EFFECT OF LOWER WORKING TEMPERATURES ON PHYSICAL AND MECHANICAL PROPERTIES OF WARM MIX ASPHALT MIXTURES

Thesis

Submitted in partial fulfillment of the requirement for degree of

Doctor of Philosophy

by

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D E C L A R A T I O N

by the Ph.D. Research Scholar

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Date: 05-01-2018

C E R T I F I C A T E

This is to *certify* that the Research Thesis~~/Synopsis~~ entitled **Effect of Lower Working Temperatures on Physical and Mechanical Properties of Warm Mix Asphalt Mixtures**, submitted by SHIVA KUMAR G., (Register Number: 135053CV13F03) as the record of the research work carried out by him~~/her~~, is *accepted as the Research Thesis~~/Synopsis~~ submission* in partial fulfillment of the requirements for the award of degree of **Doctor of Philosophy**.

(Dr. Suresha S N)

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DEDICATED TO MY MOTHER

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ABSTRACT

This thesis document present details on methodology, results, and conclusions of the research performed on warm mix asphalt (WMA) mixtures. The prime objective of this research was to evaluate mix design, workability and mechanical properties of dense-graded asphalt mixtures modified with non-foaming WMA additives at lower working (mixing and compaction) temperatures. Further, to provide wider margin between mixing and compaction temperatures that can ensure WMA mixtures for longer hauling time and better performance. Asphalt mix design properties were evaluated by the Superpave method for various design gyrations (N_{des}) and the workability properties were evaluated in terms of Superpave gyratory compactor (SGC) densification indices, using Bahia and Locking point method. Mechanical properties such as, resistance to moisture-induced damage was evaluated by the tensile strength ratio (TSR) approach, rutting resistance was evaluated by laboratory wheel tracking test using the wheel rut tester (WRT), and flexural fatigue characteristics was evaluated by four point bending using a repeated load testing machine. The effect of nominal maximum aggregate size (NMAS), working temperature, and type of mixture on properties of WMA mixtures were investigated. The experimental results were statistically analyzed to identify the major influencing factors and their significance using one way ANOVA test. Mix design properties were found statistically significant with respect to NMAS, N_{des}, working temperature, and type of mixture. WMA mixtures compacted at lower working temperature were suitable for higher traffic levels and the design asphalt content of WMA mixtures were found lower than that of control mixtures. Sasobit modified WMA mixtures (W-S) compacted at 90 ^{0}C and 70 ^{0}C are more workable and resistant to traffic. These mixtures exhibited higher resistance to moisture-induced damage, rutting and fatigue than those of control mixtures (CM), Rediset modified WMA mixtures (W-R) and Zycotherm modified WMA mixtures (W-Z). However, WMA mixtures compacted at 90 ^{0}C and 70 ^{0}C showed lower moisture-induced damage, rutting and fatigue resistance than control mixtures compacted at 130 ^{0}C. In addition, workability and mechanical properties of NMAS26.5 mixtures was significantly higher than NMAS19 mixtures. WMA mixtures prepared with saturated surface dry aggregates were more prone to moisture-induced damage compared to that of WMA mixtures made with oven dry aggregates. In addition, WMA mixtures prepared with surface saturated dry aggregates and compacted at 90 ^{0}C and 70 ^{0}C marginally fulfilled the minimum TSR requirement.

Keywords: Warm mix asphalt; Mix design properties; Workability properties; Mechanical properties; Locking point method; Bahia method.

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GLOSSARY OF TERMS

AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance
APA	Asphalt Pavement Analyzer
ASA	Anti-stripping Agent
ASTM	American Society for Testing and Materials
BC-I	Bituminous Macadam grading-1
AC	Asphalt Content
BBD	Benkelman Beam Deflection
CRMB	Crumb Rubber Modified Bitumen
CMA	Cold Mix Asphalt
CM	Control mix
CDI	Compaction Density Index
CO_2	Carbon di-oxide
CT	Compaction Temperature
DBM-II	Dense Bituminous Macadam grading-2
DOT	Department of Transportation
FHWA	Federal Highway Administration
GHC	Green House Gases
G_{mb}	Bulk specific gravity of compacted mix
G_{mm}	Theoretical maximum density of mixture
HAP	Hazardous Air Pollutant
HMA	Hot Mix Asphalt
HWMA	Half-Warm Mix Asphalt
IRC	Indian Roads Congress
IS	Indian Standard
ITS	Indirect Tensile Strength
LP	Locking Point

