphalt content, however researchers have practice to determine optimum asphalt content first with base binder and then additive is added. Than WMA mix is tested for confirming the volumetric and mechnical test peoperties of the mixture. PMB-40 was used as the base binder to produce Evotherm and Zycotherm emulsion. For preparing blend, Evotherm and Zycotherm additives were doped at the rate of 0.1% and 0.4% respectively, (as per guideline of additive production industry) by weight of base binder and then mixed by stirrer (700 rpm) at 155°C for 30 minutes using binder blander. (Kheiry et. al. 2014). The additive can also be added volumetrically as the density of Zycotherm is 1.01 gm/cc. The additive ZycoTherm and Evotherm in packed condition is shown in **Fig.3.3**

Fig. 3.3: Evotherm and Zycotherm additive used in this study

Table 3.6: Physical properties of binders

Physical properties of binder	Unit	VG-30		PMB-40		CRMB-55	
		Plain Bitumen of Viscosity Grade-30		(Elastomeric Thermoplastic Based)		(Modified Crumb Rubber Based)	
		(IS:73, 2006)		IS 15462 : 2004, IRC: SP:53, 2010			
		Test value	Specifica-tion	Test value	Specifica-tion	Test value	Specifica-tion
Penetration at 25°C, 100 gm, 5 sec (IS: 1203-1978 First Revision)	0.1 mm	52.5	50-70	40.6	30-50	55	<60
Softening Point (R&B) (IS: 1205-1978 First Revision)	°C	52.3	47 min	66.6	60 min	62	Min 55
Flash Point, COC, (IS: 1209-1978)	°C	260	220 min	280	220 min	290	220 min
Separation, difference in softening point (Ring & Ball Test)	°C	-	-	2	3 max	3	4 max
Ductility at 27/15°C (IS: 1208-1978 First Revision)	Centi-metre	81.44	75 min	64	50 min	-	-
Elastic Recovery of half thread in ductilometer at 15°C (IS: 1208-1978 First Revision)	%	NA	NA	75	Min 70	54	Min 50
Specific Gravity (IS: 1202-1978 First Revision).	Unit less	1.03		-	-	-	-
Kinematic Viscosity at 60°C Bitumen (IS: 1206-1978 First Revision),	Poise	3147	2400 Min	-	-	-	-

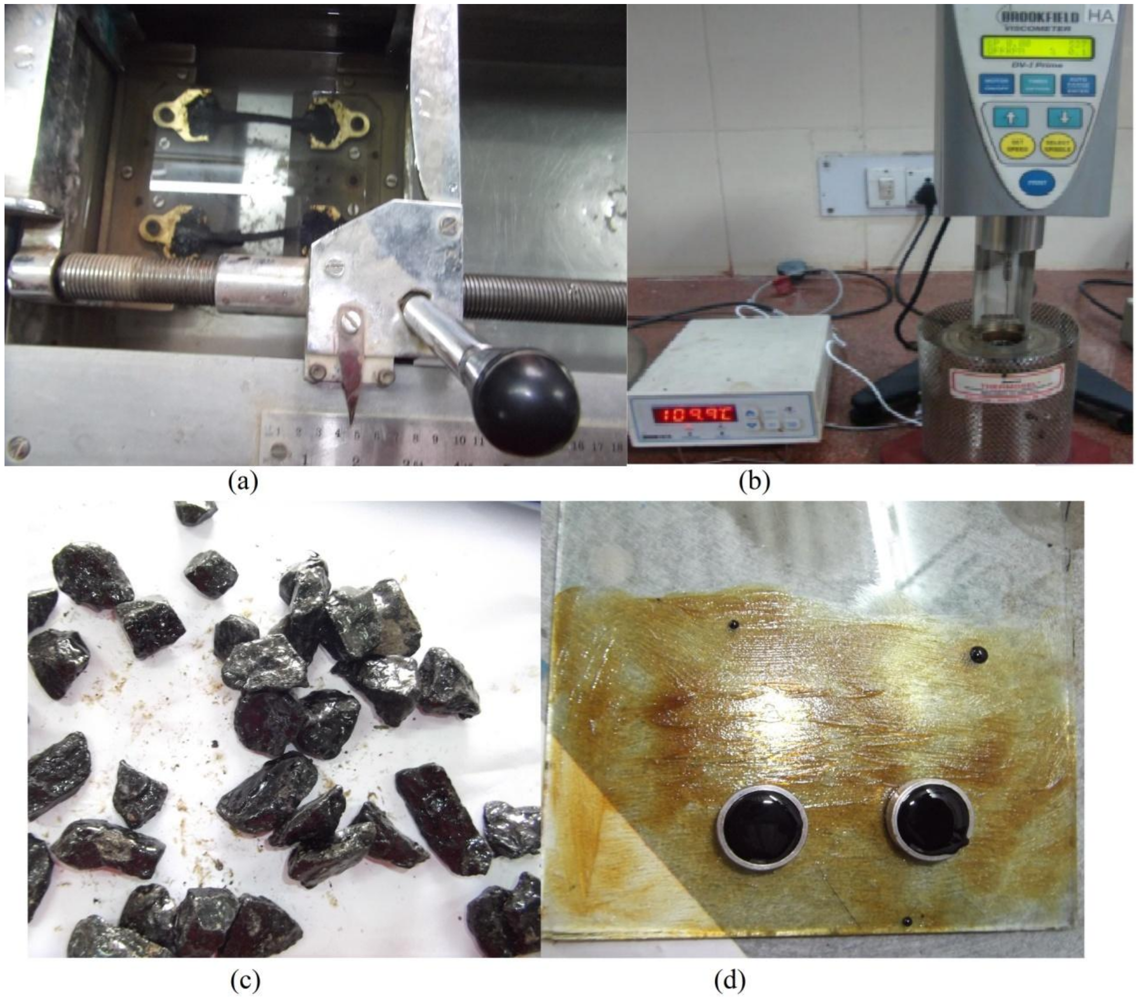

Fig 3.4: Various tests performed on Bitumen (a) Ductility Test (b) brookfield viscosity meter (c) Stripping test (d) Softening point test

3.3.2 SELECTON OF DESIGN GRADATION

Porous asphalt pavement design differs from traditional asphalt pavement design, as it allows rain water to freely pass through it and reduce amount of run off to a great extent. Coarser gradation of OGFC mix design as recommended by National Centre for Asphalt Technology (NCAT) using the nearby available aggregates, is adopted in this research work to maintain high air void of the OGFC mixes. Open gradation of the mixture is created by considering following facts-

1) For stone-on-stone contact condition of the OGFC mix without disturbing it's adequate permeability, aggregate passing 4.75 mm sieve should be less than 25%. In this research work 18.33 % aggregate is passing 4.75 mm sieve in designed gradation as shown in **Table 3.8.**

2) Open gradation of mix created by keeping 20 to 25 % air void in design mixes. In order to achieve the high percentage of air voids 50 to 60% coarse aggregate in mix should be of same particle size in between 9.5 mm to 4.75 mm sieve size with very little fines and fibers. In final achieved combined design gradation, 53.8 % particles are of same size that is in between 9.5 mm to 4.75 mm sieve size. (**Table 3.8)**

3) Open graded design with interconnected air void for proper flow of water is created by keeping particle passing 2.36 mm sieve (No. 8 sieve) less than 10% and filler should be between 2 to 4 percent. In the designed OGFC mix 6.8 % particle passing 2.36 mm sieve size and 3.31 % particle passing 0.075 mm sieve size and 3.0 % filler is used. (**Table 3.8)**

4) In adopted gradation 10-25% of aggregate are passing 4.75 mm sieve, while greater than 15% particle which passes, 4.75 mm sieve in a gradation are susceptible to significant binder draindown, hence cellulose fiber is to be added at the rate of 2.0 to 4.0 % by weight of total mix to reduce draindown.

5) Adopted gradation for OGFC mix design, as per NCAT specifications, is shown in **Table:3.7.** Sieve analysis of 19mm, 10mm, 6mm size aggregate, stone dust and lime was done and all constituents were mixed together for obtaining the desired gradation as given in **Table:3.8**, by adopting the method of 'Proportioning of Materials by Trial and Error Method' and thus the proportions of various aggregate sizes were obtained.

6) The typical S-curve showing upper and lower limit of gradation with mid value and achieved gradation is shown in **Fig.:3.5**

Table 3.7: Adopted OGFC mix GRADATION as defined by NCAT

Sieve	**Percent Passing**
19 mm	100
12.5 mm	85-100
9.5 mm	55-75
4.75 mm	10-25
2.36 mm	5-10
0.075 mm	2-4

Table 3.8: Sieve analysis of aggregate and Combined Gradation of OGFC mix

Sieve Size (mm)	Passing of Aggregates used		
	10 mm	6 mm	Stone Dust
19.00	100.00	100.00	100.00
12.50	79.39	100.00	100.00
9.50	35.17	100.00	100.00
4.75	0.11	24.08	100.00
2.36	0.79	1.55	89.08
0.0750	0.00	0.10	8.50

Sieve Size (mm)	% of Aggregates used in Job-Mix-Formula (JMF)						
	10.0 mm	6.0 mm	Stone Dust	Filler	Combined Grading Achieved	Mid Value	NCAT Specifications
	43%	51%	3.00%	3.00	100%		
19.00	43.00	51.00	3.00	3.00	100.00	100.0	100.00
12.50	34.14	51.00	3.00	3.00	91.14	92.50	85-100
9.50	15.12	51.00	3.00	3.00	72.12	65.00	55-75
4.75	0.05	12.28	3.00	3.00	18.33	17.50	10-25
2.36	0.34	0.79	2.67	3.00	6.80	7.50	5-10
0.075	0.00	0.05	0.26	3.00	3.31	3.00	2-4

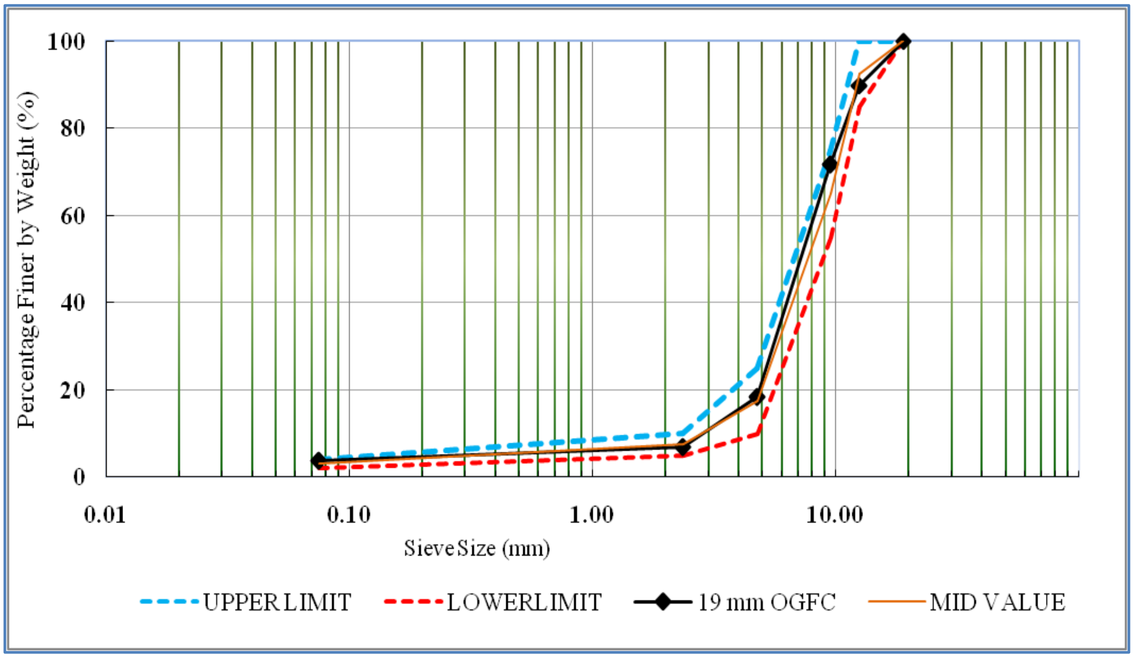

Fig.3.5 : Typical S-curve for OGFC Gradation

3.3.3 DETERMINATION OF OPTIMUM BINDER CONTENT (OBC)

Porous asphalt is significantly different from traditional dense graded mixtures in terms of mix design, behavior and functioning of the mixes. As a wearing course layer, it functions to expedite surface water removal. Binder Content is main characteristics of the mix as to ensure proper bonding between aggregate and binder. Traditional mix design methods which normally incorporates the Marshall test, are not appropriate to design porous asphalt because of the insensitivity of the Marshall stability values to variations in binder content. It is therefore appropriate to specify the design binder content (DBC) for porous asphalt rather than the optimum binder content. The design binder content incorporates an upper and a lower limit. The lower limit of the DBC can be dictated by requirements to resist disintegration while the upper limit is specified to limit binder drainage yet maintaining a porous structure that would promote permeability. Selection of OBC was done on the following basis-

i. OGFC mix blend were prepared at achieved desired gradation mentioned above for six binder contents (5 to 7.5 %) in increments of 0.5 percent for each binder type.

ii. The blend were evaluated for volumetric properties- void in coarse aggregate fraction (VCA_{MIX}) and void in coarse aggregate in dry-rodded condition (VCA_{DRC}) to ensure stone-on-stone in the mix as maintained in SMA mixture for better durability of mixture.

iii. When compared to conventional hot mix asphalt, OGFC mixtures generally have a higher asphalt content with little fine aggregates. As a result, OGFC mixtures must contain, suitable type and amount of some proper stabilizing additive, in order to control draindown and to retain the asphalt binder during production and placement. A maximum 0.3 % of draindown after one hour of test is recommended to minimize draindown. Draindown test for each design mix was conducted as per AASHTO T305 procedure..

iv. Cantabro abrasion test was performed on aged and unaged specimen to ensure resistance to disintegration of specimen.

v. Each mix specimen was compacted using 50 blows of Marshall Rammer on both faces and then air void contents were determined.

vi. The optimum asphalt content for OGFC mix should meet the following criteria:

1) a minimum of 18 percent air voids in compacted mix (higher values desired),

2) abrasion loss on unaged specimens not exceeding 20 percent,

3) abrasion loss on aged specimens not exceeding 30 percent and

4) a maximum draindown of 0.3 percent by total mixture mass.

vii. The binder content fulfils all the four requirements is selected as OBC. In case none of binder content meets the all criteria then remedial treatment (increase the dose of stabilizing agent or modifier) should be adopt.

viii. Marshall Stability and Flow Value of the mixture were determined.

ix. As per NCAT standard, freeze/thaw cycles test should be performed on compacted specimen for checking durability of OGFC mixture as its resistance to freeze-thaw damage. It is necessary to confirm the resistance to moisture-induced damage and effects of saturation and accelerated water conditioning under freezing and thawing cycles. But as per IRC, it is not required to perform this test as per Indian climate condition. Also in Rajasthan, the freezing temperatures is most rarely to prevail.

x. Moisture susceptibility of the mixtures were evaluated by conditioning the specimens in water. The retained tensile strength of the mix should be at least 80 percent.

Table 3.9: Mix Design Requirement of OGFC mix

S.No.	MIX DESIGN PROPERTY	PARAMETERS
1.	Cellulose fiber by total mixture mass	0.3%
2.	Number of Marshall hammer compaction	50 blow per side of Specimen
3.	Air-void in compacted mix	> 18 % or (20-24)
4.	VCA_{MIX}	$\leq VCA_{DRC}$
5.	Minimum Binder Content	> 6.0 %
6.	abrasion loss on unaged specimens	<20 %
7.	abrasion loss on aged specimens	<30%
8.	TSR	> 80 %

3.4 SMA MIX DESIGN

SMA is a new generation of pavement, applying successfully worldwide. Mix design of SMA is done as per standards and guideline of Ministry of Road Transport and Highway Manual Specifications for Road and Bridge Works (MORTH, 2013).

Combined aggregate gradation (coarse aggregate, fine aggregate and mineral filler) developed by MORTH, 2013 is adopted for this study. Stone Matrix Asphalt mix is designed in such a way to create stone-to-stone skeleton, as this structure is main quality of SMA, which carries traffic load and provide increased rutting resistance.

Aggregate and filler are proportioned and fully compacted in such a way, that the void in the stone skeleton exceed the volume of binder used by 3 to 5 %. Binder matrix alone is void less. The SMA mixture volume content over 60% of the coarse aggregate, approx 35% binder and 3 to 6% air void. The binder matrix contains 37% stone dust, 26% mineral filler and 37% asphalt binder.

SMA is a typical gap graded mix as illustrated in **Table 3.11** and typical S-curve gradation graph of mix is shown in **Fig. 3.6.** This study has produced a Marshall mix design procedure and material evaluation procedure for SMA mixtures. Factors evaluated were Los Angeles abrasion loss, flat and elongated particle content, mixture aggregate gradation, percent of filler finer than 0.02 mm, stone-on-stone contact, Air Void in the mix, VMA, asphalt binder content, compaction effort, draindown, moisture sensitivity, and rutting resistance.

The steps of SMA mix design are as follows:

1) Material selection
2) Selection of design gradation
3) Determination of Optimum Binder Content (OBC)
4) Marshall specimen prepared at desired gradation and OBC

3.4.1 MATERIAL SELECTION

SMA is a premium quality mixture requires high quality materials, as the mixture gains most of its strength from the stone-on-stone aggregate skeleton. Manufactured sands, mineral fillers, and fibers additive make a stiff matrix that is important to the rutting resistance of these mixes. As per MORTH specifications the bitumen for fiber- stabilized SMA shall be viscosity paving bitumen confirming to Indian Standard IS:73 or Modified Bitumen complying with IS:15462 and IRC:SP:53 of appropriate type and grade capable of yielding the design mix requirements.

Physical properties of all binders are summarized in **Table 3.5.** Same material (C.A., F.A., mineral Filler, Asphalt binder and stabilizing Agent) were used, as used for OGFC mix design and details & physical properties are presented in section **(3.4.1 to 3.4.4).** SMA mix design parameters are given in **Table 3.10.**

The main function of SMA mineral filler is basically to stiffen the binder rich SMA. But a higher percentage of very fine filler in the SMA mixture, may make mix susceptible to cracking. Hence percent passing 0.02 mm is restricted to use more than 20%. The minimum required asphalt content in SMA mixes as per IRC:SP:79 (2008) is 5.8%.

Table 3.10 : SMA mix design requirement

S.No.	Material	Specification
1.	Nominal Maximum Aggregate Size	13 mm
2.	Coarse Aggregate in the mix	70-80 %
3.	Bitumen Binder	> 5.8 % (5.5-7%)
4.	Filler	8-12 % of dry mass of aggregate
5.	Celluloid Fibers	0.2 to 0.4% by weight of the total mix (aggregate and asphalt binder)

3.4.2 SELECTION OF DESIGN GRADATION

After selection and testing of individual dry coarse aggregates, fine aggregates, filler and fiber, the aggregates were combined in desired gradation, as per following steps:

1) A range of 20-28 percent aggregates should pass the 4.75 mm sieve, which will help to ensure the formation of a proper coarse aggregate skeleton and stone-to-stone in the SMA mixtures.

2) 8-12 % amount of total aggregate should passes the No.200 sieve, to fill this requirement lime as a filler was added. This percentage is very large as compared to HMA, hence SMA performs in a very different manner and have to handle differently.
3) In a SMA mix, the percent passing 4.75 mm sieve must be below 30 percent to ensure proper stone-on-stone contact
4) Mixes were prepared with 5 to 7.5 % of binder at an increment of 0.5 % with each type of binder type. All mixes were tested for volumetric and mechanical properties using Marshall method..
5) Stone-on-stone contact, Void in the Total Mixtures (VTM), Voids in the Mineral Aggregate (VMA), asphalt binder content, and asphalt binder draindown, cantrabro abrasion and aging test parameters were evaluated for SMA mix design.
6) The SMA mixes prepared using this gradation can be used as a wearing course with nominal layer thickness ranging from 40 to 50 mm.