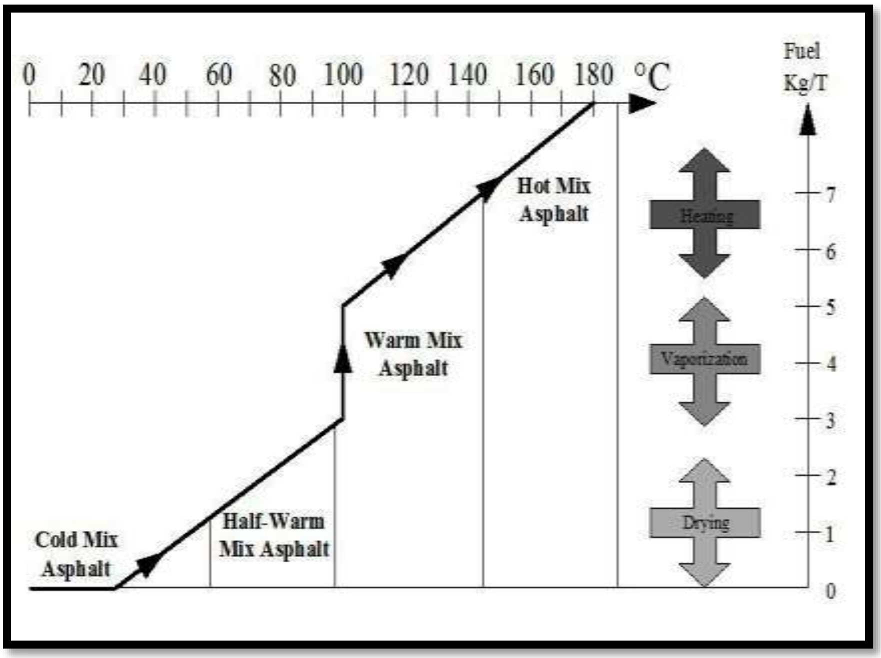
LEA	Low Energy Asphalt
MS-02	Asphalt Institute Manual, Series No. 2
MD	Method of Compaction
MoRTH	Ministry of Road Transport and Highways
N_{des}	Number of design Gyrations
NAPA	National Asphalt Pavement
NCAT	National Center for Asphalt Technology
NH	National Highway
NO_x	Nitrogen Oxides produced producing combustion
NLP	Gyrations corresponding to locking point
NMAS	Nominal Maximum Aggregate Size
NWP	Number of Wheel Passes
OAC	Optimum Asphalt Content
OGFC	Open Graded Friction Course
PMB	Polymer Modified Bitumen
PUR	Purdue University Laboratory Wheel Tracking Device
QLCA	Quantitative Life-Cycle Analysis
RAP	Reclaimed Asphalt Pavement
SCDOT	South Carolina Department of Transportation
SGC	Superpave Gyratory Compactor
SH	State Highway
SMA	Stone Matrix Asphalt
SO_2	Sulphur di-oxide
SP-02	Superpave Manual, Series No. 2
STOA	Short Term Oven Aging for 2 hours
TDI	Traffic Density Index
TM	Type of mix
TSR	Tensile Strength Ratio
TWG	Technical Working Group

UK	United Kingdom
USA	United States of America
VTM	Voids in Total Mix
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate
VOC	Volatile Organic Compounds
WMA	Warm Mix Asphalt
WRT	Wheel Rut Tester
WRS	Wheel Rut Shaper
W-R	WMA-Rediset mix
W-S	WMA-Sasobit mix
W-Z	WMA-Zycotherm mix
WSDOT	Washington State Department of Transportation

1.0 INTRODUCTION

1.1 BACKGROUND

Generally, asphalt mixtures can be classified based on the mixing temperature and energy consumed for heating the materials. Various types of asphalt mixtures include cold-mix asphalt (CMA), half-warm mix asphalt (HWMA), warm-mix asphalt (WMA), and hot-mix asphalt (HMA) shown in Fig. 1.1. The range of mixing temperature for each of these mixtures typically varies from 0 to 30 °C, 65 to 100 °C, 110 to 140 °C, and 140 to 180 °C, respectively (D'Angelo et al. 2008; Kandhal 2010; Vaitkus et al. 2008; James et al. 2011). HMA production and application involves enormous consumption of fossil fuels and emission of greenhouse gases (GHC) such as CO_2, SO_2, CO, NO_X etc. Along with these, abrupt global warming and hike in fuel prices have led many researchers and hot-mix asphalt industry to constantly explore technological improvements that will conserve fossil fuels, reduce environmental issues related to global warming, enhance the pavement performance and construction efficiency (Capitao et al. 2012; Carmen et al. 2012; Behnam et al. 2013).



[Source: Jenkins 2000; D'Angelo et al. 2008]

Fig.1.1. Classification by temperature range and energy consumption

Studies on adoption of CMA and HWMA as an alternative to HMA had various limitations. CMA had concerns related to insufficient aggregate coating, high air void content, high curing time before opening up to traffic and reduction of long term performance (Jenkins 2000; Blades et al. 2004). HWMA had concerns regarding aggregate coating and workability due to presence of initial moisture in aggregates leading to pavement distresses (Gaudefroy et al. 1998). Many researchers suggested that these technologies are best suited as patching materials and for low volume roads. However, studies on HWMA with RAP showed better laboratory than CMA performance (Punith et al. 2013). To overcome these drawbacks, WMA has been introduced, which is produced in between HWMA and HMA production temperatures.

In this context, WMA is the broad term typically used to refer technologies that seek to lower emissions and reduce energy consumption by lowering the temperature at which asphalt mixtures are produced and placed. It is also considered to be a fast emerging technology, which has a potential to replace HMA due to its various benefits like reduction in consumption of energy, lower greenhouse gas emissions (15 to 45% less than HMA) and also considerable reduction in the emission of various chemicals from the HMA plants such as hazardous air pollutant (HAP) metals, HAP organic compounds, volatile organic compounds (VOC) and volatile HAP organic compounds (EPA 2000; Ala et al. 2013). A brief history on development of WMA technologies is presented in Table 1.1. In addition, demonstration projects of WMA technologies have proved that it overcomes the demerits of CMA and HWMA (Hurley et al. 2005; Hurley et al. 2006).