Table 3.11: Sieve analysis of aggregate and Combined Gradation of SMA mixes

Sieve Size (mm)	% Passing of Aggregates used		
	10 mm	6 mm	Stone Dust
19.000	100.00	100.00	100.00
13.200	88.33	100.00	100.00
9.500	34.17	100.00	100.00
4.750	0.76	23.20	100.00
2.360	0.71	3.55	93.05
1.180	0.65	2.9	67.06
0.600	0.50	0.90	57.30
0.300	0.45	0.56	37.07
0.075	0.00	0.49	14.08

Sieve Size (mm)	% of Aggregates used in Job-Mix- Formula (JMF)						
	10.0 mm	6.0 mm	Stone Dust	Filler	Combined Grading Achieved	Mid Value	MORTH Specifications
	50 %	33%	7%	10%	100%		
19	50.00	33.00	7.00	10.00	100.00	100.00	100
13.2	44.17	33.00	7.00	10.00	94.17	95.00	90-100
9.5	17.09	33.00	7.00	10.00	67.09	62.50	50-75
4.75	0.38	7.66	7.00	10.00	25.04	24.00	20-28
2.36	0.36	1.17	6.51	10.00	18.04	20.00	16-24
1.18	0.33	0.96	4.69	10.00	15.98	17.00	13-21
0.60	0.25	0.30	4.01	10.00	14.56	15.00	12-18
0.30	0.23	0.18	2.59	10.00	13.00	15.00	10-20
0.075	0.00	0.16	0.99	10.00	11.15	10.00	8-12

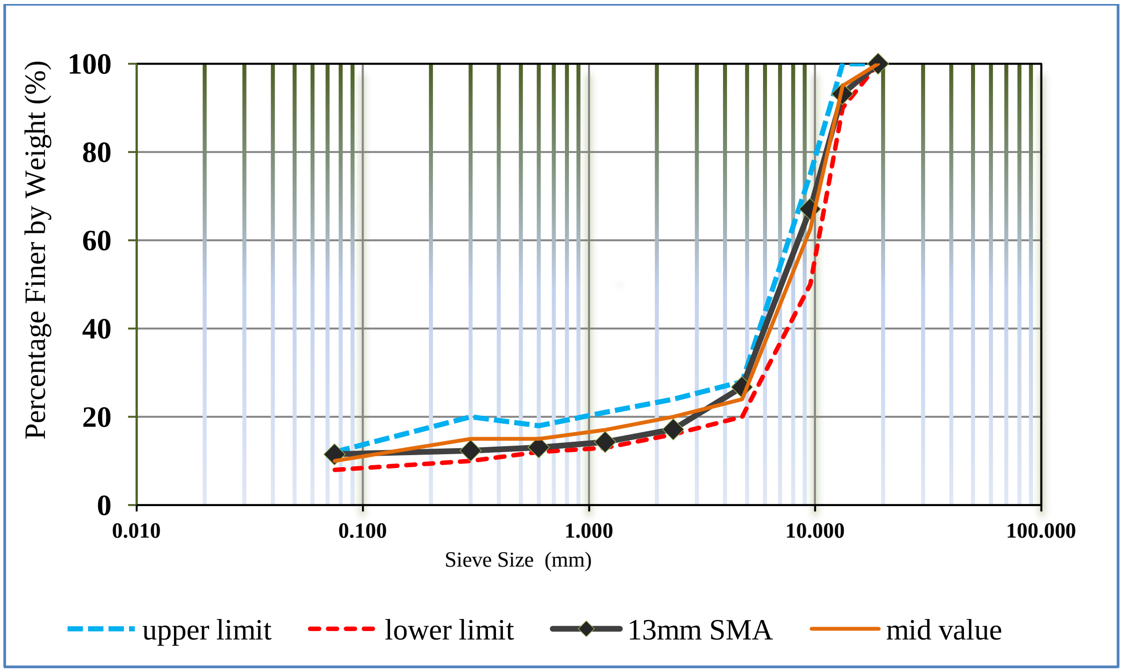

Fig.3.6 : Typical S-curve for SMA Gradation

3.4.3 DETERMINATION OF OPTIMUM BINDER CONTENT (OBC)

The amount or volume of binder is important for the durability of SMA mixtures. As per NCAT specifications, minimum asphalt binder content of 6 percent should be used in SMA mixtures. A reasonably high asphalt content for SMA mixture can be ensured by specifying a minimum asphalt content or a minimum VMA. To specify minimum VMA is better approach than other, especially when aggregate of higher specific gravity was used. As VMA is calculated on volume basis, is not affected by specific gravity of aggregate. The requirement of minimum VMA can be established, by limiting the gradation, so that 20-28 percent of the aggregate particle passes the 4.75 mm sieve. However, if aggregate are prone to break down excessively during compaction may not provide a mixture that meets VMA requirements. In general, when the Los Angeles abrasion loss is lower than 20, VMA can easily met and when abrasion loss is higher than 40, meeting the VMA requirement is more difficult.

Optimum binder content for proper bonding of aggregates was determined as per following steps-

1) Six trial mixes were compacted in Marshall mould with binder ranged from 5.0 to 7.5 at the increment of 0.5 %, for each type of binder
2) When they cooled at room temperature, the volumetric properties of each mix design is determined.
3) Following are volumetric properties calculation-

   Va % = $100 \times [1 - G_{mb} / G_{mm}]$

   VCA % = $100 - [(G_{mb} / G_{CA}) \times P_{CA}]$

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

Where,

Va	-	percent air voids in compacted mixture
VCA	-	voids in coarse aggregate fraction within compacted mixture
VMA	-	voids in mineral aggregate
G_{mb}	-	bulk specific gravity of compacted mixture
G_{mm}	-	theoretical maximum specific gravity (AASHTO T209)
G_{CA}	-	combined bulk specific gravity of the coarse aggregate fraction

G_{sb}	-	combined bulk specific gravity of the aggregates
P_{CA}	-	percent of coarse aggregate in the total mixture
P_s	-	percent of aggregate in the total mixture

4) Voids in the Compacted Mix (V_a)- The NCAT guideline recommended a SMA mixture design air void ranges of 3-4%, based on experience. One important concern of SMA mixes is the occurrences of fat spots. Fat spots are caused because of flushing of asphalt binder from SMA mixtures. This localized flushing of binder from mix surface are result of high asphalt content, Long haul distance, coarse gradation, inadequate stabilizer or very high mix temperature. All of these factor have a significant effect on air voids. A higher air void may cause fat spot while a lower air voids mixture may experience significant rutting. Setting to minimize air void to 3% is reasonable in both concern. As in case of warmer climate should be designed closer to 4.0 %.
5) A minimum asphalt binder content of 6 percent as per NCAT specification and a minimum 5.8 % binder should be used in SMA mixes, as per MORTH specification. This requirement can be used as reference but not needed as long as minimum VMA requirement are met. The minimum asphalt content can be neglected in favor of the minimum VMA requirement.
6) Mixture should be compacted with 50-blows of Marshall hammer to produce SMA mix of define density.

7) When compared to traditional hot mix asphalt, SMA mixtures generally have a higher asphalt content and more coarse aggregates. As a result, SMA mixtures must have suitable type and amount of some proper stabilizing additive, in order to control draindown and to retain the asphalt binder during production and placement. A maximum 0.3 % of draindown after one hour test is recommended to minimize draindown. Draindown test was conducted for each design mixes.
8) All trial blends were evaluated for mix properties. The optimum asphalt content meets the following criteria:-
    a. Air void limit 3-5%
    b. Voids in Mineral Aggregate (VMA) should be greater than 17%
    c. Voids in Coarse Aggregate for Mix (VCA_{MIX}), % Less than VCA_{DRC}
    d. abrasion loss on unaged specimens not exceeding 20 percent,
    e. abrasion loss on aged specimens not exceeding 30 percent and
    f. a maximum draindown of 0.3 percent by total mixture mass.

The design parameters shown in **Table 3.12** were selected for the SMA mix design

Table 3.12: Design Parameter of SMA Mixes

S.No.	MIX DESIGN PROPERTY	PARAMETER
1.	Cellulose fiber by total mixture mass	0.3%
2.	Laboratory Compaction Effort	50 Blow of Marshall hammer both side of Specimen
3.	Design Air-void	2-4 %
4.	VCA_{MIX}	$\leq$ VCA_{DRC}
5.	VMA (%)	min17 %
6.	VFB (%)	70-90
7.	Minimum Binder Content	> 6.0 %
8.	abrasion loss on unaged specimens	< 20 %
9.	abrasion loss on aged specimens	< 30 %
10.	Marshall Stability	6kN minimum
11.	Flow, 0.25 mm	8-16 (2-4 mm)
12.	Tensile Strength Ratio (TSR), AASHTO T283 (Annex E of IRC:sp:079, 2008)	Minimum 85 %

3.5 MARSHALL MIX DESIGN OF THE OGFC/ SMA MIXES

After determination of physical properties of the materials used and deciding the variables of the mix design, bituminous mix design was done according to the Marshall procedure specified in ASTM D1559.

The specified gradation of mineral aggregates and bitumen binder should be used as per NCAT/ MORTH specifications. The procedure for the Marshall method starts with the preparation of test specimens. The Marshall method uses standard test specimens of 64mm height and 102mm diameter. These were prepared using a specified procedure for heating, mixing and compacting the bitumen- aggregate mixture.

Five types of binders as already stated were used in different proportions in the mixes starting from 5% to 7.5 % with an increment of 0.5% of the total mix to obtain the optimum binder requirements and also to determine the effect of binder content and binder type on the mix properties. After some initial trials for preparation of OGFC/ SMA samples, a proper procedure could be developed.

Approximately 1200 g of mineral aggregates with fibers and binders were heated separately to the prescribed mixing temperature, given in **Table 3.13** and **3.14**. The temperature of the mineral aggregates was maintained at a temperature 10°C higher than the temperature of the binder.

Required quantity of binder was added to the pre heated aggregate-fiber mixture and thorough mixing was done manually till the color and consistency of the mixture appeared to be uniform. The mixing time was tried to maintained within 3 minutes. Mixing time may be extended (total 2-5 minutes) as to ensure homogeneously distribution of fibers throughout the mixture. The mixture was then poured in to pre-heated Marshall moulds and the samples were prepared using a compaction effort of 50 blows of Marshall hammer on each side as, 75 blows compaction is reported to result in significant degradation of aggregates as reported by Brown (1992). Also will not result in a significant increase in density over that provided with 50 blows. 50 blows of Marshall hammer is approximately equal to 100 revolutions of the Superpave gyratory compactor in terms of the resultant SMA density

The specimens were kept overnight for cooling to room temperature. Then the samples were extracted and tested at 60°C according to the standard testing procedure. The bulk density of compacted specimens was found out as per ASTM: D 2726. The vacuum pump set up as shown in **Fig. 3.8** was used to determine the theoretical maximum specific gravity of mixture at zero air voids as per ASTM D: 2041. After determining the bulk specific gravity of the test specimens, the stability and flow test was performed as per ASTM D: 6927.

The Marshall stability-flow value test apparatus is shown in **Fig. 3.7**

Table 3.13: Temperature during Marshall mix design Process

Bitumen	Bitumen Mixing (°C)	Aggregate Mixing (°C)	Mixed Material (°C)	
			Pan	Mould
VG-30	156	170	145	145
PMB-40	161	175	160	155
CRMB-55	156	170	155	150
WMA-E	120	130	100	100
WMA-Z	120	130	100	100

Fig. 3.7: Marshall Stability testing machine

Table 3.14: Percentage of Material in Marshall Specimen (in case of 6.0 % binder)

Aggregate	OGFC		SMA	
	Weight of Sample (gm)	% of Sample	Weight of Sample (gm)	% of Sample
10 mm	485	43	564	50
6 mm	575	51	373	33
Stone dust	34	3	79	7
Filler	34	3	113	10
Binder (6.0 %)	72	6	72	6

Fig. 3.8: Vacuum pump set up

3.5.1 MARSHALL STABILITY AND FLOW VALUE

Marshall test was performed to determine stability and flow characteristics of OGFC and SMA mixes. Marshall Stability of the mix is defined as the maximum load carrying capacity of the mixture at 60°C standard temperature and deformation that the specimen undergo during load is defined as flow value.

Marshall Specimen of OGFC mix were kept in water bath maintained at 60° C for a period of 30 minutes prior to testing at 60°C temperature. The time elapse between taking sample out of waterbath and testing should not be more than 30 seconds. Diametrical load at the rate of 50 mm per minute was applied on the compacted specimen till its failure. Stability and flow value were recorded from the respective dial gauges. And resistance of specimen to plastic deformation was measured. the physical property of specimen i.e. height, diameter and weight recorded before the testing. Following parameters were measured: stability, flow, unit weight, percentage air voids in total mix, voids in mineral aggregate (VMA) and voids filled by binder (VFB).

The mix design test results of OGFC and SMA mixes are presented in **Chapter 4.**

Marshall Specimen prepared at Optimum Binder Content (OBC) is shown in **Fig. 3.9**

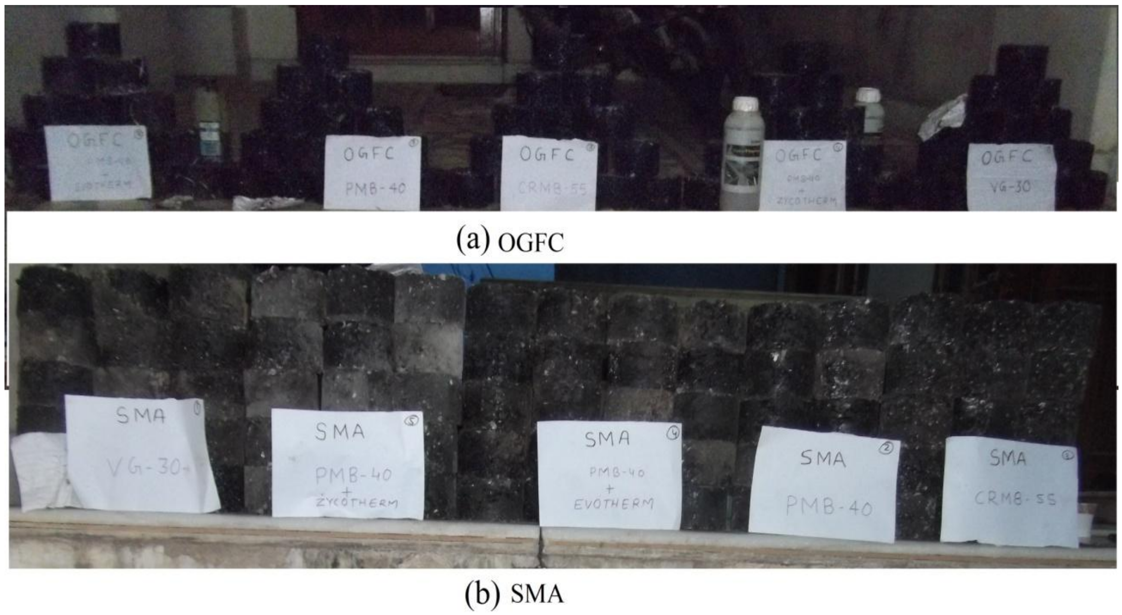

Fig. 3.9: Prepared Marshall Specimen at OBC

3.5.2 RETAINED STABILITY TEST

This test was performed as per ASTM D 1075-1979 to find out the retained stability of bituminous mould. This test measures the stripping resistance of a bituminous mixture. The standard Marshall specimens of 102 mm diameter and 64 mm height were prepared. The specimens were kept in water bath maintained at 60°C for 24 hours and thereafter tested for stability value as same as Marshall Stability test. The results are reported as the percentage of Marshall Stability determined in normal condition of the test.

3.5.3 VOIDS IN COARSE AGGREGATES (DRY RODDED METHOD)

Stone-on-stone contact in the mix is determined as per procedure developed by NCAT. Stone-on-stone contact is established when the VCA of the coarse aggregate fraction in a dry-rodded condition (VCA_{DRC}) is greater than VCA_{MIX} . After washing the coarse aggregate VCA_{DRC} is determined by compacting the aggregates in dry-rodded technique in accordance with ASTM C 29 (Annexure A of IRC:SP:079, 2008).

VCA_{MIX}: The volume in between the coarse aggregate particles. This volume includes filler, fine aggregate, air voids, asphalt binder, and fiber.

VCA_{DRC}: The volume in between the coarse aggregate particles of the final job mix formula in a dry rodded condition.

This may be calculated using the following equations:

$$VCA_{DRC} = 100 \times [(G_{CA}\gamma_w - \gamma_s) / G_{CA}\gamma_w]$$

$$VCA_{MIX} = 100 - (P_{bp} \times G_{mb} / G_{CA})$$

$$P_{bp} = P_s \times PA_{bp}$$

Where,

G_{CA}	bulk specific gravity of the combined coarse aggregate,(percent retained on the 4.75 mm sieve)
G_{mb}	bulk specific gravity of the compacted mixture

γ_w unit weight of water ($998 kg/m^3$)

γ_s unit weight of coarse aggregate, (retaining 2.36 mm sieve), in the dry-rodded condition (DRC) (kg/m^3) (AASHTO T 19),

P_{bp} percent aggregate by total mixture weight (mass), (retaining 2.36 mm sieve)

PA_{bp} percent aggregate by total aggregate weight (mass) (retaining 2.36 mm sieve

3.5.4 ABRASION TEST

Cantabro Abrasion test was conducted to measure, the resistance of compacted OGFC/ SMA specimens to abrasion loss and to evaluate the cohesion, bonding property of the mixes. This is an abrasion and impact test carried out on Marshall specimen (102mm height, 64mm dia), in the Los Angeles abrasion machine. ASTM C131 method was used to conduct the testing of the materials as per following steps-

1. Initial weight of each sample were taken to 0.1 grams and is recorded as W1
2. Individual samples were placed in a L.A. Abrasion machine, without the steel ball charge.
3. Test was performed at room temperature.
4. Machine was operated at the speed of 30 to 33 revolutions per minute up to 300 revolutions.
5. The test specimen is then taken out of machine and mass of each determined to the nearest 0.1 gram (W2)
6. The material loss from each specimen i.e. W2 -W1 is calculated

7. Particle loss for each test specimen is determine from following formula-

$$PL = \frac{(W_1 - W_2)}{W_1} \times 100$$

Where,

PL	=	Particle loss
W1	=	Initial sample weight (in grams)
W2	=	Final sample weight (in grams)

The recommended maximum permitted abrasion loss value for freshly compacted specimens is 20 percent . However, some European countries specify a maximum value of 25 percent.

3.5.5 AGING TEST

Both unaged and aged compacted OGFC were subjected to Cantabro abrasion test to evaluate the effect of accelerated laboratory aging on resistance to abrasion. Because of very high air void contents the asphalt binder in OGFC is prone to hardening at a faster rate than dense-graded hot mix asphalt (HMA), which may result in reduction of cohesive and adhesive strength leading to raveling. Therefore, the mix design should be subjected to an accelerated aging test. Aging was accomplished by placing five Marshall specimens in a forced draft oven set at 60°C for 168 hours (7 days). The specimens are then cooled to 25°C and stored for 4 hours prior to Cantabro abrasion test. The average of the abrasion losses obtained on 5 aged specimens should not exceed 30 percent, while no individual result should exceed 50 percent. The test was performed with each binder type separately, for both SMA and OFGC Marshall mixes.

3.5.6 DRAINDOWN

One of the important criteria in OGFC/ SMA mixes is to control the draindown of the binder. When compare to conventional hot mix asphalt, OGFC and SMA mixtures generally have a higher asphalt content and more coarse aggregate. In order to reduce the draindown of the binder, one can either increase the surface area of the aggregate skeleton or can use high viscosity binders. The surface area can be increased by using either fillers or stabilizers in SMA..

Draindown test was performed to decide maximum binder content of OGFC/ SMA mixtures for all five binder type as per Schellenberg's drainage test or ASTM D 6390 brinder drainage test procedure.

Prepared loose mixes at 175 ºC was placed on a plate in a wire basket of mesh size 6.3 mm. Drainage basket used in this study is shown in **Fig. 3.10.**. The mix on the plate in basket is placed in oven at approx 175°C (at mixing temperature or 15° C higher than mixing temperature). After one hour basket containing sample is taken out of oven, along with plate. Increase in mass of plate is noted.

A maximum draindown of 0.3 percent by weight of total mix is recommended for SMA and is also considered applicable to OGFC.

In order to achieve proper workability of the mix, the modified binders were heated to relatively higher temperatures compared to the unmodified binder. However, in order to avoid using two variables (binder type and test temperature) the draindown test was conducted at the same temperature for mixes with both unmodified and modified binders so that the influence of modification could be captured.

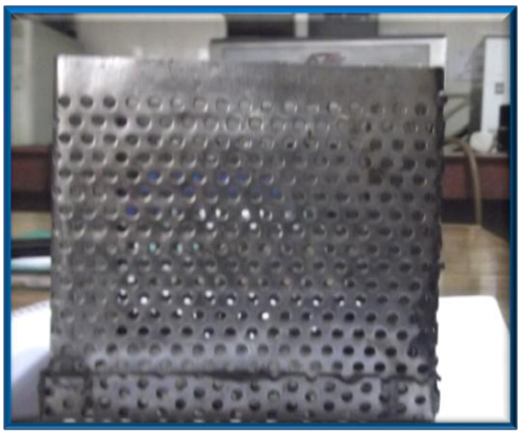

Fig. 3.10 Drainage Basket

The draindown of binder from the mixture was calculated using the following equation-

Draindown = (A/ B) * 100 %

A is the increase in the mass of plate

B is the initial weight of sample

3.6 PERFORMANCE TESTS ON BITUMINIOUS MIXES

The performance and durability of bituminous mixes were investigated through following laboratory tests.

1) Indirect Tensile Strength Test (ITS)
2) Tensile Strength Ratio (TSR)
3) Resilient Modulus (Mr)
4) Dynamic Creep Test
5) Wheel Rut Depth Test

The test method and parameters used in this study are as described below:

3.6.1 INDIRECT TENSILE STRENGTH TEST (ITS)

Property of mixture to distribute traffic stresses on the pavement surface or stiffness of the pavement can be measured in terms of tensile strength. In laboratory tensile strength characteristics of the mixture is measured by Indirect tensile strength test. ITS test result may also be used for estimating the potential for rutting or cracking to evaluate the relative quality of different OGFC/ SMA mixes. The indirect tensile tests were carried out as per specifications given in ASTM D 6931-07.

This test was conducted at 25°C, by applying diametric load to the cylindrical specimens with a deformation of 50 mm/minute (constant stress mode). In this test, the cylindrical specimens were subjected to compressive load between two loading strips with a concave surface having a radius of curvature equal to the nominal radius of specimen. The test set up for ITS is shown in **Fig.3.11**. The applied load creates tensile stress, perpendicular to and along the diametric plane causing splitting failure (tensile failure) of specimen. The maximum load at failure was recorded and indirect tensile strength was calculated by using the equation:

$$ITS = \frac{2000P}{\pi \, t \, D}$$

Where,

ITS	=	Indirect tensile strength	kPa
P	=	Failure load	N
D	=	Diameter of specimen	mm
T	=	Average thickness of specimen	mm

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

Fig. 3.11: Indirect Tensile Strength Test Set-up

3.6.2 TENSILE STRENGTH RATIO (TSR)

Moisture susceptibility or Moisture induced damage of OGFC/ SMA mixes was evaluated in terms of TSR, which is expressed as the percentage of average static indirect tensile strength of the conditioned specimens to the average static indirect tensile strength of the non conditioned specimens. Testing was conducted as per AASHTO T 283 specifications to evaluate the moisture-induced damage for mixtures. OGFC/ SMA mix specimens are conditioned in water bath maintained at

60°C for 24 hours, followed by placing the same specimens in a water bath maintained at 25° C for 2 hours and then subjecting these specimens to Indirect Tensile Test; the results of which are compared with the unconditioned specimens. TSR value more than 80 percent is considered acceptable.

TSR value can be calculate by the following equation:

Tensile Strength Ratio (TSR) = $(ITS_{WET/} ITS_{DRY}) * 100\ \%$

Where ITS_{WET} and ITS_{DRY} are average indirect tensile strength of wet and dry sample respectively.

3.6.3. RESILIENT MODULUS (Mr) TEST

Elastic property of OGFC/ SMA mixes is a important factor as design of flexible pavements has been carried out on mechanistic approach. The bituminous material are not elastic and there is a little or more permanent deformation after each load application depending on the load nature. Since, very small load is being applied on the bituminous mixes during the test, the same specimen can be utilized for testing the resilient modulus value of specimen under different loading and environmental conditions.

When a wheel load being applied at some point on the pavement surface, at a considerable distance from that point, the stress remains zero and at the same point , the stress becomes the maximum. Therefore, the stress pulse is assume to be a haversine or triangular loading in the test.

The standard ASTM D 4123- 82 (1995) covers procedure for preparing and testing laboratory-fabricated cores of bituminous mixtures to determine resilient modulus using the repeated-load indirect tension test..

The indirect tensile resilient modulus test was conducted using the Universal Testing Machine (UTM according to ASTM D4123). In this test, The resilient modulus test apparatus and fixtures are shown in **Fig 3.12 and 3.13** respectively.

The equipment is computer controlled and uses a pneumatic actuator to apply the load. A cylindrical specimens of diameter 102 mm and 64 mm height was used as test specimen. A compressive load in a form of haversine wave was applied in the vertical diametrical plane of cylindrical specimens through a loading strip and the resulting horizontal recoverable deformations was measured with the help of two linear variable displacement transformers (LVDT). The specimen is tested at four points of loading each perpendicular to one another The test was performed at three temperature i.e. 25°C, 35°C and 45°C, to simulate field condition. Each cylindrical specimen was kept in environmental chamber for 6 hours for conditioning before testing, at respective temperature of testing.

The samples were initially subjected to 5 condition pulses. A 1000 N peak load was applied along the vertical diameter of the sample. The pulse period and pulse width were respectively 3000 ms and 100ms while the rise time was 50ms pulse repetition of 1.0 second. Linear variable differential transducers monitored the resultant indirect tensile strain along the horizontal diameter. The resilient modulus of elasticity is calculated with an assumed Poisson’s ratio. Since the test is not destructive, upon completion of this test, the same specimen was used for Dynamic creep test. The resilient modulus of the mixes is calculated using the following relationship:

$$M_R = \frac{P(\mu + 0.2734)}{H\ t}$$

Where,

M_R	=	Resilient Modulus	(MPa)
P	=	Magnitude of Dynamic Load	(Newton)
μ	=	Poisson's ratio	
H	=	Recoverable Deformation	(Millimeter)
T	=	Mean thickness of specimen	(Millimeter)

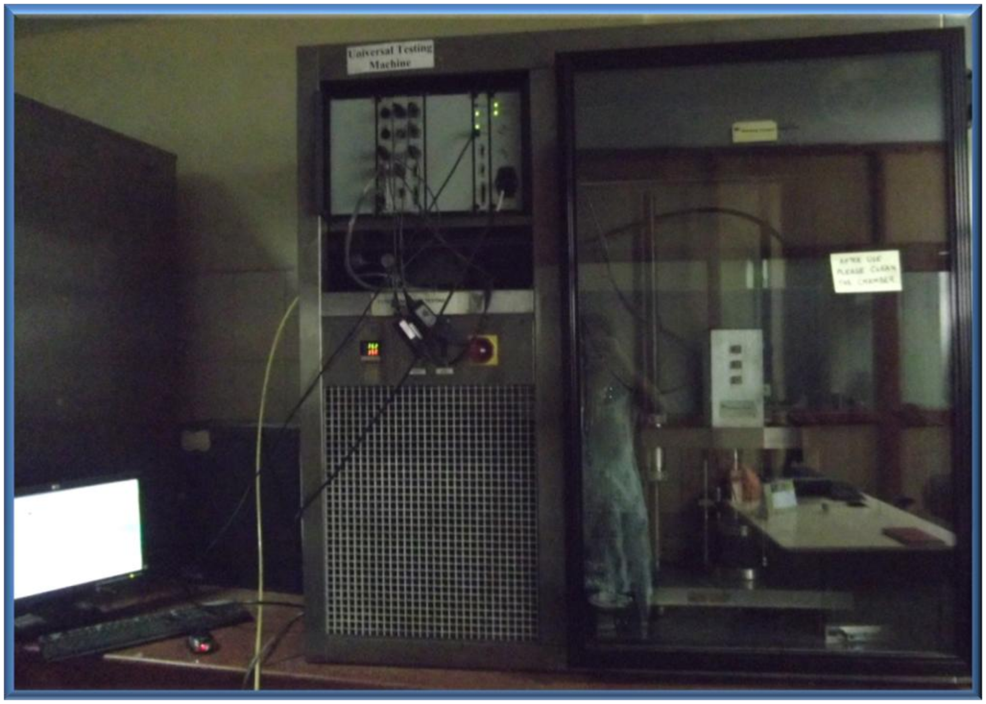

Fig. 3.12: Universal Testing machine (UTM)

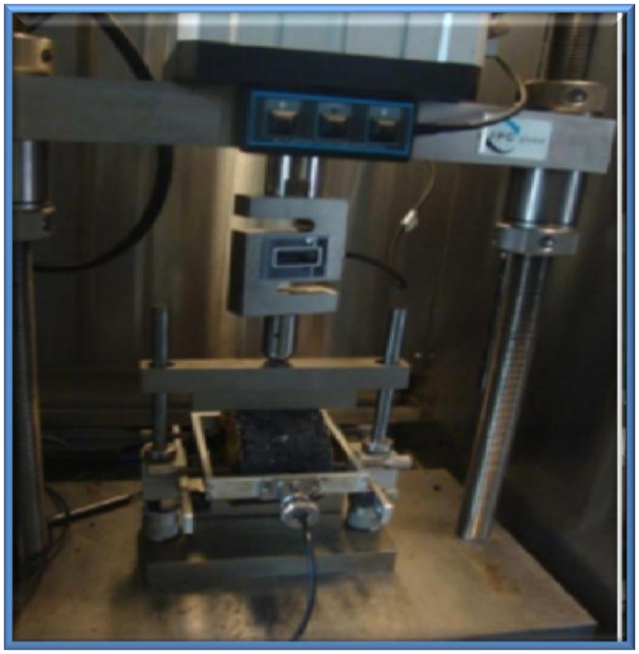

Fig. 3.13: Resilient Modulus test apparatus

3.6.4 DYNAMIC CREEP TEST

Permanent deformation is one of the an important factor to be considered in the design of OGFC/ SMA pavements. Higher traffic load and tire pressure occurs in the upper layers of pavement is the main cause of permanent deformation in pavement.

The grading, shape and texture of aggregates have great effect on deformation resistance. Mixes with angular and rough textured crushed aggregates shows better resistance to permanent deformation due to better interlocking than smooth and rounded aggregates. Resistance to permanent deformation is also depend on stiffness of binder, field temperature and method of compaction.

Permanent deformation of asphaltic mixes can be assessed in laboratory by static creep test, or dynamic creep test. Permanent deformation in paving materials develops gradually with increasing number of load applications, and it appears as longitudinal depression in the wheel paths accompanied by small upheavals at the sides. The creep test provides sufficient information to determine the instantaneous elastic (recoverable) and plastic (irrecoverable) component of deformation

In this research, resistance of the OGFC/ SMA mixes against permanent deformation was measured by dynamic creep test. This test simulates the passage of moving traffic loads on the pavement to study the permanent deformation characteristics of bituminous materials and its ability to resist the creep distress under repeated load.

OGFC pavement is typically suggested for higher and fast moving traffic level due to debris logging and higher construction cost. SMA pavement also recommended mainly for higher traffic load and higher speed pavement due to its improved performance and higher construction cost. Permanent deformation also increases due to increased traffic load and tire pressure in the upper layers of pavement.

The creep test provide much information about the mixes response characteristics. Either one cycle load/unload (static creep) or cyclic loading (dynamic creep) is used to interpret strain/time response of materials. creep test provides significant parameters, which describe the instantaneous elastic/plastic and viscoelastic/plastic components of the materials response (Mahrez , 2008).

The creep test was carried out using the Asphalt Universal Testing Machine in accordance with procedures outlined in ASTM D4123.

Dynamic creep test set up used in this study is shown in **Fig. 3.14** and close up of specimen in **3.15.**

In laboratory, accumulated strain was recorded by applying a repeated uniaxial load. Accumulated strain as a function of load cycles was recorded by LVDT's along the same axis. Cylindrical specimens of 101 mm x 64 mm (diameter x height) were kept in environmental chamber at 40°C for 2 hours. In this test haversine loading with cyclic stress 69 KPa and seating stress of 11 KPa was applied, which prevented the lifting of sample during rest period. The load cycle width was 100 ms (0.1 s) and rest period was kept 900 ms (0.9 s) i.e. Load cycle repeat time was 1000 ms. Preload stress was 20 kpa and preload time was 600 s. Confining stress was 100 kpa, Termination cycle count was 3600 and termination strain was 5%. The test was performed at 40°C and continued for 3600 cycles or up to the 10000 micro strains, whichever occurs first (approx 1 hour testing period for one specimen). The Dynamic Creep Test Parameters Adopted in this Study is shown below in **Table 3.15**

Table 3.15 : Dynamic Creep Test Parameters

Parameter	**Duration**
Pulse period (ms)	1000
Pulse width (ms)	200
Test Loading Stress (kPa)	100
Terminal Pulse Count	3600
Test Temperature	40°C

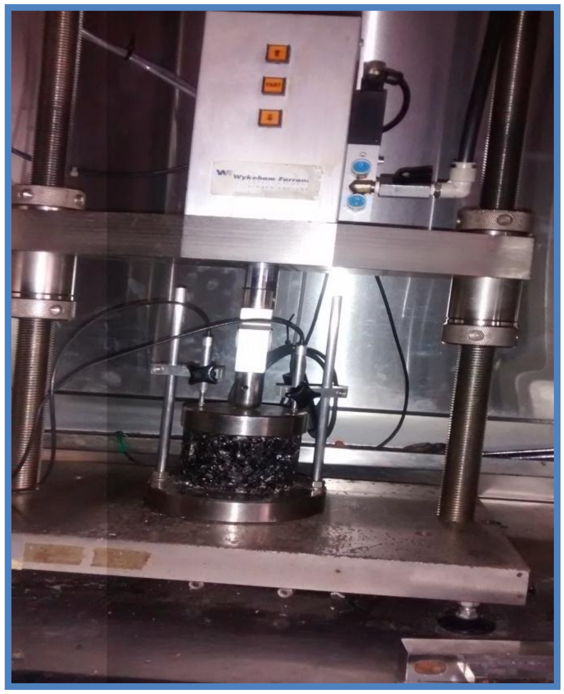

Fig. 3.14: Dynamic creep test set up

Fig. 3.15: Dynamic creep test specimen

3.6.5 Wheel Tracking Test

Rutting is one of the primary distresses in asphalt pavements, especially in hotter summer temperatures and/or under heavy loads. Permanent deformation in the pavement under wheel path of traffic is called Rutting.

Performance of the OGFC and SMA mix regarding susceptibility to rutting is evaluated by Hamburg Wheel Tracking Device (HWTD). Shown in **Fig. 3.19.** It simulates resistance to permanent deformation and correlate well with in-service pavement rutting. The standard HWTD wheel tracking test setup shown in **Fig. 3.18**

Due to the repetitive traffic loads on asphaltic pavement surface densification (volume change) and shear deformation take place, which caused Permanent deformation. Rate of permanent deformation depends on maximum aggregate size, proportion of filler and binder, binder type. The rate of permanent deformation increases with increase in test temperature.

The rate of permanent deformation increases with increase in temperature. Susceptibility of bituminous mixes to rutting can be measured by wheel tracking device (WTD).

It was used to measure the permanent deformation of OGFC mixes using a LVDT. This test was conducted as per BS: 598-1998 on the laboratory prepared OGFC/ SMA mixes slab specimen of size 300 x 300 x 50 mm. Shown in **Fig. 3.17.** The OGFC slabs were prepared using the roller compactor shown in **Fig. 3.16** to the target density. The sample was kept in environmental chamber for 2 hours at the 40°C prior to the testing. The test specimen was placed in a confined mold rigidly restrained on all its four sides. The test was performed at 45°C and 20000 passes were applied. Test duration is kept 480 minutes for each slab. A solid rubber steel wheel connected to a cantilever arm, bears on a load of 310 N was applied through and indent a straight track on the test specimen held on a reciprocating table. The contact area between the wheel and specimen was about 545.7mm^2, which gives a normal pressure of 566 kPa. The table moves to and fro beneath the wheel in the fixed horizontal plane with a frequency of 21 cycles per minute (42 passes per minute) and it travel a distance of 230±5 mm per cycle.

An automatic displacement measuring device which is connected to recording equipment is attached to the system to measure the vertical position of the wheel. The depth of the deformation was recorded at the midpoint of its length. A 20 mm maximum rut depth can be measured by using this system.

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Fig. 3.16: Slab Compaction machine

Fig. 3.17: Compacted SMA and OGFC Slab

Fig. 3.18: Wheel Tracking Test in progress

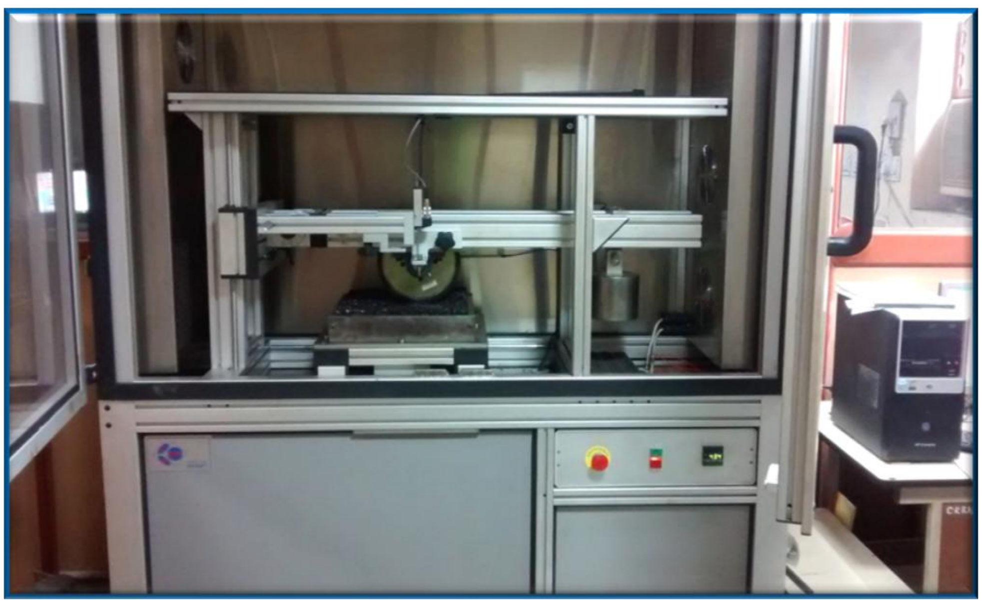


Fig. 3.19: Wheel Tracking Device Set-up

The performance and durability tests on OGFC and SMA mixes were conducted. The comparison of mixes with plain bitumen was done with modified and warm asphalt mixes was carried out. The results and analysis of these tests have been described in **Chapter 4.**

CHAPTER 4

ANALYSIS OF TEST RESULTS AND DISCUSSION

==

4.1 INTRODUCTION

The design of OGFC and SMA mixtures were carried out by Marshal mix design method, as per guidelines of NCAT and MORTH. It is mentioned earlier that five type of binders VG-30, PMB-40, CRMB-55, WMA-E and WMA-Z were used in the OGFC and SMA mix designs. Different volumetric and mechanical properties of the each type of mixes were found out. The detailed procedure of the experiments carried out on these OGFC and SMA mixes are given in the previous chapter. In this chapter the results and observations of the stability, cantrabro, drain-down etc. tests conducted are analyzed and discussed. Moisture susceptibility of the design mixes at OBC was examined by Tensile Strength Ratio (TSR) test. Durability of asphaltic mixes were evaluated through a series of performance tests in laboratory such as indirect tensile strength, resilient modulus, dynamic creep and rut depth by wheel tracking device.

This chapter is divided into five sections. In first section, result of various tests performed for OGFC mix design is presented. In second part, result of the various performance tests perform on OGFC specimen at OBC is discussed. In the third part, result of tests performed to prepare design mix of SMA is presented. In the fourth part result of the performance tests on the SMA specimen at OBC is analyzed. In fifth section comparison of the results of both the mixes is done.

4.2 TEST RESULT OF OGFC MIX DESIGN

Trial OGFC mixes were prepared to determine Optimum Binder Content (OBC). Selected desire gradation and aggregate proportioning are shown in previous chapter. Aggregates were mixed in proportion by taking 10 mm aggregate 43%, 51 % aggregate of 6.0 mm size and 3.0 % stone dust with addition of 3% filler by dry mass of aggregates at desired temperature. The trial mixes were prepared for each binder type with 5 to 7.5 % binder in increments of 0.5 percent . For controlling drain down Cellulose fiber were added at the rate of 0.3 % by weight of the total mix (aggregate and asphalt binder), on trial basis.