Different technologies are available to produce WMA mixtures, all these technologies are broadly grouped under the following categories (i) foaming processes (sub-divided into water containing and water based processes); (ii) addition of organic additives; (iii) addition of chemical additives (D'Angelo et al. 2008; Bonaquist 2011; James et al. 2011; Carmen et al. 2012).

Table 1.1. Brief history on development of WMA

Year	Invention/Development	Reference
1928	"Foam Asphalt" was first realized and patented by August Jacob in Germany	Gaudefroy et al. 1998
1956	Invention of "Foamed Asphalt" by injecting steam into hot asphalt by Prof. Ladis Csanyi at Iowa state university	Jenkins 2000
1968	Mobil of Australia (Europe) acquired patent rights and modified the process by replacing it with cold water (Jenkins, 2000).	Jenkins 2000
1970	Conoco Inc. got license to market in USA for both laboratory and field studies	Chowdhury and Button, 2008
1977	Chevron developed "Mix Manual" of emulsified asphalt	Button et al. 2007
1985	Use of foam asphalt in RAP	Robert et al. 1984
1994	CMA with foam asphalt	Maccarone et al. 1994
1995-96	First laboratory experiments on WMA (foaming process) conducted jointly by Kolo Veidekke and Shell in Europe.	Koenders et al. 2000
1997-99	German Bitumen Forum and first test section in Norway using WMA-Foam technology.	Kandhal 2010
2002	NAPA initiated study tour to Europe (Germany and Norway).	D'Angelo et al. 2008
2003	European scan tour report was featured at NAPA's annual convention.	Newcomb 2006
2004	Demonstration at the World of Asphalt Show and first U. S field trials with Asphamin.	Chowdhury and Button, 2008
2005	Technical working group (TWG) was initiated by NAPA and FHWA.	Button et al. 2007
2006	NCAT publishes research on Asphamin, Sasobit, and Evotherm.	Hurley et al. 2005, Hurley et al. 2006

Year	Invention/Development	Reference
2007	NCHRP initiated projects on WMA (Project 09-43 and 09-47).	Anderson et al. 2008
2009	WMA paving at Boston-Logan international airport (FHWA and WMA TWG).	Prowell et al. 2007
2011-14	NCHRP publishes reports on WMA (Report Nos. 691 and 763).	Bonaquist et al. 2011; Martin 2014

(i) Foaming technologies: It is a process of injecting cold water into the hot binder or by adding synthetic zeolite directly into the asphalt mixing chamber. As evaporation occurs rapidly, water is encapsulated into the binder forming large volume of foam (1 liter of water forms about 1200 liters of steam). The foaming action in the binder temporarily increases the volume of the binder and lowers the viscosity, which improves coating and workability (Larsen 2001). The foaming technologies can either be water based technologies (direct method) or water containing technologies (indirect method). In the water based technologies, water is directly injected into hot binder flow using special nozzle equipment. The water rapidly evaporates, producing a large volume of foam, which slowly collapses. These technologies are best suited for cold and damp aggregates and/or recycled asphalt pavement (Jenkins, 2000; Blades et al. 2004). Some of these technologies include Double Barrel Green, Ultra foam GX, and Low Energy Asphalt etc. (Larsen 2001; Chowdhury and Button, 2008; Zaumanis 2010).

In case of water-containing technologies, a synthetic zeolite composed of crystalline hydrated aluminium silicate is used to produce foam. As temperature rises, around 20% of water is released from zeolite structure which causes a micro foaming effect in the asphalt mix, which lasts about 6-7 hours (Barthel et al. 2004). The structure of the zeolite has large air voids where cation groups (such as water) can be hosted and ability of losing and absorbing water without damaging the crystalline structure is the main characteristic of this silicate framework (D’Angelo et al. 2008). These technologies include Aspha-Min and Advera.

(ii) Organic (wax) additives: It typically consists of paraffinic hydrocarbons, which are added to asphalt mix to achieve the temperature reduction by reducing viscosity of binder above the melting point of the waxes (Gandhi 2008). Due to crystallization, stiffness of binder increases which in turn resist deformation. The added paraffin's are long-chained hydrocarbons that do not adversely affect the properties of the base binder. The type of wax must be selected carefully so that the melting point of the wax is higher than expected in service temperature and to minimize embrittlement of the asphalt at low temperatures (Chowdhury and Button, 2008; Zaumanis 2010). These technologies include Sasobit, Asphaltan A, and Sonnewarmix, etc.

(iii) Chemical additives: It is a combination of emulsification agents, surfactants and polymers which improves coating, mixture workability, and compaction. These products do not depend on foaming or viscosity reduction for lowering mixing and compaction temperatures and also act as an antistripping agent (D'Angelo et al. 2008; Zaumanis 2010). The dosage rate and temperature reduction depends on the specific product used and wide varieties of chemical packages are used for different products (James et al. 2011). These technologies include Evotherm ET, Rediset WMX, and Zycotherm, etc.

In India, Indian roads congress (IRC) has approved some of the commercially available WMA products namely Evotherm, Shell Thiopave and Rediset WMX 8017. To study the performance of WMA, the first two types of additives have been used on selected highway stretches (Ambika et al. 2013). The details of the same are provided in Table 1.2. Other WMA technologies namely Rediset LQ, Sasobit and Zycotherm are also commercially available in the Indian market. Recent review articles (D'Angelo et al. 2008; Carmen et al. 2012; Behnam et al. 2013) provided the summary of various types of WMA additives available world-wide. An attempt has been made to add few more additives to the list and the same is shown in Table 1.3.