Detailed procedure of mix design of OGFC mix is explained in previous chapter. Results are discussed step by step in following section-

4.2.1 VOID IN COARSE AGGREGATE

Adopted OGFC mix design gradation with trial binder content for each binder type was checked for stone-to-stone contact. Void in coarse aggregate in dry rodded condition and Void in compacted mix is shown in **Table 4.1**

Table 4.1: Void in Coarse Aggregate test results

OGFC design mix type	$VCA_{(DRC)}$	VCA_{MIX}					
		Binder Content %					
		5.0	5.5	6.0	6.5	7.0	7.5
VG-30	43.6	37.8	37.8	38.5	38.5	39.6	39.8
PMB-40	43.6	37.9	37.9	38.8	38.9	39.8	39.9
CRMB-55	43.6	38.0	38.0	39.4	39.6	41.1	41.2
WMA-E	43.6	37.6	37.9	38.5	38.9	39.1	39.8
WMA-Z	43.6	37.9	38.5	38.9	38.9	40.6	41.1

As per above result, voids in dry rodded condition is higher for all the mixes at all six percentage of binder. Hence stone to stone contact can be maintained in the mix at all trial binder percentage for each binder type.

4.2.2 DETERMINATION OF OPTIMUM BINDER CONTENT (OBC)

As per NAPA [National Asphalt Pavement Association] specifications, the Optimum asphalt content for porous/ OGFC mixes is determined on the basis of two basic requirements i.e. binder content at which specimen have air void greater than 18%, and draindown less than 0.3%. However, advance recommendation of NCAT

[National Centre for Asphalt Technology], specimen should also check for cohesion and bonding property of mixes in both normal and conditioned specimen.

NCAT defines OBC for OGFC mixes as a binder content at which specimen met air voids greater than 18% and drain down less than 0.3% and in addition to these two, two more requirement should be met i.e. Cantabro Abrasion of un-aged specimens should be less than 20% and Cantabro Abrasion of aged specimens should be less than 30%.

In the present research work, advance standards recommended by NCAT for obtaining optimum binder content were adopted. Desire OGFC mixes were prepared at design gradation adopted for each binder type. On the compacted trial mixes following tests were performed to find out Optimum Binder Content (OBC) for each mix type-

1) Air void in mix
2) Cantrabo Abrasion Loss (Unaged)
3) Cantrabo Abrasion Loss (Aged)
4) Marshall Stability of mixes
5) Drain Down of binder (this test was performed on loose sample of trail mixes).

The test result of above experiments are shown in tabular and graphical form, for VG-30, PMB-40, CRMB-55, WMA-E AND WMA-Z. respectively in **Table. 4.2 to 4.6 and Fig. 4.1 to 4.5.**

Table 4.2 : Test results of trial mixes for determination of Optimum Binder Content (OBC) for OGFC mix design with VG-30 binder

S.NO.	Binder content %	Air Voids	Cantabro Abrasion Loss (Unaged)	Cantabro Abrasion Loss (Aged)	Draindown %
		Min 18 %	**Max. 20%**	**Max 30%**	**Max 0.3%**
1	5.0	32.06	43.25	55.10	0.223
2	5.5	28.31	35.62	42.36	0.298
3	6.0	25.03	30.35	38.89	0.355
4	6.5	24.09	28.17 .	35.36	0.492
5	7.0	26.11	19.20	28.21	0.589
6	7.5	28.32	13.60	24.21	0.883

(-The yellow colored cell/block in each table of this chapter, shows the value which is inappropriate as per NCAT standards of OGFC mix design)

From **Table 4.2**, it is clear that mix does not meet, all the requirements for any binder content. Although at all binder percentage mix have, sufficient air void content. From binder content percent 5.5 to 6.5% binder does not have proper bonding and cohesion, i.e. binder fail in cantrabro test both in aged and unaged condition. From 6.0 to 7.5 % binder content, mixes fail due to excessive draindown due to higher binder content. At 6.5 % binder content mix have higher abrasion loss in un-aged condition and at 7.5 % binder content mix design also fail due to less aging resistance potential.

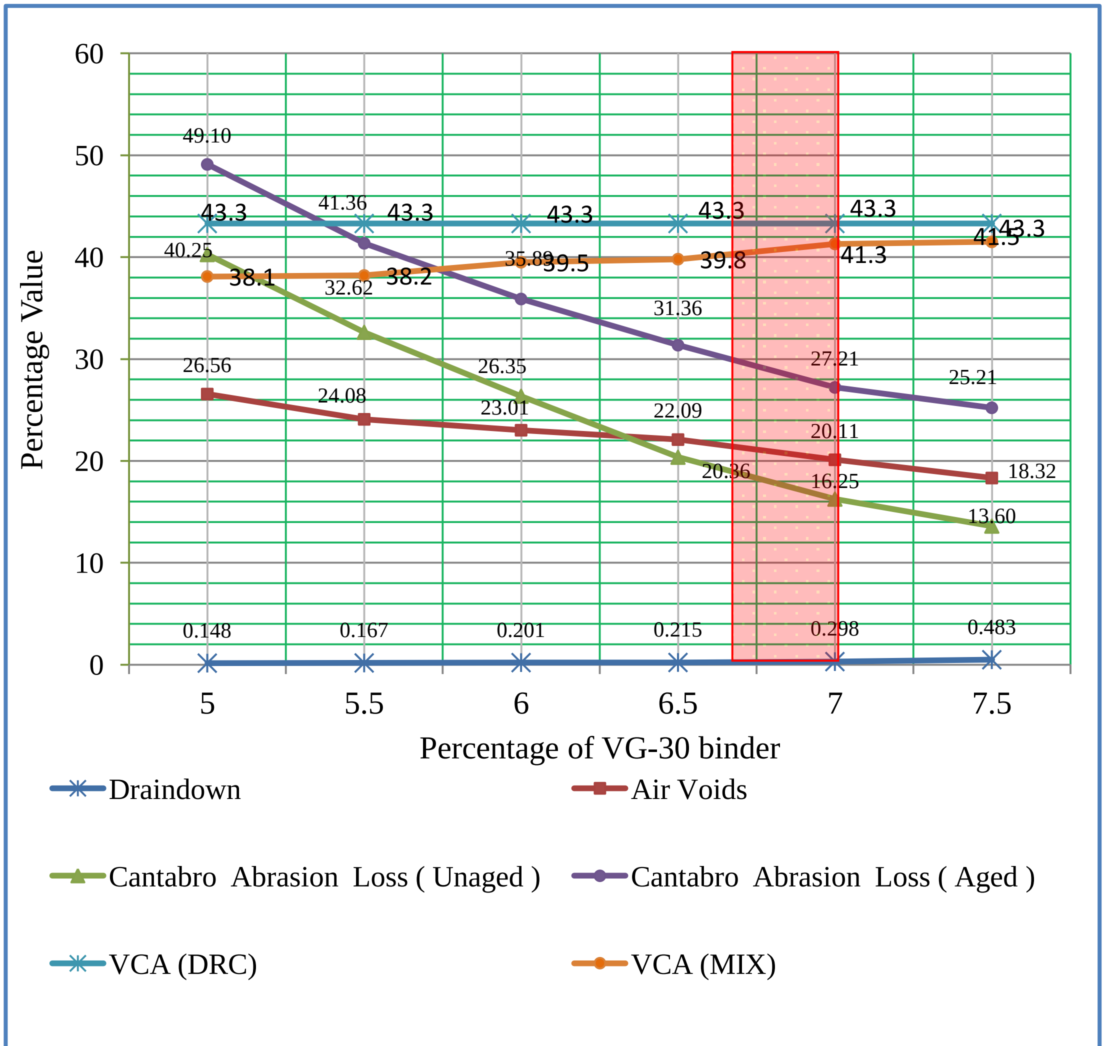
As a remedial treatment, amount of cellulose fiber was increased for reducing draindown and it will also improve abrasion loss and aging potential of the mix, to some extent. In next trial session, amount of cellulose fiber was increased from 0.3 % to 0.4 %. VCA_{mix} of compacted specimen with 0.4 % cellulose fiber is again calculated for confirming stone-to - stone contact in mix. as, result shows (**Table 4.3),** as VCA_{MIX} is less than VCA_{DRC} , stone-to-stone contact of the mix is maintained.

From **Table 4.3** and **Fig. 4.1,** at 6.75 to 7.0% range of binder content only VG-30 binder mix fulfills the all above mentioned requirements. Hence, optimum binder content with VG-30 was found to be 6.8 % for OGFC mix.

Table 4.3: Test results for determination of Optimum Binder Content (VG-30) for OGFC mix with 0.4 % cellulose fiber

S.NO.	Binder content %	Air Voids	Cantabro Abrasion Loss (Un-Aged)	Cantabro Abrasion Loss (Aged)	Draindown %	VCA $_{(DRC)}$	VCA $_{(MIX)}$
		Min 18 %	Max. 20%	Max 30%	Max 0.3%	VCA$_{(DRC)}$ ≥VCA$_{(MIX)}$	
1	5.0	26.56	40.25	49.10	0.148	43.3	38.1
2	5.5	24.08	32.62	41.36	0.167	43.3	38.2
3	6.0	23.01	26.35	35.89	0.201	43.3	39.5
4	6.5	22.09	20.36	31.36	0.215	43.3	39.8
5	7.0	20.11	16.25	27.21	0.298	43.3	41.3
6	7.5	18.32	13.60	25.21	0.483	43.3	41.5

([blue box] - The blue line/ row in each table of this chapter, shows the binder content at which mix shows all the recommended specifications of OGFC mix design).



(- Binder ranges in between two red line passes all the required specification of the OGFC mix design).

Fig 4.1: Determination of Optimum Binder Content using VG-30 binder for OGFC Mix

Table 4.4 : Test results of trial mixes for determination of Optimum Binder Content (OBC) for OGFC mix design with PMB-40 binder

S.NO.	Binder content %	Air Voids	Cantabro Abrasion Loss (Un-Aged)	Cantabro Abrasion Loss (Aged)	Draindown %
		Min 18 %	Max. 20%	Max 30%	Max 0.3%
1	5.0	29.56	38.05	51.23	0.155
2	5.5	26.03	26.09	35.03	0.193
3	6.0	24.13	16.10	24.12	0.248
4	6.5	23.06	9.69	19.32	0.305
5	7.0	20.32	8.23	20.36	0.448
6	7.5	23.46	15.60	35.96	0.691

As shown **in Table 4.4 and Fig. 4.2,** Range of suitable binder content, at which binder passes all the requirement are wider than VG-30. Results are also improved. PMB-40 binder shows better adhesion quality both in normal and aged condition. Air void also increases, may be due to less amount of binder. Optimum binder content on the basis of above desired specification and test results, with PMB-40 as a binder was found to be 6.0%.

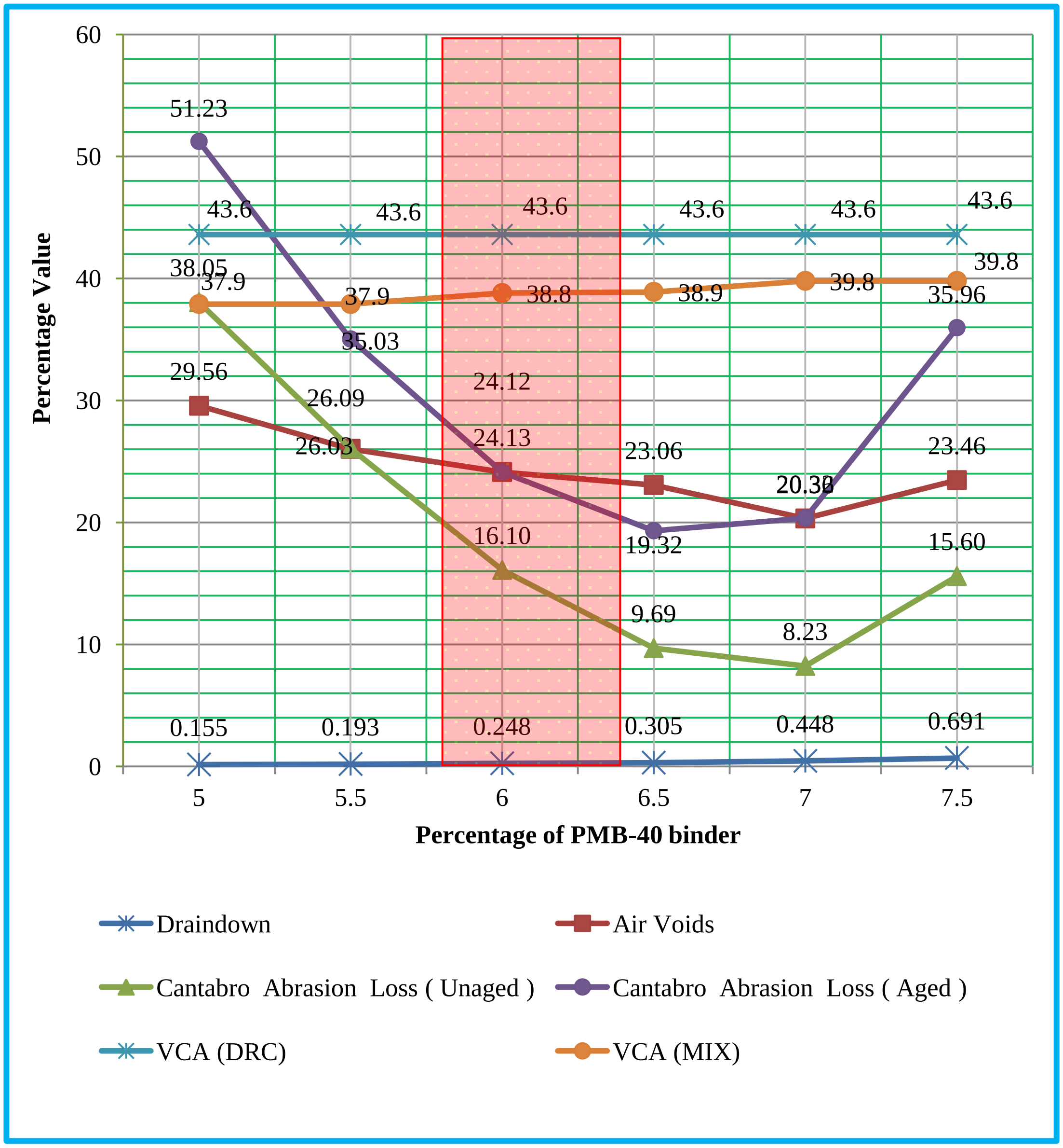


Fig 4.2: Determination of Optimum Binder Content using PMB-40 binder for OGFC Mix

Table 4.5 : Test results for trial mixes for determination of Optimum Binder Content (OBC) for OGFC mix design with CRMB-55 binder

S.NO.	Binder content %	Air Voids	Cantabro Abrasion Loss (Unaged)	Cantabro Abrasion Loss (Aged)	Draindown %
		Min 18 %	Max. 20%	Max 30%	Max 0.3%
1	5.0	27.73	38.31	48.29	0.156
2	5.5	25.17	27.53	35.61	0.185
3	6.0	22.48	19.10	31.30	0.213
4	6.5	20.06	11.65	25.03	0.278
5	7.0	24.85	9.10	20.04	0.481
6	7.5	26.60	14.50	27.94	0.582

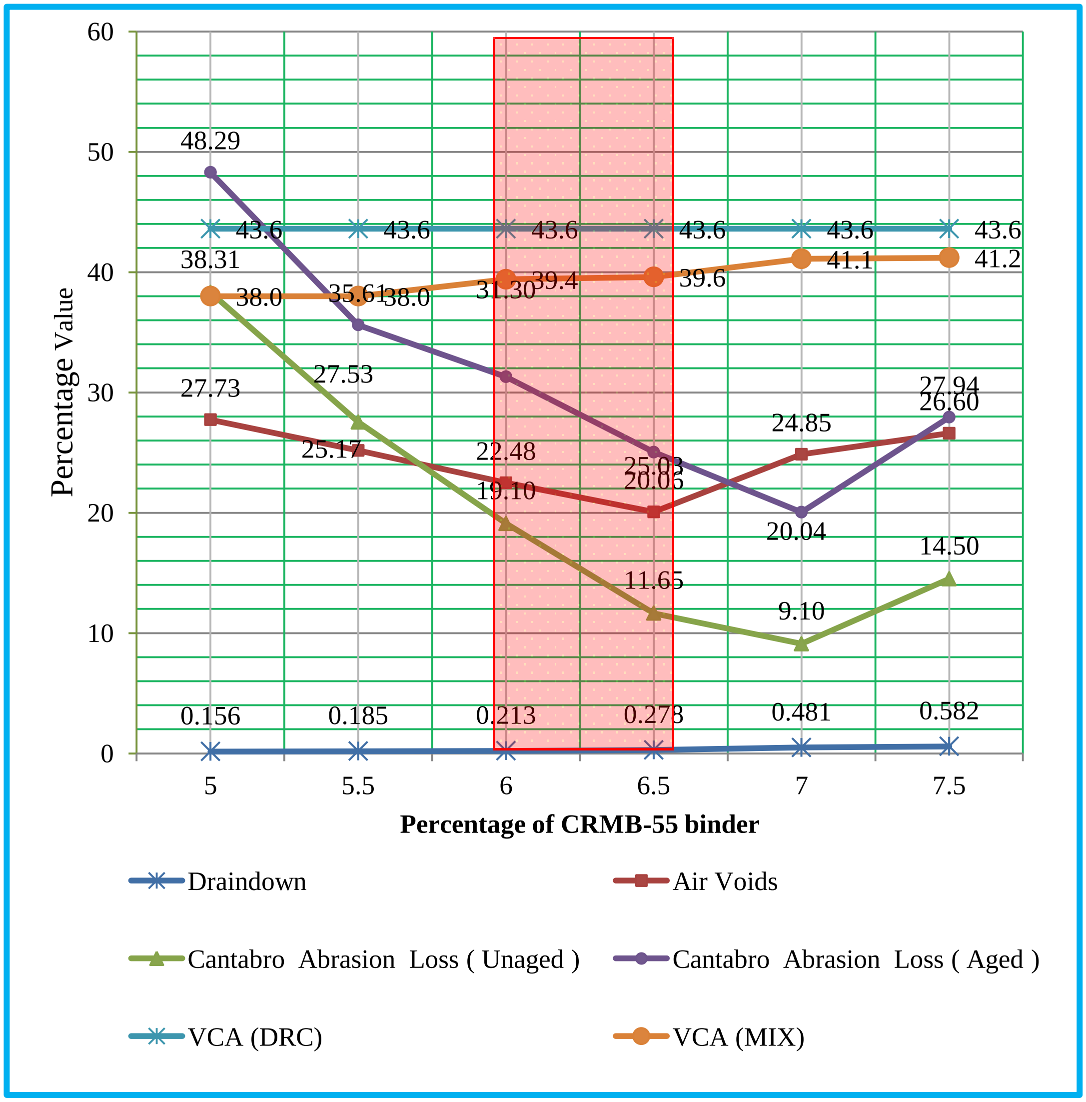


Fig 4.3: Determination of Optimum Binder Content using CRMB-55 binder for OGFC Mix

As shown in **Table 4.5 and Fig. 4.3,** CRMB-55 also improved the mix properties. Optimum binder content on the basis of above mentioned specification for OGFC mix and test results, with CRMB-55 as a binder is taken 6.5 %.

Table 4.6 : Test results of trial mixes for determination of Optimum Binder Content (OBC) for OGFC mix design with WMA-E binder

S.NO.	Binder content %	Air Voids	Cantabro Abrasion Loss (Un-Aged)	Cantabro Abrasion Loss (Aged)	Draindown %
		Min 18 %	**Max. 20%**	**Max 30%**	**Max 0.3%**
1	5.0	30.13	32.19	48.63	0.151
2	5.5	28.71	23.53	32.54	0.175
3	6.0	26.18	14.32	22.61	0.216
4	6.5	22.12	12.65	21.03	0.359
5	7.0	18.14	10.30	24.04	0.595
6	7.5	16.56	18.30	28.94	0.609

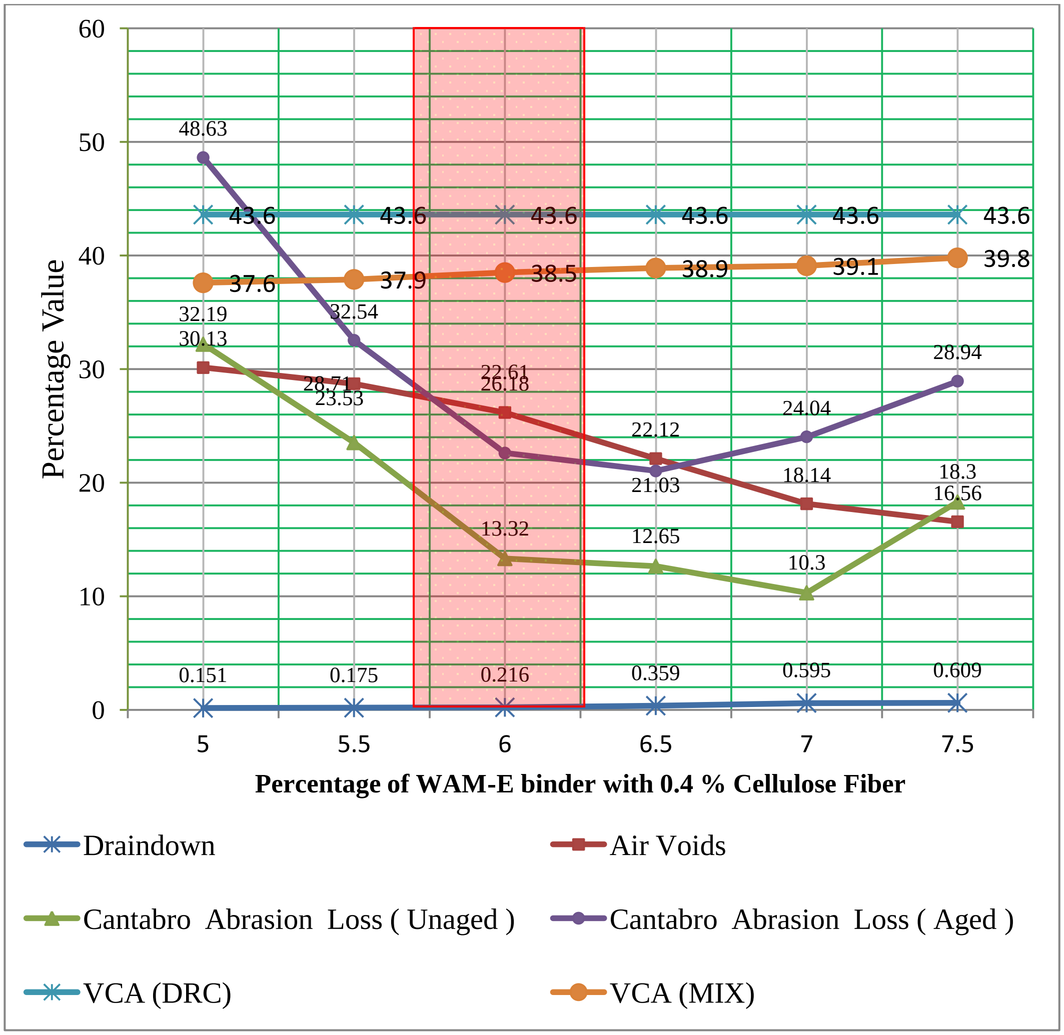


Fig 4.4: Determination of Optimum Binder Content using WMA-E binder for OGFC Mix

As shown in **Table 4.6 and Fig. 4.4,** WMA-E also improved the mix properties even at lower binder content. Optimum binder content on the basis of above mentioned specifications for OGFC mix and test results, with WMA-E as a binder is taken 6.0 %.

Table 4.7 : Test results of trial mixes for determination of Optimum Binder Content (OBC) for OGFC mix design with WMA-Z binder

S.NO.	Binder content %	Air Voids	Cantabro Abrasion Loss (Unaged)	Cantabro Abrasion Loss (Aged)	Draindown %
		Min 18 %	Max. 20%	Max 30%	Max 0.3%
1	5.0	30.21	33.19	42.65	0.182
2	5.5	28.09	24.37	35.30	0.200
3	6.0	24.46	12.32	24.11	0.219
4	6.5	23.06	8.36	20.03	0.319
5	7.0	18.41	15.69	28.32	0.521
6	7.5	15.6	25.36	34.31	0.664

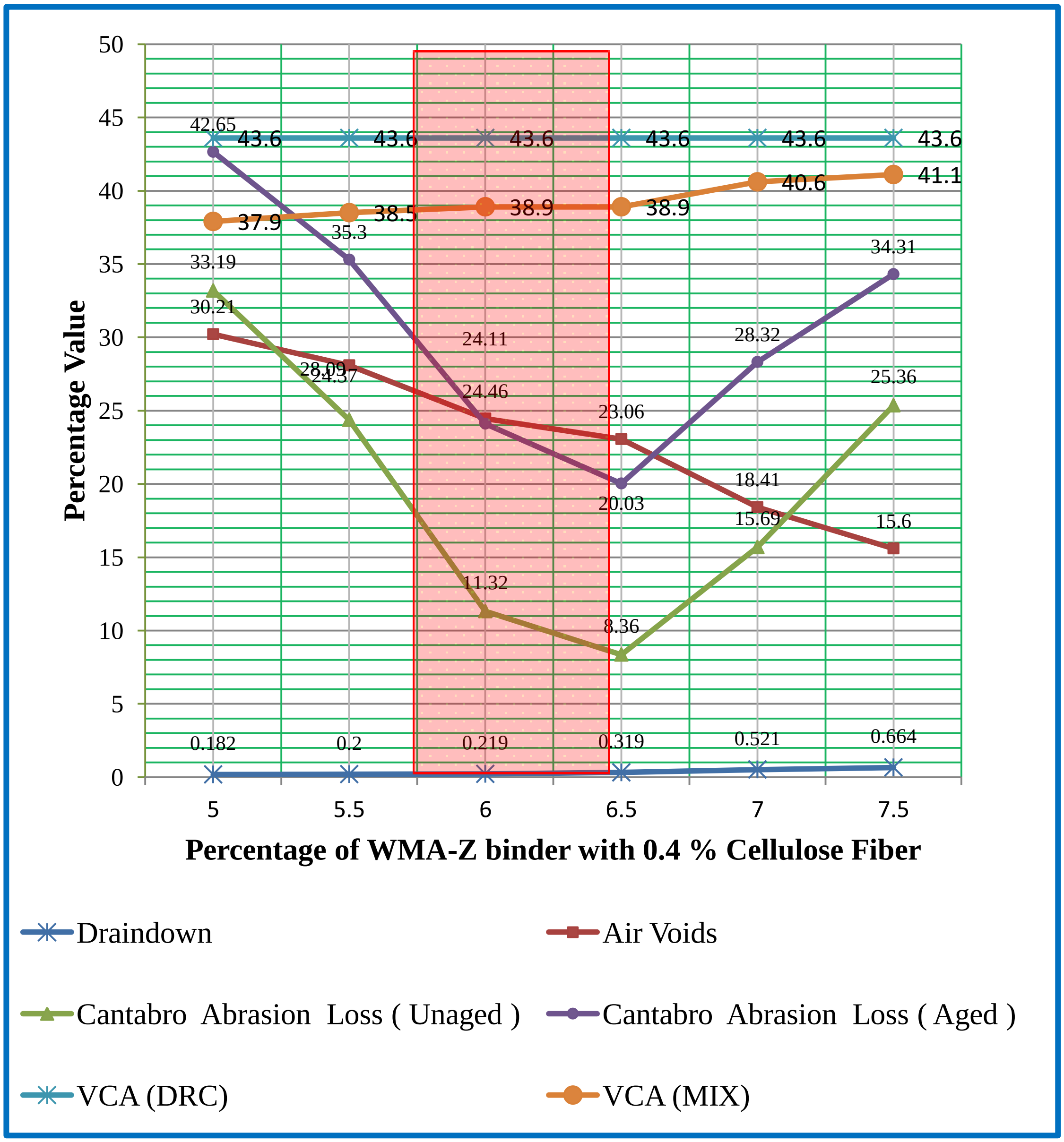


Fig 4.5: Determination of Optimum Binder Content using WMA-Z binder for OGFC Mix

As shown in **Table 4.7 and Fig. 4.5,** WMA-Z also improved the mix properties even at lower binder content. Optimum binder content on the basis of above mentioned specifications for OGFC mix and test results, with WMA-E as a binder is found to be 6.0% of total aggregate weight.

In all above test results, draindown performed as limiting factor for maximum binder content and abrasion loss value performed as limiting factor for minimum binder content.

4.2.3 Marshall Stability Of Various Mixes

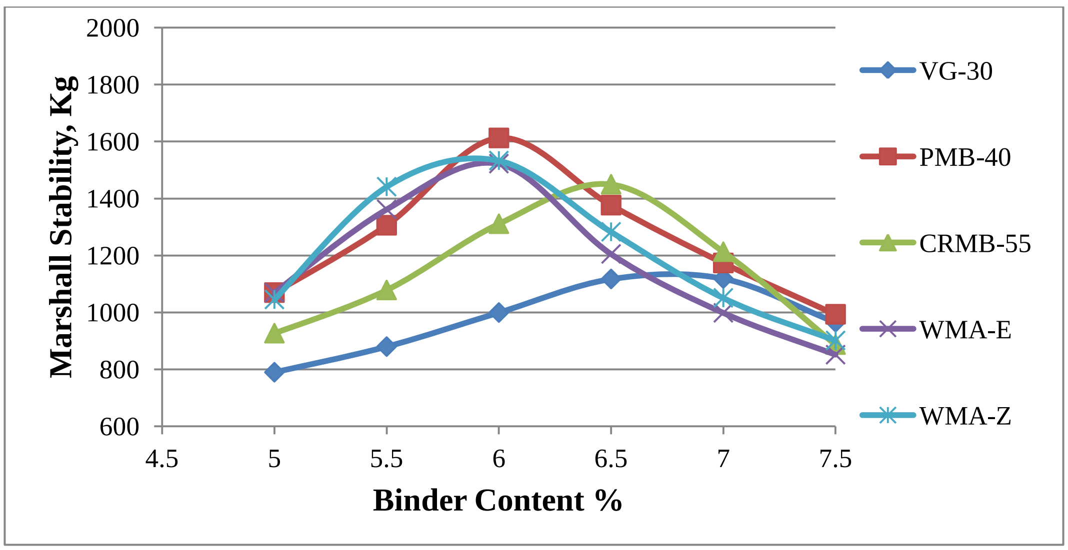


Fig. 4.6: Marshall Stability of OGFC mixes versus binder content with various binder

Stability test was performed to determine ability of OGFC mix to withstand traffic loads without distortion or deflection, especially at higher temperature. The curve of Stability versus bitumen content for the OGFC mixes with all type of binders are shown in **Fig. 4.6**. Results indicate that stability first increases up to a certain maximum value and then gradually decreases with the increase in bitumen content for the same mix. PMB-40 showed highest stability value and VG-30 showed lowest stability value. The value of Marshall stability was improved satisfactory with modified binder and warm asphalt mixes. PMB-40, CRMB-55, WMA-E and WMA-Z increased Marshall stability value of mix at OBC 44.18%, 29.60%, 36.13% and 37.03 % respectively in comparison to VG-30 bitumen.

4.2.4 TEST PROPERTIES OF THE OGFC MIXES AT OPTIMUM BINDER CONTENT (OBC)

OGFC mix properties at Optimum Binder Content (OBC) with all binder type used in this study, are shown in **Table 4.8.** Modified binder and Warm Mix Asphalt improved mix properties and also reduced optimum binder content. Optimum Binder Content value for VG-30, PMB-40, CRMB-55, WMA-E and WMA-Z binder was decided as 6.8%, 6.0 %, 6.5%, 6.0% and 6.0% respectively on the basis of results and specification of mix design. PMB-40, CRMB-55, WMA-E and WMA-Z reduces draindown of binder from mix up to 17 %, 7%, 28% and 27% respectively. Retained Marshall stability of OGFC mix at OBC was increased 73%, 48%, 65% and 66 % with the use of PMB-40, CRMB-55, WMA-E and WMA-Z respectively.

Table 4.8: Various test properties of OGFC Mixes at OBC

MIX DESGIN PROPERTY AT OBC	VG-30	PMB-40	CRMB-55	WMA-E	WMA-Z
Binder (% Total Weight of Aggregate)	6.8	6.0	6.5	6.0	6.0
Vv (Air Void in the mix) %	22.09	24.13	22.48	26.18	24.46
Vb (Air void in the mix) %	8.6	6.1	7.5	3.2	5.7
VMA (Void in Mineral Aggregate) %	30.7	30.2	30.0	29.4	30.2
VFB (Voids filled with bitumen) (%)	28.0	20.1	25.1	11.0	19.0
Bulk Density (gm/cm3)	1938.0	1958.0	1945.0	1950.0	1952.0
Draindown (%)	0.298	0.248	0.278	0.216	0.219
Marshall Stability Kg	1118	1612	1449	1522	1532
Marshall Stability of water conditioned Specimen	827	1434	1231	1369	1378
Retained Stability %	74	89	85	90	90
Flow Value (mm)	3.3	2.4	2.9	2.8	2.7

4.3 INVESTIGATING THE PERFORMANCE AND DURABILITY OF OGFC MIXES

The performance and durability of OGFC mixes were investigated through laboratory tests. At optimum binder content, additional specimens were prepared and following investigations were carried out to assess the performance and durability of bituminous mixes.

1) Indirect Tensile Strength (ITS)
2) Tensile Strength Ratio (TSR)
3) Resilient Modulus (M_R)
4) Dynamic Creep Test
5) Rut Depth by Hamburg Wheel Tracking Device (HWTD)

The method and parameters used to perform the above stated tests have already described in **Section 3.5**

4.3.1 Indirect tensile strength test result

For evaluating stiffness of the OGFC pavement, Indirect tensile test was performed both in normal and wet condition and test results are shown in **Table 4.9.**

Table 4.9: ITS test result of OGFC mixes with various binders

OGFC design mix type	Dry ITS (Mpa)	Wet ITS (Mpa)
VG-30	0.45	0.35
PMB-40	0.84	0.79
CRMB-55	0.55	0.46
WMA-E	0.72	0.63
WMA-Z	0.65	0.58

Due to higher void content, stiffness of porous asphalt mixture is lesser than dense graded mixtures, approximately one-half to two-thirds of dense-graded mixtures. Higher the percentage of voidss in OGFC, lower the stiffness of the mixtures.

Fig. 4.7 shows both normal and conditioned ITS value for each mix. PMB-40 shows highest ITS value both in dry and wet condition. Warm Mix Asphalt technology improve results even at lower compaction temperature i.e. reduce the chance of moisture damage due to lower temperature during compaction. CRMB-55 also improved results satisfactorily.

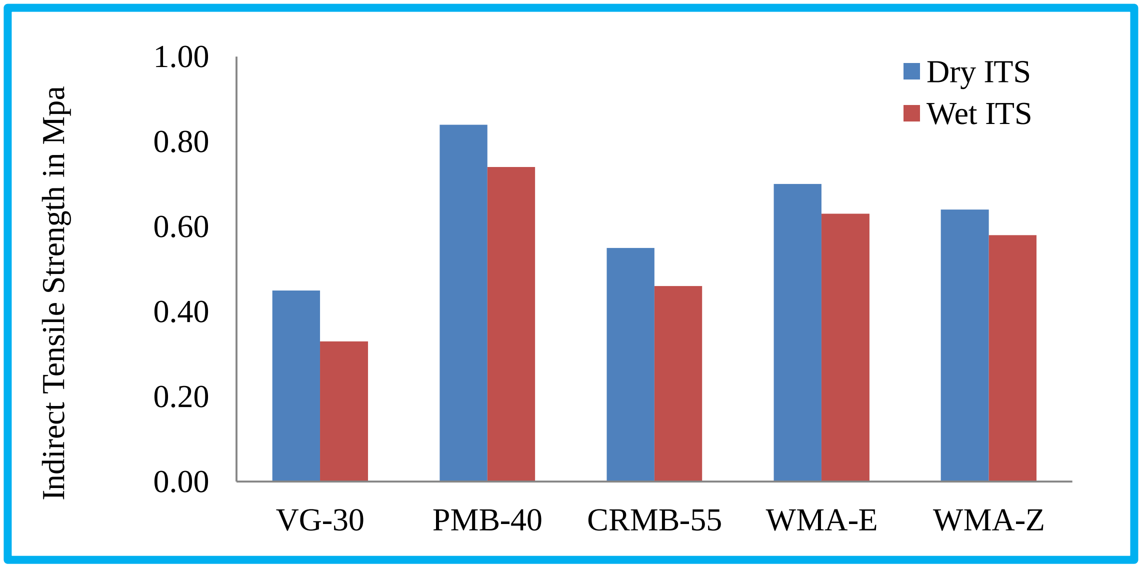


Fig.4.7 : Test results of Indirect Tensile Strength Test of OGFC mixes

The increase in normal condition ITS values with PMB, CRMB, WMA-E and WMA-Z mix was found to be 1.87, 1.22, 1.56 and 1.42 times respectively to that of the conventional asphalt mix. Improvement in conditioned ITS value with PMB, CRMB, WMA-E and WMA-Z mix was found to be 2.24, 1.39, 1.90 and 1.75 times respectively to that of conventional asphalt mix.

Increase ITS value with the addition of modified and warm asphalt in OGFC mixes might be due to improve adhesion or better interlocking action. As mentioned earlier Warm Mix Asphalts reduces binder absorption by aggregate thus provide higher effective binder content in matrix. In case of modified binders, this improvement may be due to improve tensile properties of the mixture with the use of polymer modified and crumb rubber modified binder. The mixes having higher value of ITS can withstand higher level of tensile strain prior to cracking.

4.3.2 Tensile Strength Ratio (TSR) Test Results

Moisture Susceptibility/ Moisture Sensitivity of the OGFC mixes was determined by tensile strength ratio test. The test results of OGFC mixes are shown in **Table 4.10**. the VG-30 mix showed the highest water damage, while the WMA-Z mix had the lowest water damage.

Table 4.10: TSR value of OGFC mixes with various binders

OGFC design mix type	**TSR %**
VG-30	73.33
PMB-40	88.10
CRMB-55	83.64
WMA-E	90.00
WMA-Z	90.63

Moisture Susceptibility/ Moisture Sensitivity As shown in **Fig.4.8,** VG-30 have 0.73 TSR value, which is less than acceptable value (0.80). Hence use of modified binder and warm mix asphalt are expected to improve the moisture susceptibility characteristics of OGFC mix.

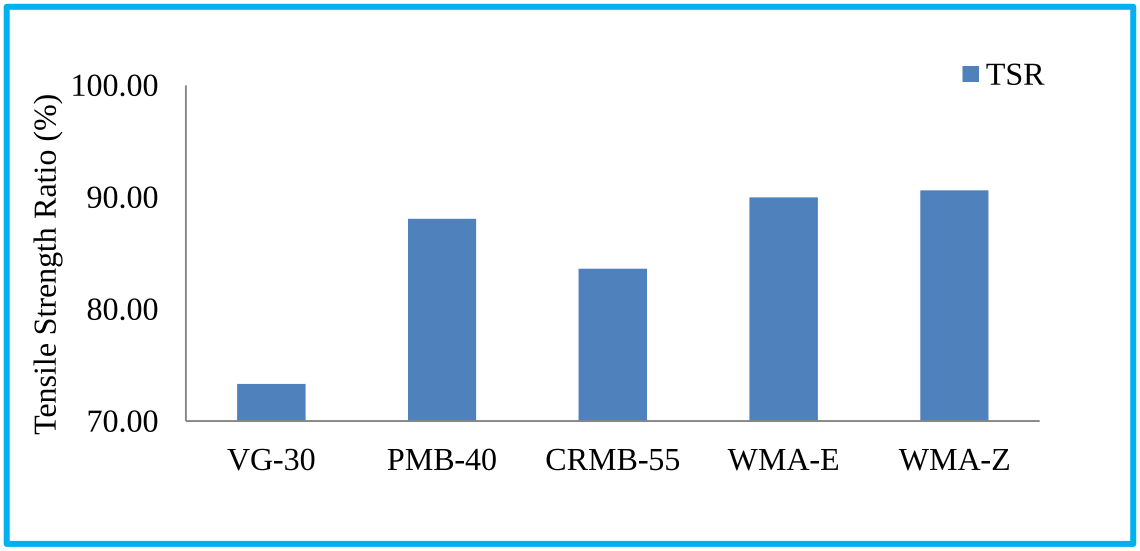


Fig.4.8 : Test results of Tensile Strength Ratio of various OGFC mixes

Percentage increase in tensile strength for mixtures with PMB-40, CRMB-55, WMA-E and WMA-Z was found to be approx 20.13%, 14.0 %, 22.73% and 23.58% respectively to that of conventional mix with VG-30 and It was felt that the results showed decreased pronounced tensile strength since the material was an open-graded mixture.

4.3.3 Resilient Modulus (Mr) Test

Resilient modulus tests were performed to measure elastic property of OGFC mixes with VG-30 in comparison to modified and warm mix asphalt, at three different temperatures. The test temperatures were selected, so as to simulate field temperature condition. Test was performed at Minimum, Medium and Maximum value of most prevailing field temperature i.e. 25°C, 35°C and 45°C on all OGFC mixes and results are shown in **Table 4.11.**

Table 4.11: Resilient Modulus value of OGFC mixes with different binder types.