Table 1.2. Details of WMA projects in India (Ambika et al. 2013)

Type of additive	Project details and location	Chainage (m)/ Section length details (km)	Field performance studies
Shell Thiopave	NH-3 near Nashik	595 to 575	Deflection(BBD) of 0.548 mm
Evotherm	SH-5 near Godhra	One km in length	Deflection(BBD) of 0.68 mm

1.2 BENEFITS AND DRAWBACKS

The characteristics of WMA additives in reducing production temperature bring many potential benefits which include (D'Angelo et al. 2008; Capitao et al. 2012; Carmen et al. 2011)

1. Less fuel consumption to dry and heat the aggregate,
2. Reduction in stack emissions and less wear and tear in the asphalt mixing plant,
3. Reduction in emission of greenhouse gases and gain in Carbon footprint,
4. Inclusion of 50 % or more of recycled asphalt pavement (RAP),
5. Similar or better physical and mechanical properties than conventional HMA, and
6. Potential to extend the haul distances from the asphalt mixing plant.

The lower production temperature of WMA had drawbacks regarding the performance and implementation which include (Kristjansdottir 2006; Chowdhury and Button, 2008; Zaumanis et al. 2010; Miller et al. 2010)

1. Initial higher costs could discourage contractors,
2. Improper drying of aggregates increases the potential for moisture-induced damage,
3. Less ageing of the asphalt causes rutting problems,
4. Field test sections are still few in number and have short life (seven years in the USA and over ten years in certain European countries), and
5. Quantitative life-cycle analysis (QLCA) and long-term environmental benefits or energy savings are still to be assessed.

Table 1.3. Overview of WMA technologies

WMA Technology	Product/Additive	Company	Description	Dosage of additive	Country used	Production or Reduction in temperature (^{0}C)
Foaming process						
Water containing	Aspha-Min	Eurovia and MHI	Water-containing technology using zeolites	0.3% w/m	USA, Germany, France, worldwide	20–30
Water containing	Advera	PQ Corporation	Water-containing technology using zeolites	0.25% w/m	USA	10–30
Water based	Double Barrel Green	Astec	Water-based foaming process	2% w/b	USA	116–135
Water based	WAM-Foam	Shell and Kolo-Veidekke	Soft binder coating followed by foamed hard binder	2–5% w/b	Worldwide	100–120
Water based	Ultrafoam GX	Gencor Industries	Water-based foaming process	1–2% w/b	USA	Not specified
Water based	LT Asphalt	Nynas	Foam bitumen with hydrophilic Additive	0.5–1% w/b	Netherlands, Italy Worldwide	90
Water based	Low Energy Asphalt (LEA)	LEACO	Hot coarse aggregate mixed with wet sand	3% water with fine sand	USA, France, Spain, Italy	>100
Organic						
FT Wax	Sasobit wax	Sasol	Fischer-Tropsch wax	1.0-3.0% w/m	Germany, worldwide	20–30
Montan Wax	Asphaltan B	Romonta GmbH	Refined montan wax with fatty acid amide for rolled asphalt	2.0–4.0% w/b	Germany	20–30
Fatty Acid	Licomont BS	Clariant	Fatty acid amide	3.0% w/b	Germany	20–30
Chemical						
Chemical	Evotherm	Mead Westvaco	Chemical packages, with or without water	0.5% w/b	USA, France, India, Worldwide	85–115
Chemical	Rediset	Akzo Nobel	Cationic surfactants and organic additive	1.5–2% w/b	USA, Norway	30
Chemical	REVIX	Mathy-Ergon	Surface-active agents, waxes, processing aids and polymers	Not specified	USA	15–25
Chemical	Cecabase RT	CECA	Chemical package	0.2–0.4% w/m	USA, France	30
Chemical	Zycotherm	Zydex industries	Chemical package	0.1% w/b	India	30
Chemical	Shell Thiopave	Shell Global	Sulphur-based and complementary non-sulphur based additive pellets.	up to 25% w/b	USA, Germany, India , worldwide	20-40
Chemical	Iterlow T	IterChimica	NA	0.3–0.5% w/b	Italy	120

1.3 PROBLEM STATEMENT

In recent years, abrupt global warming and hike in fuel prices have led many researchers and HMA industry to constantly explore technological improvements that will conserve fossil fuels, reduce environmental issues related to global warming, enhance pavement performance, and achieve construction efficiency (Capitao et al. 2012; Carmen et al. 2012; Behnam et al. 2013). Further, to overcome the drawbacks of HMA, CMA and HWMA, WMA has been introduced, which is produced between HWMA and HMA production temperatures. Recent global experiences (Hurley et al. 2006; D' Angelo et al. 2008; Stacey et al. 2008; Bonaquist 2011) suggest, WMA has the potential to replace HMA technology and has many benefits as HMA. Hence, several highway agencies, and Departments of Transportations (DOTs) all over the world are working to develop suitable specifications based on the performance. However, despite benefits, it is more prone to moisture-induced damage due to varying physical and chemical properties of the aggregates, and rutting due to lesser aging of binder and higher air voids as it is produced at lower mixing and compaction temperature. The present research focuses on the effect of (i) lower working (mixing and compaction) temperature, (ii) WMA additive, and (iii) design traffic level and nominal maximum aggregate size (NMAS) on the mix design, mechanical, and workability properties of WMA mixtures.