OGFC design mix type	Resilient Modulus (MPa)		
	25°C	**35°C**	**45°C**
VG-30	3154	1493	814
PMB-40	4534	2925	1016
CRMB-55	3943	2612	811
WMA-E	7127	3957	1331
WMA-Z	6594	3871	1602

As shown in **Fig. 4.9,** WMA technology improved more resilient modulus qualities than modified binders. WMA-Z mix shows lowest drop in resilient modulus or elastic property at higher temperature. WMA-E mix showed highest resilient modulus at 25°C and 35°C. At 45°C, WMA-Z show highest M_R values. At low temperatures Modified binders showed no significant differences. PMB-40 improves mix quality at all the three temperatures. CRMB-55 mix were having higher M_R values at 25°C and 35°C, However lower M_R were observed at 45°C. The typical resilient modulus test results are shown in **Fig. 4.9**

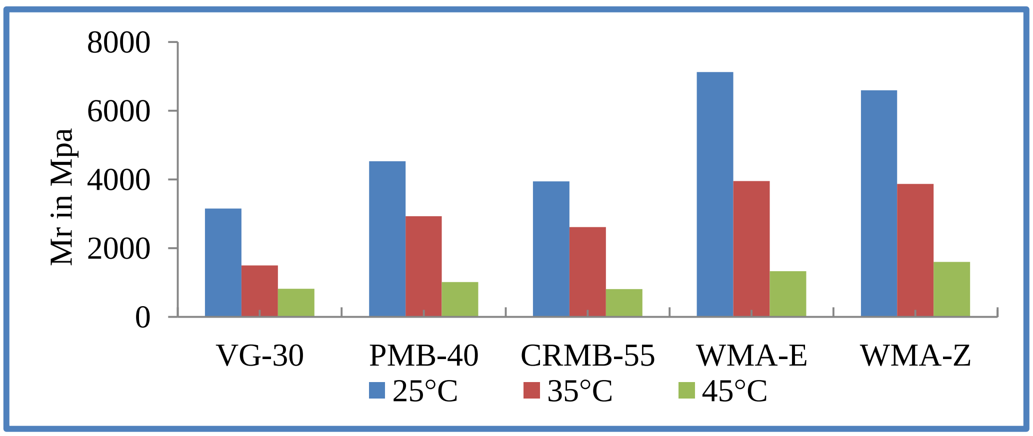


Fig. 4.9 : Resilient modulus Test Results of OGFC mixes with various binder type

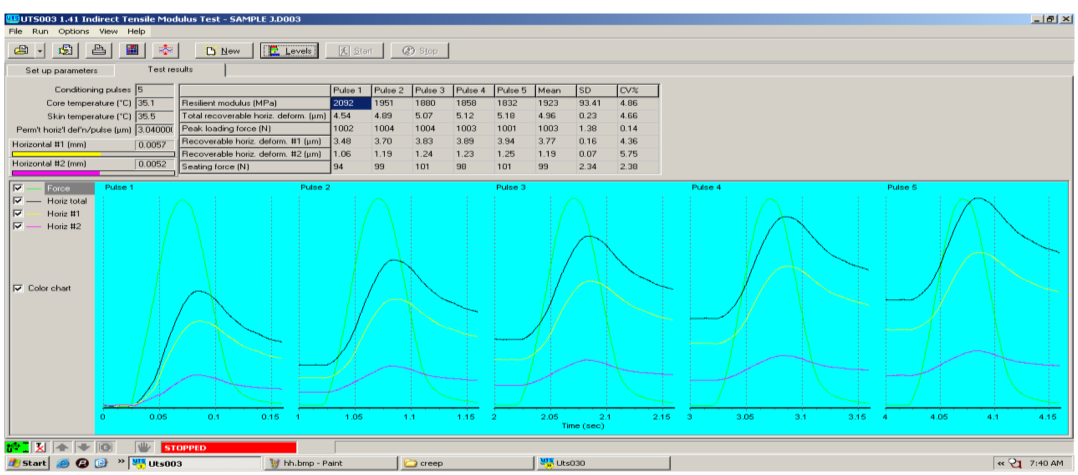


Fig. 4.10 Typical results of Resilient Modulus test in UTM

(Sample-SMA mix design with VG-30 binder @35°C)

4.3.4 Dynamic Creep Test Results

The resistance of the OGFC mixes against permanent deformation is measured by dynamic creep test. Dynamic creep test results on OGFC mixes in terms of percentage cumulative strain are presented in **Table 4.12**. In design of OGFC pavement, permanent deformation is a important factor. Decrease in the value of cumulative strain reflects improvement in resistance against permanent deformation and vice-versa.

Table 4.12: Cumulative Strain of OGFC mixes with all binder types

Type of binder mix	Cumulative Strain %
VG-30	51.3
PMB-40	18.2
CRMB-55	36.7
WMA-E	25.6
WMA-Z	44.3

Rate of increase of rut depth (permanent deformation) decreased with increased number of passes (cycles), the increase in deformation is essentially due to reduction in air voids. The rate of air voids reduction is higher (steeper slope) in the conventional mix when compared to rate of air voids reduction in modified and warm mix. The performance of the conventional mix is lower than the warm asphalt and modified asphalt mix. This might be possibly due to difference in internal structure evolution with number of passes for the mix with modified and WMA in comparison to plain bitumen. **Fig.4.11** shows the permanent deformation plotted against the number of passes for all type of binders ..

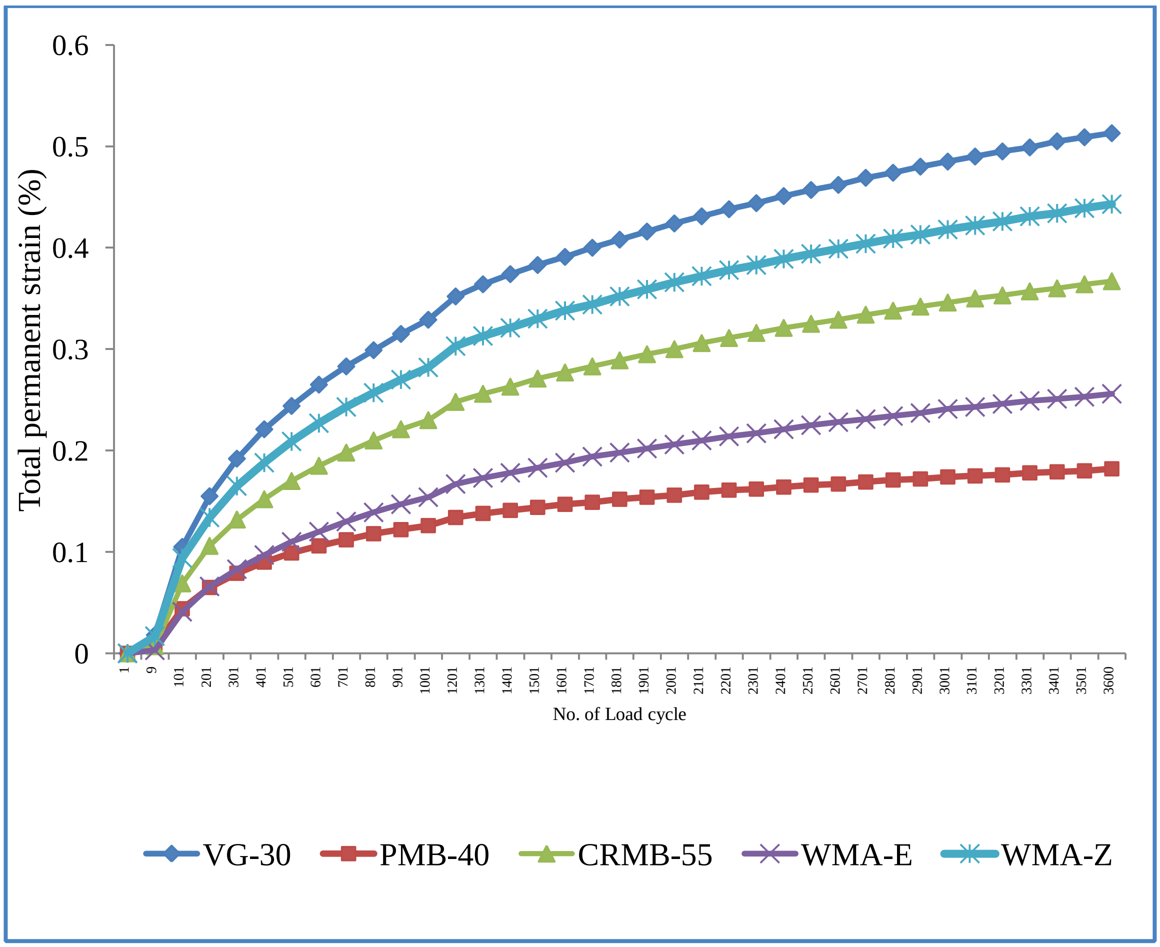


Fig.4.11: Cumulative Strain Vs No. of load Cycle Curve of creep test for various OGFC mixes.

When comparing to VG-30, PMB-40 reduced permanent deformation up to 64%, WMA-E reduced permanent deformation up to 50%, CRMB-55 reduced permanent deformation up to 29% and WMA-Z reduced permanent deformation up to 14%.

In case of OGFC, deformation is very much important factor. Higher deformation reduces air void content which adversely affect its drainage function. The typical test results in form of software generated graph is shown in **Fig.4.12**

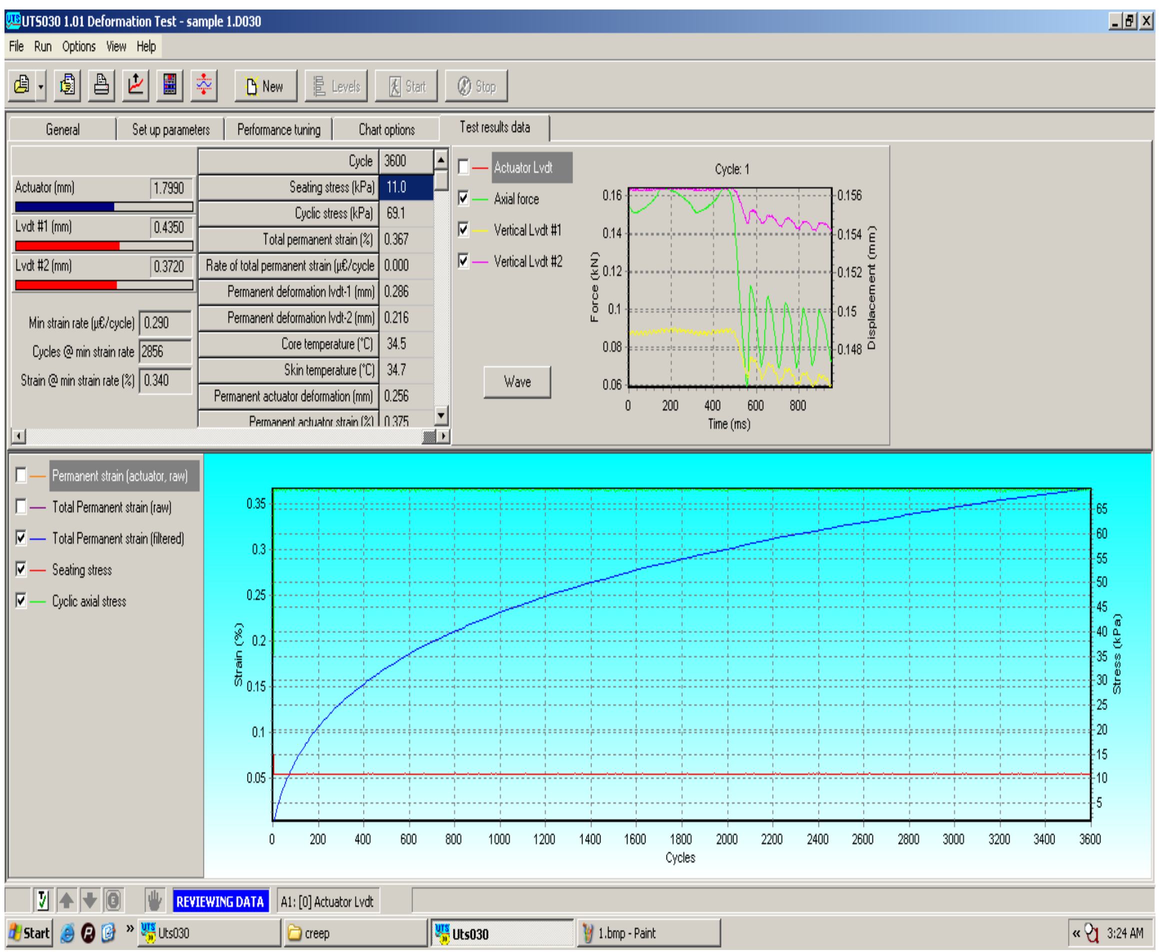


Fig. 4.12: Typical results of Dynamic Creep test in UTM (Sample-OGFC mix design with CRMB-55 binder)

4.3.5 Wheel Tracking Test

A wheel-tracking test was performed to evaluate the rutting characteristics of OGFC mixes. Final rut depth after 20,000 passes of wheel are shown in **Table 4.13**

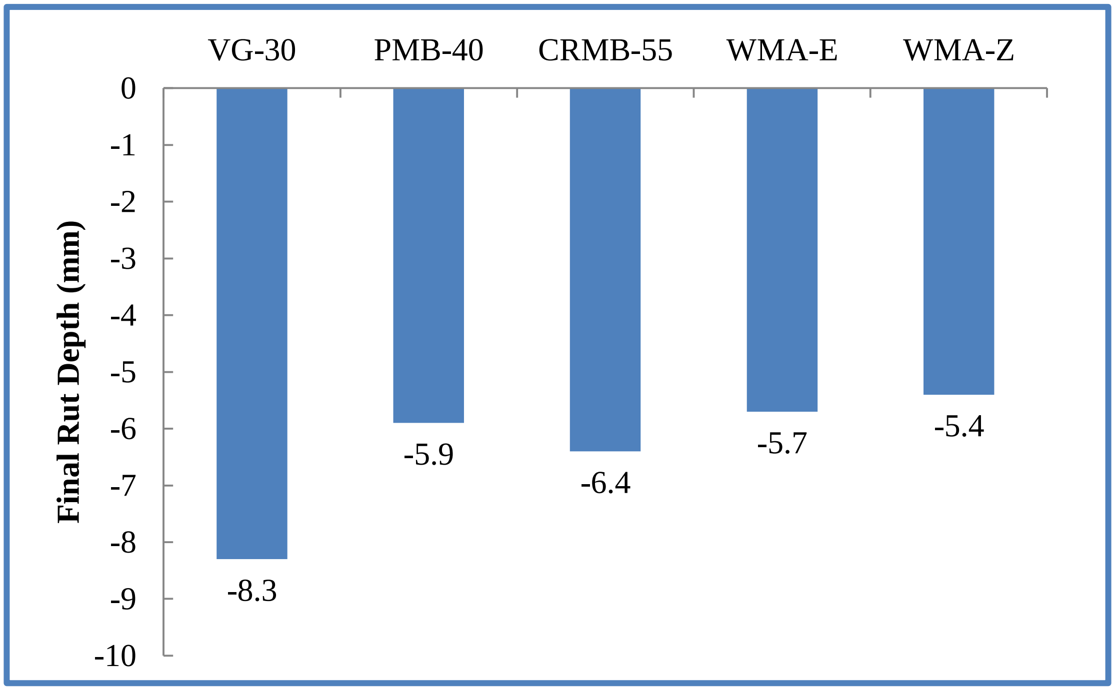


Fig. 4.13: Rut depth of OGFC mixes by wheel tracking device

Rut depth test results indicated that due to lower compaction temperature of WMA, the mixtures with WMA-Z showed lowest rutting. PMB-40 reduces rut depth up to 28.92% ,CRMB-55 reduced rutting up to 22.89%, WMA-E reduced rutting up to 31.32% and WMA-Z reduced rutting up to 34.94% as compared to conventional VG-30. Typical test result of Hamburg Wheel Tracking Device (HWTD) Hamburg Wheel Tracking Device (HWTD) is shown in **Fig. 4.13.**

From above results, it is also concluded that rutting test value of OGFC mixes is more correlated with M_R test result value than Dynamic creep test result value. In Wheel rut depth test and Resilient Modulus test, WMA perform better than modifier binders while in Dynamic creep test Polymer modifier binder perform better than Warm Mix Asphalt and CRMB-55, perform better than WMA-Z.

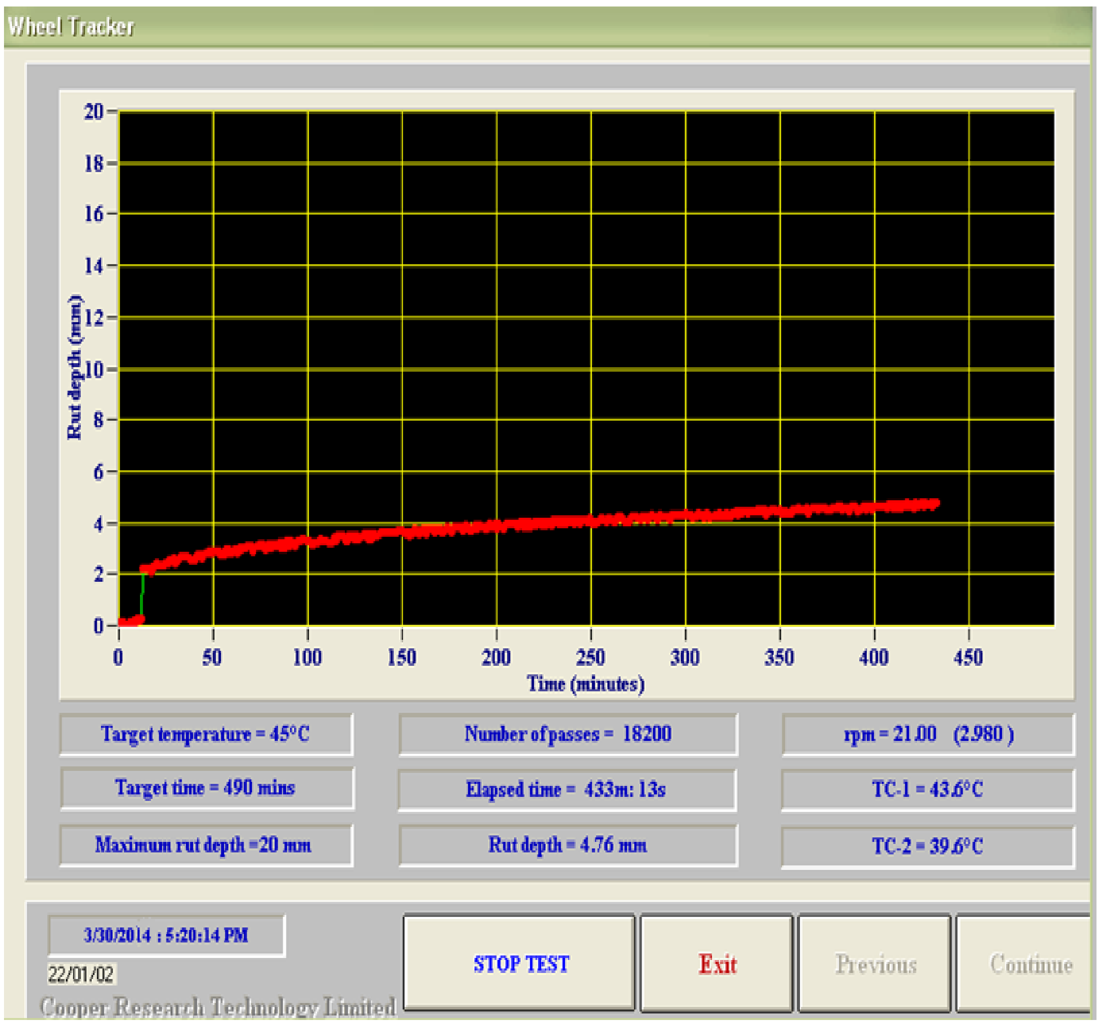


Fig. 4.14 Typical results of rutting test in HWTD (Sample-SMA mix design with CRMB-55 binder)

4.4 TEST RESULT OF SMA MIX DESIGN

SMA design were initially performed with each binder type using compaction effort of 50-blow of Marshall rammer on each face. SMA mixtures were prepared according to Marshall method of mix design specified by Asphalt Institute Manual Series (MS-2). Loose SMA mixture with cellulose fiber were prepared for bitumen contents 5.0, 5.5, 6.0, 6.5, 7.0 and 7.5 by weight of aggregate for each binder type. The volumetric properties from trial blends were evaluated as shown in **Fig. 4.15** against the volumetric properties.