(i) Mixing and compaction temperature: Different mixing and compaction temperatures were adopted by the researchers worldwide for evaluation of properties of WMA mixtures. Further, the effect of mixing and compaction temperatures were addressed upto 130 °C and 110 °C, respectively, and margin between these temperatures were not larger than 20 °C (Kanitpong et al. 2007; Akisetty et al. 2009; Lee et al. 2012; Xiao et al. 2013; Jamshidi et al. 2013). In India, mixing and compaction temperatures for HMA mixtures were selected based on Ministry of Road Transport and Highway (MoRTH) requirements for different grades of binder as presented in Table 1.4. The margin between mixing and compaction temperatures for HMA mixtures is more compared to WMA mixtures. In addition, interim guidelines for production and evaluation of warm mix asphalt mixtures published by IRC suggest a mixing and compaction temperature of 120-135 °C and 90 °C, respectively.

Table 1.4. Mixing, Laying and Rolling temperatures for asphalt mixtures (°C)

Binder Viscosity Grade	Binder Temperature	Aggregate Temperature	Mixed Material Temperature	Laying Temperature	*Rolling Temperature
VG-40	160-170	160-175	160-170	150 Min	100 Min
VG-30	150-165	150-170	150-165	140 Min	90 Min
VG-20	145-165	145-170	145-165	135 Min	85 Min
VG-10	140-160	140-165	140-160	130 Min	80 Min

*Rolling must be completed before the mat cools to these minimum temperatures

(ii) WMA additive: Review of research findings summarizes various types of WMA additives available world-wide as presented in Table 1.3 (D'Angelo et al. 2008; Carmen et al. 2012; Behnam et al. 2013). In India, IRC has approved some of the commercially available WMA products namely Evotherm, Shell Thiopave and Rediset WMX 8017. Other WMA additives namely Rediset LQ, Sasobit and Zycotherm are also commercially available in the Indian market. The effect of these WMA additives on performance of WMA mixtures have not been addressed by the researchers in Indian Subcontinent.

(iii) Design traffic level and NMAS: The compaction efforts criteria for mix design of HMA in addition to the design number of gyrations (N_{des}) are recommended in SUPERPAVE (superior performing pavements) mix design method. From the review of literature, it is evident that the N_{des} adopted by various authors and road agencies for the design of WMA mixtures were not the same for selected NMAS (Hurley et al. 2005; Hurley et al. 2006; Liu et al. 2010; Xiao et al. 2011; Kanitpong et al. 2012; Ahmed et al. 2013; Kavussi et al. 2014).

Laboratory evaluation of mix design and mechanical properties of WMA mixtures are necessary during the design process, subsequently the ability to quantify compactability of WMA mixtures would be very much helpful. Significant research was carried out with conventional HMA for defining compaction characteristics of asphalt mixtures using different methods while compaction characteristics of WMA mixtures were carried out only using the Bahia method (Kanitpong et al. 2007; Hanz et al. 2010; Sanchez-Alonso et al. 2011; Mo et al. 2012) and Locking point method has not been addressed. Hence there is a need for study of effect of lower mixing and compaction (working) temperatures on mix design, workability, and mechanical properties of WMA mixtures. This will provide wider margin between mixing and compaction temperatures that can ensure WMA mixtures for longer hauling time and better laboratory performance.

1.4 RESEARCH OBJECTIVES AND SCOPE

The main aim of the present research is to investigate the effect of lower working temperatures and non-foaming WMA additives on properties of asphalt mixtures. The specific objectives of present research are as follows:

1. To review research findings related to mix design, workability and mechanical properties of WMA mixtures,
2. To study the mix design properties of WMA mixtures used in the structural layers,
3. To study the workability properties of WMA mixtures, and
4. To study the mechanical properties (rutting, flexural fatigue and moisture-induced damage) of WMA mixtures.

The Scope of this work includes review of the research findings related to mix design, workability and mechanical properties of WMA mixtures and evaluation of physical properties of aggregate and binder modified with non-foaming WMA additives.

Two aggregate gradations, Dense Bituminous Macadam (DBM) grading-II (NMAS26.5) with NMAS of 26.5mm (equivalent to Superpave dense mix gradation with NMAS of 25 mm) and Bituminous Concrete (BC) grading-I (NMAS19) with NMAS of 19mm (equivalent to Superpave dense mix gradation with NMAS of 19 mm) were selected based on the MoRTH specifications (MoRTH 2013). Straight-run (plain) bitumen of viscosity grade VG 30 (equivalent to penetration grade 60/70) and granite aggregate source was used. The WMA additives used included Rediset LQ, Sasobit and Zycotherm.

Mix design properties were evaluated using Superpave mix design method. Workability properties were evaluated in terms of Superpave gyratory compactor (SGC) densification indices using the Bahia and locking point concept. Wheel rut tester (WRT), a small size wheel tracking test device was used to evaluate the rutting properties as per EN 12697-22 at a testing temperature of 60 °C and flexural fatigue properties in four point bending using repeated load testing machine.

To investigate the effect of aggregate conditions (oven dry and saturated surface dry) on moisture-induced damage in terms of tensile strength ratio (TSR) according to AASHTO T-283. In order to identify the treatment factors that will have significance effect on response properties, the experiment results were analyzed using one-way analysis of variance (ANOVA) tests.

1.5 THESIS ORGANIZATION

This thesis is organized into five chapters. The background on WMA (definition, history on development, overview of different technologies and details of projects in India), benefits and drawbacks of WMA, statement of research problem, objectives and scope of work, and thesis organization of this research are presented in the Chapter 1.

A comprehensive review of literature on mix design concept, physical (mix design properties) and mechanical properties (moisture-induced damage, rutting and fatigue) of WMA technologies with summary of research finding are summarized in Chapter 2. The details of various materials used during laboratory investigation, details of aggregate gradations, physical properties of non-foaming WMA modified binders, the method of mix design and specimen preparation, the details of different laboratory tests, and the details of the research plan are provided in Chapter 3.

Chapter 4 deals with the evaluation of mix design, workability, rutting, flexural fatigue and moisture-induced damage properties of asphalt mixtures modified by non-foaming WMA additives such as WMA Rediset (W-R), WMA Sasobit (W-S), and WMA Zycotherm (W-Z) mixtures and were compared with the control asphalt mixtures (CM).

Superpave method of mix design was performed to evaluate the asphalt mix design properties on four types of mixtures and at three lower working temperatures for varying design gyrations and binder contents.

Workability properties of asphalt mixtures were evaluated in terms of SGC densification indices using Bahia and Locking point method. Rutting and flexural fatigue properties of the asphalt mixtures using WRT and Repeated load testing machine respectively.

Resistances to moisture-induced damage of the mixtures were evaluated as per AASHTO T-283. In addition, the effects of oven dry and surface saturated dry aggregate conditions on moisture-induced damage of the mixtures were evaluated in terms of TSR. Conclusions and recommendations drawn based on the present investigation are given in Chapter 5.

2.0 LITERATURE REVIEW

2.1 GENERAL

A comprehensive review of literature on mix design concept, physical (mix design properties) and mechanical properties (moisture-induced damage, rutting and fatigue) of WMA technologies were carried out. All these properties were compared with properties of conventional HMA technology and details are presented in subsequent sections.

2.2 WMA MIX DESIGN CONCEPT

The key elements in mix design of WMA is similar to conventional HMA which includes proper compaction method, selection of ingredients, selection of aggregate gradation, selection of binder content, laboratory mixing and compaction temperature and proper conditioning (Button et al. 2007; Bonaquist 2011; Carmen et al. 2011).

WMA mix can be compacted using Marshall hammer and SGC. The standard SGC condition of 125 gyrations, 30 rpm, 600 kPa, and a slight angle of 1.25° adopted for HMA is acceptable for WMA mixtures (Hurley et al. 2005a; Bonaquist et al. 2011). The Marshall method for heavy traffic condition (75 blows on both sides) as adopted in HMA is accepted for WMA mixtures (Hugo et al. 2010).

Aggregate selection for WMA mix is same as conventional HMA but it is advisable to use stiffer and high-temperature asphalt for satisfactory rutting performance (Hurley et al. 2005; Bonaquist 2011). In addition, studies on WMA mixtures with low Emission Asphalt (LEA) suggest that the same proportion and same grade of asphalt can be used as in conventional HMA (Romier et al. 2006).

The dosage rate of incorporating additive should be selected based on manufacturer's recommendations. Anti-stripping agents (ASA) and hydrated lime are used to resist loss of adhesion and coating between asphalt and aggregates especially with foaming process and some of the chemical additives but these is not true with all WMA processes (D'Angelo et al. 2008; Carmen et al. 2011).

Most of the WMA marketing technologies and road construction agencies all over the world have evaluated WMA technologies both in the laboratory and field using conventional dense-graded mix gradation. Many authors suggested that WMA processes can be equally applicable to typical types of asphalt mixtures other than dense-graded mixtures [i.e. stone mastic asphalt (SMA) and open graded friction coarse (OGFC), etc.] and have been successfully adopted in mixtures containing RAP, RAS and Bio-asphalt (Hill, 2011; Punith et al. 2012; Shu et al. 2012). The lower production temperature and better compaction of WMA process indicates lower optimum asphalt content (OAC) and lesser air voids. The OAC of WMA mixtures are usually lower by about one-half a percentage than the conventional HMA mixtures which may reduce durability and moisture-induced damage properties of asphalt mixture (Button et al. 2007; Chowdhury and Button, 2008).

The laboratory mixing and compaction temperatures of WMA mixtures vary depending upon the technology adopted. In order to achieve proper coating of aggregates and mixture workability one has to adopt optimum temperature window within certain time period (Carmen et al. 2012). These can be achieved by knowing viscosity-temperature relationship of binders modified with WMA additives or by comparing bulk density of WMA mixture with reference to the control HMA mixture (Button et al. 2007). WMA additives such as Sasobit and Asphaltan B that do not incorporate moisture don't require conditioning. However, additives like Aspha-Min, WMA-Foam and Evotherm that incorporate moisture to promote aggregate coating, workability, and compaction requires conditioning (Short term oven ageing of 2 hours) to expel the moisture (Button et al. 2007; Martin 2014).

2.3 MIX DESIGN PROPERTIES OF WMA MIXTURES

The mix design properties of WMA were studied with reference to control HMA based on the Superpave method as reported by various researchers in Table 2.1. WMA technology, additive and corresponding dosage rate, nominal maximum aggregate size (NMAS), design number of gyrations (N_{des}) and production temperature were reviewed. Three WMA technologies were studied by various researchers and additives used are Asphamin, Sasobit, Evotherm and Rediset WMX. The dosage range of these additives are 0.3-0.5% of w/m, 0.8-4.0% of w/b, 0.5-10.0% of w/b and 2.0% of w/b, respectively.