4.4.1 Volumetric and Marshall Properties of SMA design mixes

The theoretical maximum specific gravity (G_{MM}) of un-compacted loose mixture (aggregate, filler and fiber) was determined as per procedure of ASTM D 2041. SMA Marshall specimens were prepared as per specifications of Asphalt Institute Manual Series (MS-2). After compacting samples, their dimension and weight measurement were noted to determine the bulk specific gravity (G_{MB}), air void (Vv),Void in Mineral Aggregate (VMA), Void Filled with Bitumen (VFB), VCA Ratio (VCA_{MIX} / VCA_{DRC}) etc. Results are shown in **Table 4.13 to 4.17** for each binders.

4.4.2 DETERMINATION OF OPTIMUM BINDER CONTENT

The Optimum asphalt content for each binder was determined on the basis of specifications described in detail in previous chapter and trial mix design results.

SMA is a premium mix, require higher quality mix properties in comparison to conventional BC or DBM mixes, as describe in detail in previous chapter.

As, shown in **Table4.13,** results of trial mixes of SMA with VG-30 binder. From 5.0 to 6.0 % binder range, SMA mixes were not having sufficient abrasion resistance both in aged and unaged condition. Also at 5.0 and 5.5 % binder, mix does not have sufficient Void in Mineral Aggregate (VMA) and also not fulfill the minimum binder requirement. Marshall stability of the mix also less than minimum specified value i.e. 6.0 KN.

At higher binder content i.e. 7.0 - 7.5 %, SMA mixes have shown higher flow value and draindown. These results present the need of increasing percentage of some modifier like cellulose fiber.

At 6.5 % VG-30 binder, SMA mixes shows better results, However the results are on borderline and flow value of mix is slightly higher (4.2mm) than acceptable flow value i.e. maximum 4.0 mm.

These results, rises the need of modification of mixes to meet the design standards of premium quality Stone matrix Asphalt (SMA).

From above results, the Optimum Binder Content (OBC) for SMA mix with VG-30 binder is determined as 6.5 % of total aggregate mass. Results with modified binders and Warm Mix Asphalt binders are shown in subsequently section.

As shown results of trial mixes of SMA with PMB-40 binder in **Table 4.14,** at 6.0 % binder, SMA mix shown better result and also achieved all defied specification. Hence 6.0 % PMB-40 of total aggregate weight is taken as Optimum Binder Content (OBC).

PMB-40, improved mix quality. Marshall stability of mix was increased 29.52 %, and drain down also decreased approx 25 %. Abrasion resistance of SMA mix also increases 20.8 % and 13.3% in normal and aged condition respectively.(in comparison to VG-30)

The results of SMA trial mixes with CRMB-55 are shown in **Table 4.15**., at 6.5 % CRMB-55, shown better results and also satisfied all standards of SMA mix design described earlier. At 6.0 %, CRMB-55 binder have lower higher air void than specified limit and also shown less stability and VMA value than 6.5 % CRMB-55. Abrasion resistance of SMA mix also improved with increasing CRMB-55 binder percent from 6.0 to 6.5.

CRMB-55 improved Marshall Stability approx 7.0% and reduced draindown up to 9.5 % and further increases resistance to abrasion 19.5 % and 10.7% of normal and conditioned specimen in comparison to VG-30.

As shown in **Table 4.16,** results of SMA mixes with trial percentage of WMA-E binder, at 6.0 % WMA-E of total aggregate weight, SMA mixes achieved better results with all required specifications.

WMA-E improved Marshall stability by 16%, improve binder retention in mix by 17 % and also reduces abrasion loss of unaged and aged specimen by 41 % and 32 % respectively.

Results of SMA mixes with WMA-Z trial percentage, have shown in **Table 4.17.** At 6.0% WMA-Z binder, mix have better result and within specified standards of SMA mix.

WMA-Z binder increased Marshall stability by 44%, reduce draindown of binder up to 21% and decreases abrasion loss up to 31 %and 19 % for normal and conditioned sample respectively.

As per above results, at Optimum Binder Content (OBC), WMA-Z have shown highest Marshall stability i.e. 15.2 KN, PMB-40 shown lowest draindown i.e. 0.221 % and WMA-E shown highest abrasion resistance of SMA mix both in unaged and aged condition in among all five binder type used for this study.

Table 4.13: Determination of Optimum Binder Content (OBC) for SMA mix with VG-30 binder

Binder content	Air void	VMA	VCA_{MIX} (%)	VCA_{DRC} (%)	VCA Ratio	VFB	Marshall Stability	Flow value	Drain-down	Abrasion loss on unaged specimens	Abrasion loss on aged specimens
> 6.0 %	2-4 %	> 17 %	$VCA_{MIX} \leq VCA_{DRC}$		≤ 1	70-90 %	> 6.0 KN	3-4 mm	< 0.3 %	< 20 %	< 30 %
5.0	4.93	15.40	40.50	43.10	0.94	67.99	5.1	3.1	0.196	35.14	45.2
5.5	4.54	16.80	40.90	43.10	0.95	72.98	5.9	3.5	0.208	30.01	35.01
6.0	3.65	17.40	41.60	43.10	0.97	79.02	8.8	3.8	0.216	23.50	30.25
6.5	3.17	17.60	41.70	43.10	0.97	81.99	10.5	4.2	0.296	18.01	26.08
7.0	2.02	18.40	41.90	43.10	0.97	89.02	7.7	5.8	0.521	15.65	26.31
7.5	1.38	17.30	43.00	43.10	1.00	92.02	4.9	6.2	0.863	25.30	34.54

Table 4.14: Determination of Optimum Binder Content (OBC) for SMA mix with PMB-40 binder

Binder content	Air void	VMA	VCA_{MIX} (%)	VCA_{DRC} (%)	VCA Ratio	VFB	Marshall Stability	Flow value	Drain-down	Abrasion loss on unaged specimens	Abrasion loss on aged specimens
> 6.0 %	2-4 %	> 17 %	$VCA_{MIX} \le VCA_{DRC}$		≤ 1	70-90 %	> 6.0 KN	3-4 mm	< 0.3 %	< 20 %	< 30 %
5.0	5.10	15.23	40.19	43.10	0.93	65.86	6.4	2.9	0.172	33.54	41.21
5.5	4.20	16.70	40.49	43.10	0.94	71.50	7.3	3.2	0.198	26.63	34.16
6.0	3.50	19.50	41.19	43.10	0.96	77.27	13.6	3.8	0.221	14.25	22.60
6.5	3.44	20.41	41.24	43.10	0.96	80.23	10.5	4.1	0.278	15.52	25.30
7.0	2.35	17.45	41.44	43.10	0.96	87.26	8.5	4.9	0.432	21.65	29.32
7.5	1.69	15.35	42.54	43.10	0.99	90.26	5.2	5.5	0.513	23.30	36.89

Table 4.15: Determination of Optimum Binder Content (OBC) for SMA mix with CRMB-55 binder

Binder content	Air void	VMA	VCA_{MIX} (%)	VCA_{DRC} (%)	VCA Ratio	VFB	Marshall Stability	Flow value	Drain-down	Abrasion loss on unaged specimens	Abrasion loss on aged specimens
> 6.0 %	2-4 %	> 17 %	$VCA_{MIX} \leq VCA_{DRC}$		≤ 1	70-90 %	> 6.0 KN	3-4 mm	< 0.3 %	< 20 %	< 30 %
5	5.51	15.30	39.98	43.10	0.93	64.0	5.8	2.5	0.119	30.14	39.21
5.5	5.01	16.70	40.08	43.10	0.93	70.0	6.9	2.9	0.189	24.01	32.10
6	4.31	17.20	40.78	43.10	0.95	75.5	9.6	3.2	0.203	19.05	27.60
6.5	3.74	20.40	40.78	43.10	0.95	78.5	11.2	3.5	0.268	14.50	23.30
7	2.64	18.20	40.98	43.10	0.95	85.5	8.6	4.2	0.412	15.65	19.62
7.5	1.97	17.10	42.08	43.10	0.98	88.5	5.3	5.1	0.523	16.30	20.54

Table 4.16: Determination of Optimum Binder Content (OBC) for SMA mix with WMA-E binder

Binder content	Air void	VMA	VCA_{MIX} (%)	VCA_{DRC} (%)	VCA Ratio	VFB	Marshall Stability	Flow value	Drain-down	Abrasion loss on unaged specimens	Abrasion loss on aged specimens
> 6.0 %	2-4 %	> 17 %	$VCA_{MIX} \leq VCA_{DRC}$		≤ 1	70-90 %	> 6.0 KN	3-4 mm	< 0.3 %	< 20 %	< 30 %
5.0	5.11	15.25	40.29	43.10	0.93	66.5	8.1	3.4	0.106	25.40	34.20
5.5	4.09	16.70	40.63	43.10	0.94	71.9	10.3	3.6	0.178	19.21	28.00
6.0	3.52	17.20	41.33	43.10	0.96	77.8	12.5	4.0	0.246	10.56	19.21
6.5	3.00	17.40	41.39	43.10	0.96	80.7	10.5	4.5	0.278	10.89	21.03
7.0	2.24	18.37	41.59	43.10	0.97	87.8	8.7	5.8	0.421	13.65	22.31
7.5	1.59	17.27	42.69	43.10	0.99	90.8	7.0	5.6	0.469	28.30	35.54

Table 4.17: Determination of Optimum Binder Content (OBC) for SMA mix with WMA-Z binder

Binder content	Air void	VMA	VCA_{MIX} (%)	VCA_{DRC} (%)	VCA Ratio	VFB	Marshall Stability	Flow value	Drain-down	Abrasion loss on unaged specimens	Abrasion loss on aged specimens
> 6.0 %	2-4 %	> 17 %	$VCA_{MIX} \leq VCA_{DRC}$		≤ 1	70-90 %	> 6.0 KN	3-4 mm	< 0.3 %	< 20 %	< 30 %
5.0	5.31	15.32	40.22	43.10	0.93	65.3	7.8	3.4	0.116	20.14	28.32
5.5	4.15	16.73	40.49	43.10	0.94	71.0	12.3	3.6	0.185	15.65	22.01
6.0	3.10	17.27	41.19	43.10	0.96	76.7	15.2	4.0	0.234	12.30	21.25
6.5	2.95	17.47	41.24	43.10	0.96	79.7	10.3	4.5	0.358	8.60	17.32
7.0	2.44	18.32	41.44	43.10	0.96	86.7	9.7	5.8	0.495	16.65	24.21
7.5	1.78	17.22	42.54	43.10	0.99	89.7	8.7	5.6	0.513	21.50	31.65

4.4.3 TEST PROPERTIES OF THE MIXES AT OPTIMUM BINDER CONTENT (OBC)

SMA mix properties at Optimum Binder Content (OBC) with all binder type used in this study, are shown in **Table 4.18.** Modified binder and Warm Mix Asphalt improved mix properties and also reduced optimum binder content. Optimum Binder Content value for PMB-40, CRMB-55, WMA-E and WMA-Z binder was decided as 6.5 %, 6.0 %, 6.5%, 6.0% and 6.0% respectively on the basis of results and specification of mix design. PMB-40, CRMB-55, WMA-E and WMA-Z reduces draindown of binder from mix up to 25 %, 10%, 17% and 21% respectively in comparison to VG-30. Marshall stability of SMA mix at OBC was increased 29%, 7%, 17% and 45 % with the use of PMB-40, CRMB-55, WMA-E and WMA-Z respectively in comparison to VG-30. Retained stability of SMA mixes was increased 13.6%, 7.4%, 13.6% and 14.8 % respectively in comparison to VG-30.

Table 4.18: SMA mix properties at optimum binder content with various binder type

S.NO.	MIX DESGIN PROPERTY AT OBC	VG-30	PMB-40	CRMB-55	WMA-E	WMA-Z
1.	Binder (% Total Weight of Aggregate)	6.5	6.0	6.5	6.0	6.0
2.	Vv (Air Void in the mix) %	3.17	3.50	3.74	3.52	3.10
3.	Vb (Air void in the mix) %	14.43	14.59	13.66	14.25	13.78
4.	VMA (Void in Mineral Aggregate) %	17.6	19.5	17.4	17.2	17.27
5.	VFB (Voids filled with bitumen) (%)	81.9	77.27	78.5	77.8	76.7
6.	VCA Ratio	0.97	0.96	0.95	0.96	0.96
7.	Gmm (gm/cm3)	2.41	2.52	2.48	2.56	2.68
8.	Gmb(gm/cm3)	2.31	2.43	2.35	2.48	2.51
9.	Draindown (%)	0.296	0.221	0.268	0.246	0.234
10.	Marshall Stability Kg	10.5	13.6	11.2	12.5	15.2
11.	Marshall Stability of water conditioned Specimen	8.505	12.512	9.744	11.5	14.136
12.	Retained Stability %	81	92	87	92	93
13.	Flow Value (mm)	4.2	3.8	3.5	4.0	4.0

4.5 INVESTIGATING THE PERFORMANCE AND DURABILITY OF SMA MIXES

The performance and durability of SMA mixes were investigated through laboratory tests. At optimum binder content, additional specimens were prepared and following investigations were carried out to assess the performance and durability of bituminous mixes.

1) Indirect Tensile Strength (ITS)
2) Tensile Strength Ratio (TSR)
3) Resilient Modulus (M_R)
4) Dynamic Creep Test
5) Rut Depth by HWTD Wheel Tracking Device

The method and parameters used to perform the above stated tests has been already described in **Section 3.6**

4.5.1 Indirect tensile strength test result

For evaluating stiffness of the SMA pavement, Indirect tensile test was performed both in normal and wet condition and test results are shown in **Table 4.19.**

Table 4.19: ITS test results of SMA mixes with various binders

SMA design mix type	Dry ITS (Mpa)	Wet ITS (Mpa)
VG-30	0.73	0.64
PMB-40	1.13	1.06
CRMB-55	0.95	0.84
WMA-E	1.23	1.12
WMA-Z	1.29	1.19

Fig. 4.15 shows both normal and conditioned ITS values for each SMA mix. WMA-Z shows highest ITS values both for conditioned and unconditioned specimen. Warm Mix Asphalt technology improved results even at lower compaction temperatures and so reduces the chance of moisture damage due to lower temperature during compaction. With WMA-Z and WMA-E binders, SMA mixes shown better stiffness than dense graded mixes.

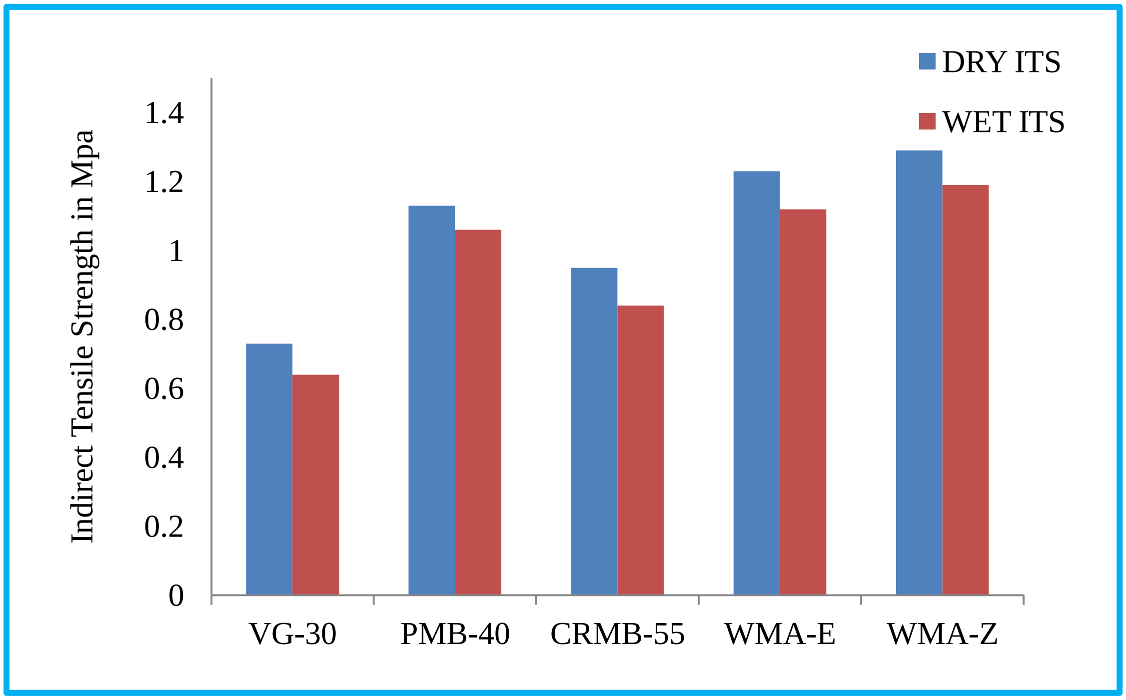


Fig.4.15 : Test results of Indirect Tensile Strength Test of SMA mixes

The increase in normal ITS values with PMB, CRMB, WMA-E and WMA-Z mix were found to be 1.54, 1.30, 1.68 and 1.76 times respectively to that of the conventional asphalt mix. Improvement in conditioned ITS values with PMB, CRMB, WMA-E and WMA-Z mixes was found to be 1.65, 1.31, 1.75 and 1.85 times respectively to that of conventional asphalt mix.

Modified binder and Warm Mix Asphalt improve the tensile strength property of SMA mixes. This may be due to improved adhesion quality of the mixtures with these binders.

Tensile failure of conditioned SMA specimen during ITS test is shown in **Fig 4.17**

4.5.2 Tensile Strength Ratio (TSR) Test Results

The test results of Tensile Strength Ratio (TSR) Test performed on SMA mixes are shown in **Table 4.20**. the VG-30 mix showed the highest water damage, while the PMB-40 mix had the lowest water damage.

Table 4.20: TSR values of SMA mixes with various binders

SMA design mix type	TSR %
VG-30	87.67
PMB-40	93.81
CRMB-55	88.42
WMA-E	91.06
WMA-Z	92.25

As shown in **Fig.4.16**, the VG-30 mix showed the lowest TSR value, while the PMB-40 mix had the lowest water damage. Percentage increase in tensile strength for mixtures with PMB-40, CRMB-55, WMA-E and WMA-Z were found to be approximately 7.0% , 0.85 %, 3.86 % and 5.22 % respectively to that of conventional asphalt mix.

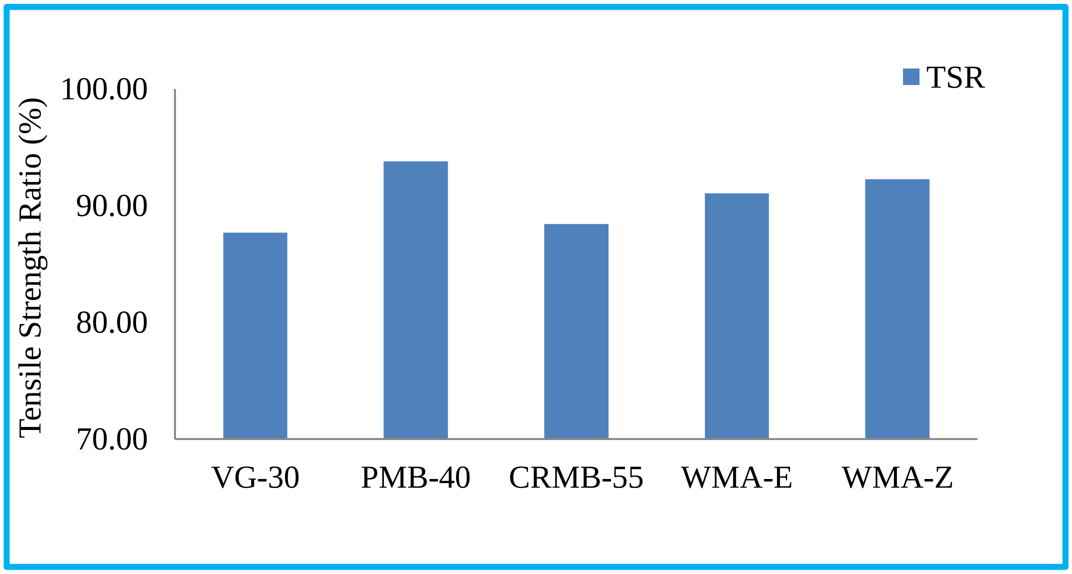


Fig.4.16 : Test results of Tensile Strength Ratio of various SMA mixes

SMA mixes with all binders used in this study, have shown Tensile Strength Ratio more than 85%, as specified minimum value by MORTH, 2013.