The production temperatures varies with the technology adopted, and the temperature reduction of WMA mixtures with reference to HMA mixtures were compared. The temperature reduction range of foaming technology (Asphamin and Advera) was found to be (20-40) °C, Organic additives (Sasobit, Surfactant, Lulu bang, sonnewarmix and synthetic/artificial wax) showed a reduction of (20-40) °C and Chemical additives (Evotherm, Rediset WMX, Cecabase RT and Thiopave) achieved a reduction of (15-37) °C.

Most of the road agencies and researchers investigated performance of dense-graded WMA mixtures with NMAS of 9.5mm, 12.5mm, 13.2mm and 19.0mm adopting various N_{des}. Even, studies with open graded mixtures, such as, SMA and OGFC, have been reported (Punith et al. 2012; Yi Weng et al. 2013). The Superpave mix design properties, such as, Voids in Total Mixtures (VTM), Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA) of WMA mix with reference to the control HMA mix studied by various authors were compared along with the design asphalt content (OAC). The OAC of WMA mixtures was lower than the control HMA mixtures but similar or higher values were observed with inclusion of RAP and WMA modified SMA mixtures. In most of the studies, VTM of 4.0±1.0% were adopted for the WMA mixtures irrespective of N_{des}.

The National Center for Asphalt Technology (NCAT) conducted studies on 12.5mm WMA mixtures by adopting N_{des} of 125 gyrations and concluded that mix design properties of WMA mixtures were lower compared to the HMA mixtures but well within the Superpave volumetric mixture design (SP-2) requirements but OACs were found to be higher compared to the HMA mixtures (Hurley et al. 2005; Hurley et al. 2006; Hossain et al. 2012). Studies with 12.5 mm WMA mixtures adopting N_{des} of 75 gyrations (Akisetty et al. 2009; Liu et al. 2010; Bonaquist, 2011; Xiao et al. 2011; Kanitpong et al. 2012; Ahmed et al. 2013) and N_{des} of 100 gyrations (Bennert et al. 2010; Lee et al. 2012) indicated higher OAC compared to N_{des} of 125 gyrations. It was even true with unconventional N_{des} of 60, 70 and 85 gyrations with the same NMAS (Diefenderfer and Hearon 2008; Hill 2011; Kavussi et al. 2014). Further, studies with larger NMAS (19mm and above) and open-graded WMA mixtures indicated lower OAC (Cooper III et al. 2011; Punith et al. 2011).

2.4 WORKABILTY PROPERTIES OF WMA MIXTURES

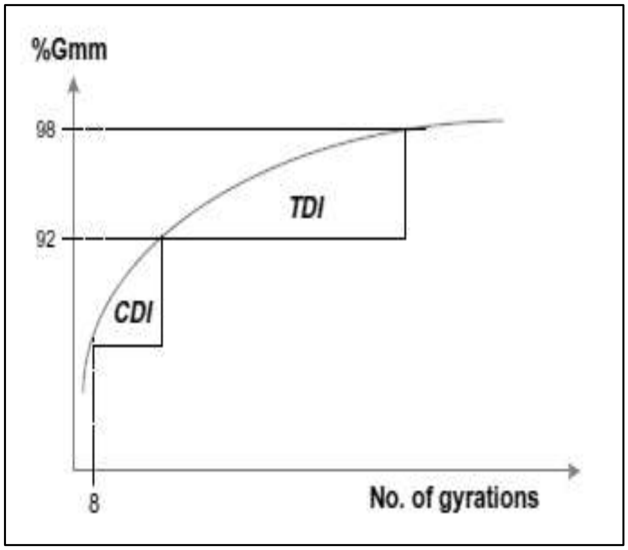
Workability of the asphalt mixtures are evaluated in terms of compactibility which is defined as the effort required for achieving consolidation of asphalt mixtures and is critical for effective long-term performance in the field. During the design process, evaluation of mix design and mechanical properties of asphalt mixtures are necessary, subsequently the ability to quantify compactibility would be very much useful (Kanitpong et al. 2007; Sanchez-Alonso et al. 2011; Mo et al. 2012).

Asphalt mixture compactiblity in terms of Compaction Densification Index (CDI) and Traffic Densification Index (TDI) was introduced by Hussain Bahia in 1998 using the SGC densification curves. He proposed the use of the SGC curve to evaluate the constructability of the mixtures as well as their resistance to traffic loading. CDI and TDI are energy indices used to relate to construction and in-service performance of HMA mixtures respectively. The energy indices were calculated using the region from N = 8 to N at 92% G_{mm} of the densification curve for the CDI and from N at 92% G_{mm} to N at

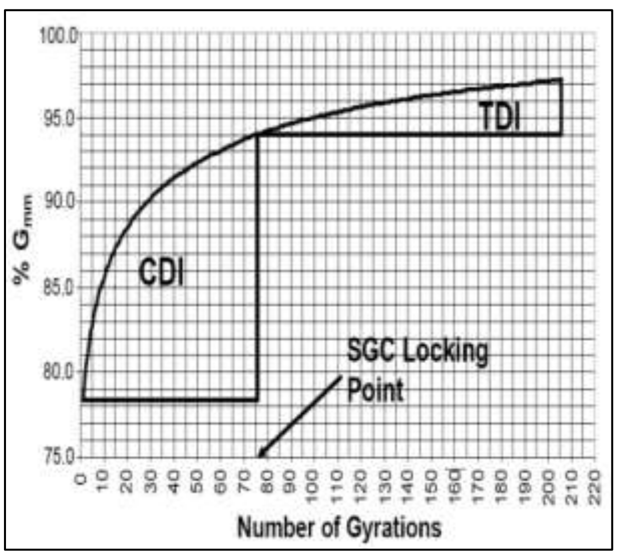
98% G_{mm} for the TDI (Fig. 2.1a). He also assumed that the first eight gyrations represent the constant compaction energy applied by the paver screed (Bahia et al. 1998).