Fig. 4.17: Tensile Failure of Conditioned Specimen during ITS test

4.5.3 Resilient Modulus (Mr)

Table 4.21 shows Mr value for various SMA mixes respectively at most prevailing temperatures i.e. 25°C, 35°C and 45°C temperature.

Table 4.21: Resilient Modulus values of SMA mixes with different binder types.

SMA design mix type	Resilient Modulus (MPa)		
	25°C	**35°C**	**45°C**
VG-30	5167	1923	1008
PMB-40	7034	4738	1103
CRMB-55	5943	2859	1087
WMA-E	7232	4957	1998
WMA-Z	9834	4361	1738

As shown in **Fig. 4.18,** WMA technology and modified binder improved resilient modulus qualities of the mix. WMA-E mix shows lowest drop in resilient modulus and highest Mr values at higher temperature (35°C and 45°C) . WMA-Z mix showed highest resilient modulus at 25°C . PMB-40 and CRMB-55, improves mix quality at 25°C and 35°C. However at higher temperature (45°C), modified binders mix shows no significant improvement.

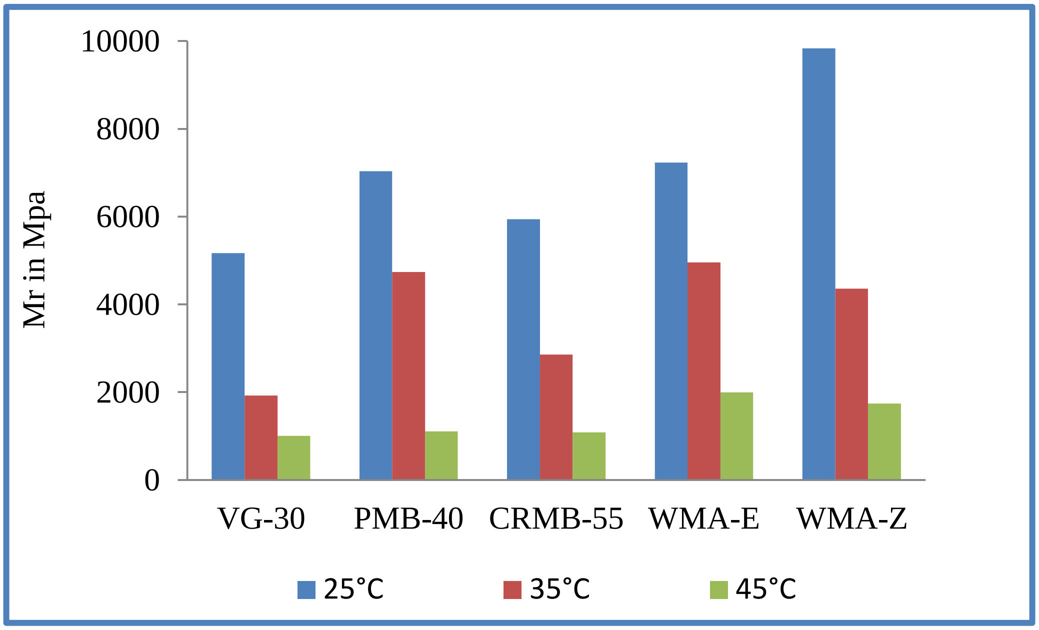


Fig. 4.18 : Resilient modulus Test Results of SMA mixes with various binder type

4.5.4 Dynamic Creep Test Results

Dynamic creep test results on SMA mixes in terms of percentage cumulative strain are presented in **Table 4.22**

Table 4.22: Cumulative Strain of SMA mixes with all binder types

Type of binder mix	Cumulative Strain %
VG-30	44.2
PMB-40	22.6
CRMB-55	34.0
WMA-E	11.2
WMA-Z	24.1

Fig.4.19 shows the permanent deformation plotted against the number of passes for all types of binders.

Decrease in the value of cumulative strain reflects improvement in resistance against permanent deformation and vice-versa. Reduction in air void content of the mix with no. of load cycles, causes permanent deformation in the SMA mixes.

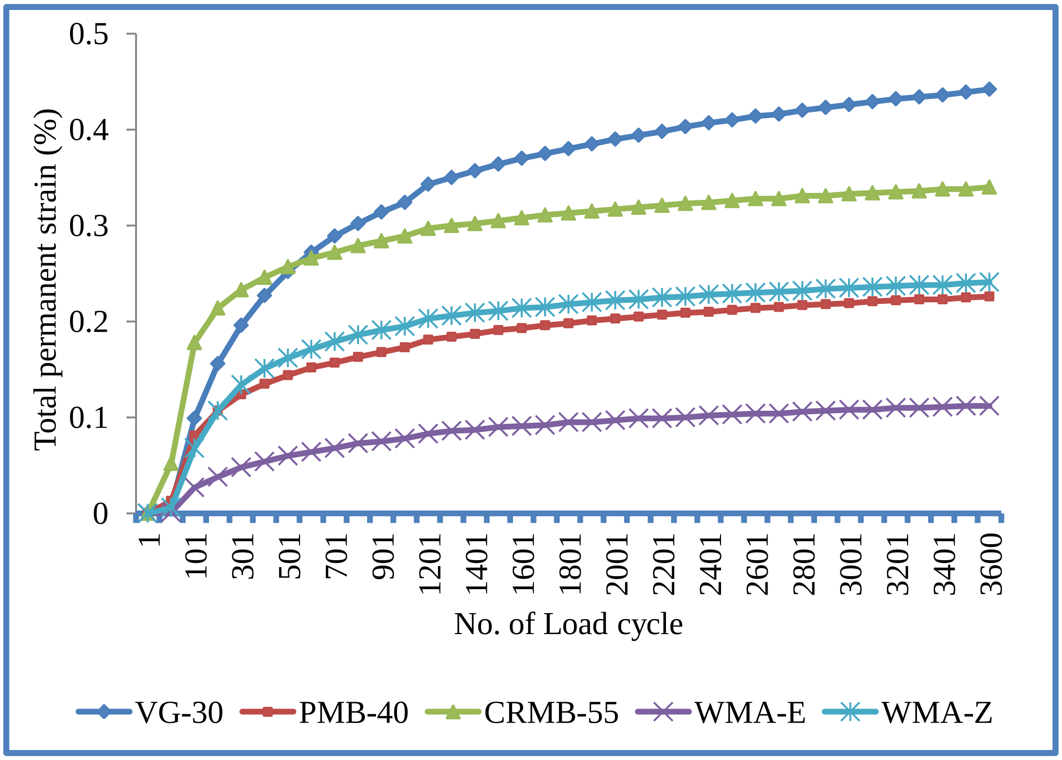


Fig.4.19: Cumulative Strain Vs No. of load Cycle Curve of creep test for various SMA mixes.

As shown in above figure, that VG-30 have steepest slope in all the SMA mixes. Although, CRMB-55 lowered cumulative strain in the mix as compared to VG-30, however shown steeper slope initially. This may be due to higher air void in SMA mix with CRMB-55. And adhesion improvement quality of CRMB-55 binder may also be lesser as compare to polymer modified and WMA binders.

In SMA mixes, WMA-E reduces permanent deformation up to 73%, PMB-40 reduces permanent deformation up to 48%, WMA-Z reduces permanent deformation by 45% and CRMB-55 reduces permanent deformation up to 23% respectively.

4.5.5 Wheel Tracking Test

A wheel-tracking test was performed to evaluate the rutting characteristics of SMA mixes. Final rut depth after 20,000 passes at 40°C of wheel are shown in **Fig. 4.20**

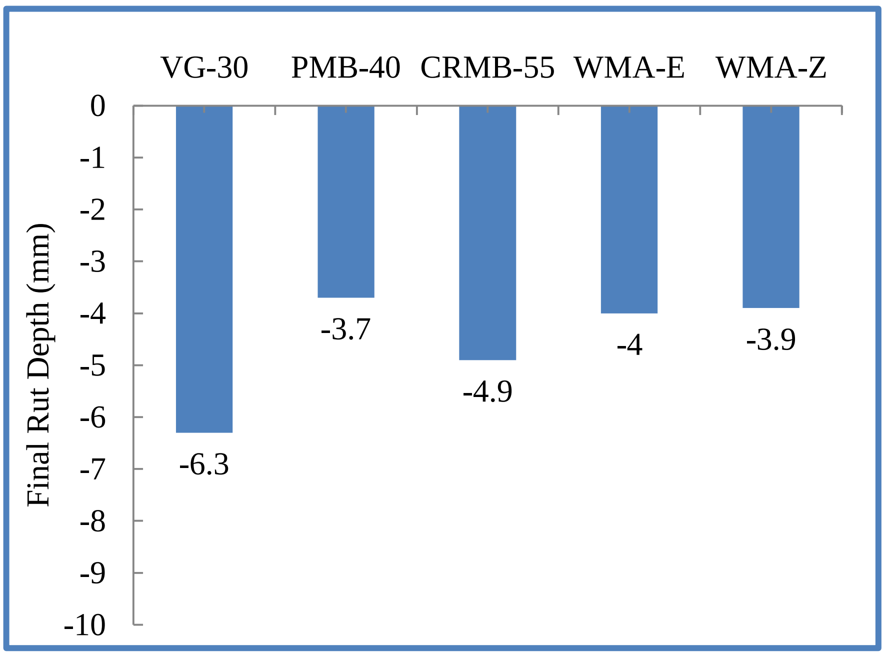


Fig. 4.20: Rut depth of SMA mixes by wheel tracking device

In SMA mixtures, Rut depth test results indicated that due to the stiffening effect of the modified binder the mixtures with PMB-40 showed lowest rutting. PMB-40 reduces rut depth up to 41.27% ,CRMB-55 reduced rutting up to 22.22%, WMA-E reduced rutting up to 36.50% and WMA-Z reduced rutting up to 38.09% as compared to conventional VG-30.

Mogawer and Stuart (1995) suggested maximum allowable rut depths by Hamburg wheel tracking device of 4 mm at 10,000 passes and 10 mm at 20,000 passes for design of SMA mixture with desire rutting resistance and durability potential. Rut depth after HWTD rutting test was within limit for all the SMA binder nixes.

4.6 Comparison of OGFC and SMA test performance

OGFC mix is designed for a open gradation type pavement serving main purpose of immediate removal of water from pavement surface, for better skid resistance property and improve visibility, consequently which serve the purpose of reduce rain water evaporation and runoff, also make possible infiltration of rain water through pavement surface or storage of rain water in the temporary reservoir, under the pavement surface.

Porous pavement also controls splash and spray and hydroplaning problems, thus reduces accident causes. In a properly designed and constructed porous pavement, there is almost no stagnant water. Which also controls the Moisture susceptibility, potholes and stripping problems very effectively.

Whereas, a SMA mix is design for a more durable and rut resistance pavement, providing smother pavement service. SMA mix is gap graded structure provided stone-on-stone contact. The strength of mix is due to its high quality aggregate structure, which carries or transfer load to subgrade area.

The durability and strength of SMA pavement is more than Open graded pavement**.** Function of both the pavements are different, selection of pavement mix should be done on the basis of requirement of particular site.

Comparison of SMA and OGFC mix are shown in graphical form from **Fig. 4.21 to 4.23**

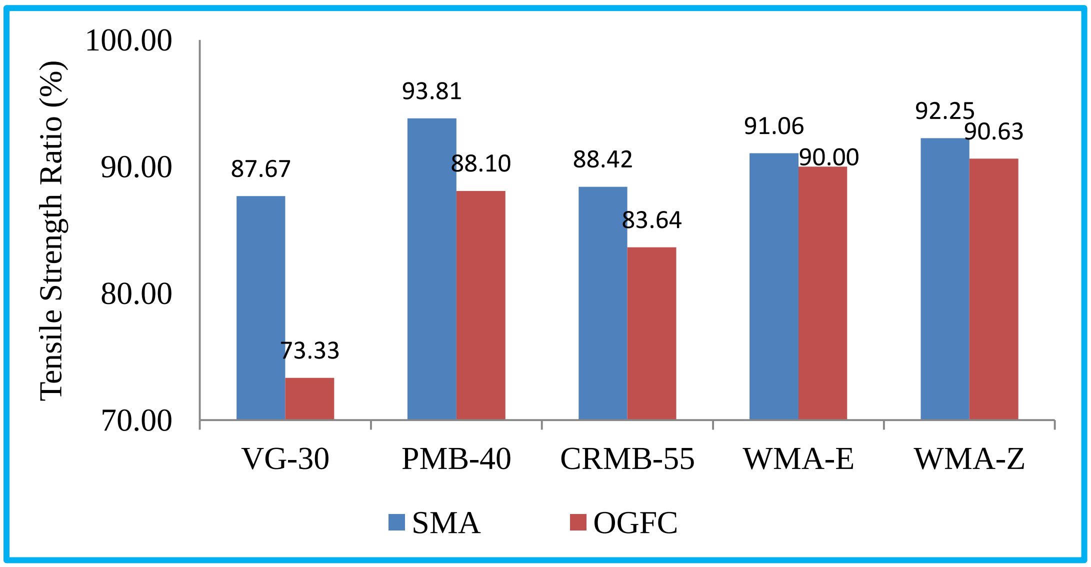


Fig. 4.21: Comparison of TSR values of SMA and OGFC mixes.

As shown in **Fig. 4.21**, SMA mixes having better moisture susceptibility property than OGFC mixes. In case of Cumulative strain (results of 3600 load cycle of dynamic creep test), SMA mixes performed better than OGFC mix, however with PMB-40 binder, SMA mix have shown higher strain value than OGFC mix .(**Fig 4.22)** . Result of HWTD rut depth test results for SMA and OGFC mixes are shown in **Fig. 4.23.** SMA mixes with VG-30, PMB-40, CRMB-55, WMA-E, WMA-Z binder shows 32 %, 60 %, 31%, 42% and 39 % less rut depth respectively in comparison to OGFC mixes with respective binders.

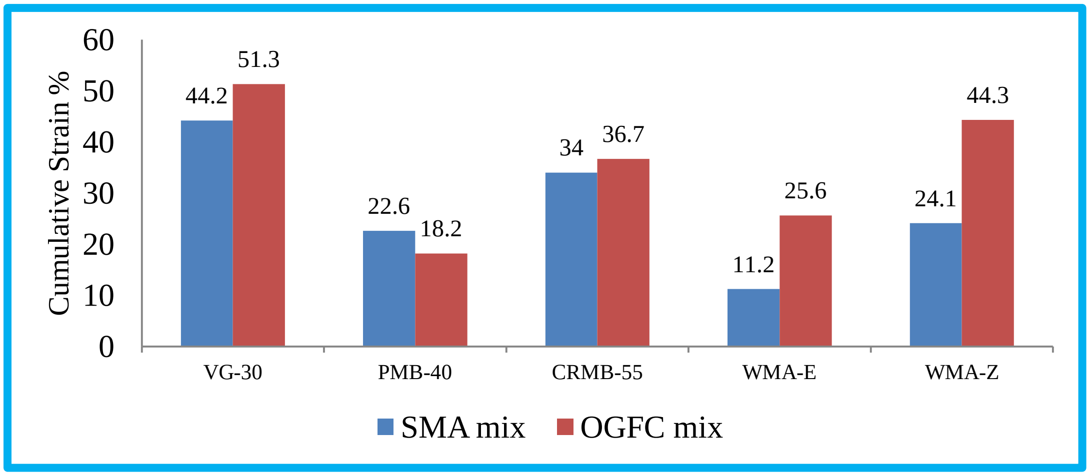


Fig. 4.22: Comparison of cumulative strain in SMA and OGFC mixes.

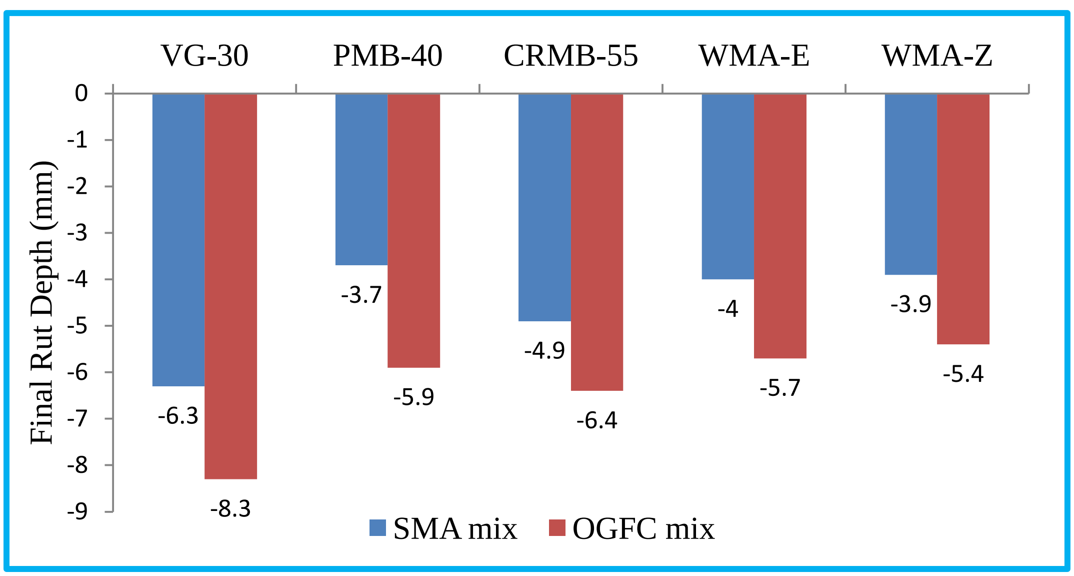


Fig. 4.23: Comparison of Rut Depth test results of SMA and OGFC mixes.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

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5.1 CONCLUSIONS

This study evaluated the laboratory results of using modified binder and warm mix asphalt in OGFC and SMA mixes in comparison to plain bitumen. The following conclusions were drawn -

1. As per ITS test results, the performance of the mixes and strength of the pavement surface to distribute traffic pressure improved with modified binder and warm mix asphalt as compare to conventional asphalt (VG-30).
2. As per TSR test result, moisture susceptibility property of the OGFC and SMA mixtures improved with warm mix asphalt and modified binder due to chemical modification of the plain bitumen as adhesion promoter with lower binder absorption capacity.
3. Elastic property of OGFC and SMA mixes decreased with increase in test temperatures for all types of mixtures. WMA had shown increased Resilient Modulus of the mixes, at all the three temperature parameters than modified and plain bitumen.

4. As per dynamic creep test result, modified binder and WMA reduces the rate of plastic deformation, this might be possibly due to difference in internal structure evolution with number of load cycle (passes).
5. Modified binder and WMA showed better resistance to permanent deformation than conventional asphalt binder.
6. In case of PMB-40 and CRMB-55, reason behind reduced rut depth is the characteristic of the stiffening effect of the binder owing to the addition of specially blended polymer and crumb rubber fiber, making the binder homogenous and storage stable.
7. In case of WMA increased rutting resistance is due to reduced mixing and compaction temperatures which decreases aging of binder and so increased resistance of the mixes.
8. In SMA mixtures, PMB-40 and WMA-Z shown better result than WMA-E and CRMB-55. In case of OGFC mixture PMB-40 and WMA-E shown better result than WMA-Z and CRMB-55. VG-30 produce lowest quality of OGFC and SMA mixture in comparison to modified and WMA binder. CRMB-55 shown less improves results than PMB-40 and WMA binder in both the mixes.
9. Modified binder and Warm mix Asphalt also improved Marshall property (Stability and Retain Stability) of both SMA and OGFC mixes in comparison to VG-30.

10. As per Draindown test result of SMA and OGFC mixes at OBC, modified binder and warm mix asphalt technology, reduces draindown of binder in comparison to conventional asphalt.
11. In all above mentioned performance test, SMA mixtures shown better result than OGFC mixture.

RECOMMENDATIONS

Laboratory test results conducted in this study have proved that modified binders and Warm Mix Asphalt have potential to be used in SMA and OGFC mixes for Indian pavement condition. It is recommended that the findings of this research may be evaluated using further advance testing on the bituminous mixtures such as dynamic modulus test and fatigue test to develop a more detailed understanding about performance and durability of OGFC and SMA pavement. Specification should be finalized for OGFC mixes by Indian Road Congress.

- The study should be extended for different gradation and binder range for OGFC and SMA mixes.
- OGFC pavement should also further consider for potential for stripping of the surface and underlying pavement (they do not seal the underlying pavement against moisture intrusion) and permeability test
- A trial stretch of OGFC pavement should be laid and various field test should be performed specially in rainy and winter season, and correlation between field and test result should be developed.

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LIST OF PUBLICATIONS

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