Later, Vavrik et al. (1999) continued the use of densification curves to quantify compactibility, and developed the locking point concept. They defined locking point as the first gyration where three gyrations of the same height are proceded by two sets of two gyrations at the same height. CDI is area under the densification curve from first gyration to gyration at locking point and TDI is the area under the densification curve from gyration at locking point to gyration at 98% G_{mm} or the end of compaction, whichever comes first (Fig. 2.1b). Higher CDI values indicate that the mixtures are difficult to compact but lower values of CDI are desired because they represent a mix that is more workable and easier to compact. Higher TDI values signify a mix that has better mixture stability and resistance to permanent deformation (Loauy et al. 2007).

Studies on the number of gyrations to reach 92% G_{mm}, CDI, and locking point of HMA mixtures suggested that NMAS and aggregate type had significant effect on compactibility (Stakston et al. 2002; Mohammad and Khalid, 2007; Leiva et al. 2008). Most of the research was carried out with HMA mixtures for defining compaction characteristics using both Bahia and Locking point methods, while little work has been done for WMA mixtures adopting the Bahia method. Addition of WMA additives improved the compactability of mixtures, enabling the reduction of mixing and compaction temperatures and hence, saving energy (Mo et al. 2012). WMA mixtures evaluated for compaction characteristics at varying compaction temperatures indicated that the benefits of WMA additives were not recognized until compaction temperatures dropped below 110 °C (Hanz et al. 2010). Sasobit modified WMA mixtures have greater resistance to densification under simulated traffic (92% G_{mm} to 98% G_{mm}) and higher resistance to permanent deformation under traffic loads due to higher TDI values than the HMA mixtures (Kanitpong et al. 2007). Sanchez-Alonso et al. 2011 conducted studies on the ease of compaction and concluded that WMA mixtures compacted at 120 °C reduced the energy needed for densification due to lower CDI values than HMA mixtures compacted at 160 °C, while TDI values were found to be quite similar.



(a) Bahia method



(b) Locking point method

[Source: Bahia et al. 1998; Loauy et al. 2007]

Fig. 2.1. SGC curve showing densification indices

Table 2.1. Summary on Superpave mix design properties

WMA Technology	Additive	Dosage rate (%)	NMAS (mm)	No. of gyrations	Production temp. of WMA w.r.t HMA	Volumetric properties of WMA mix w.r.t Control HMA mix				References
						OAC (%)	VMA (%)	VFA (%)	VTM (%)	
Foaming	Asphamin	0.3 w/m	12.5	125	149-34	5.1±0	15.0-0.4	70.8+2.4	4.4-0.5	Hurley et al. (2005a)
Foaming	Asphamin	0.3 w/m	12.5	125	163-28	5.3±0	14.4±0	71.9±0	4.4-2.1	Hossain et al. (2009)
Foaming	Asphamin	0.3 w/m	12.5	75	158-19	5.7±0	14.1+4.0	72.2+5.7	4.0±0.0	Akisetty, (2008)
Foaming	Asphamin	0.3 w/m	12.5	75	155-25	5.9±0	17.0-2.8	77.5-5.5	4.0±0.0	Feipeng et al. (2011a, b)
Foaming	Asphamin	0.3 w/m	12.5	75	150-20	6.0±0	14.8±0	73.2-0.1	4.0±0.0	Ahmed et al. (2013)
Foaming	Asphamin	0.3 w/m	12.5	80	160-30	5.8±0	17.5-2.4	76.0-3.0	4.0±0.0	Kavussi et al. (2012)
Foaming	Asphamin	0.3 w/m	13.2	NA	173-20	4.6±0	14.6+0.2	74.2+0.6	4.0±0.0	Wang et al. (2013)
Foaming(RAP)	Asphamin	0.3 w/m	12.5	80	155-25	4.7-0.1	13.8-0.1	70±0	4.0±0.0	Adriana et al. (2012)
Foaming(PMB)	Asphamin	0.3 w/m	12.5	75	150-10	5.1±0	13.9+2.2	72.6+1.1	4.0±0.0	Kim et al. (2012/2013)
Foaming(SMA)	Asphamin	0.3 w/m	12.5	75	155-25	5.5±0	17.0+0.1	82.0+3.0	4.0±0.0	Punith et al. (2012)
Foaming	Advera	0.25 w/m	12.5	75	150-40	6.0±0	14.8-0.4	73.2+3.2	4.0±0.0	Ahmed et al. (2013)
Organic	Sasobit	0.8 w/b	12.5	125	149-39	5.1±0	15.0-1.0	70.8+5.9	4.4-1.2	Hurley et al. (2005b)
Organic	Sasobit	1.5 w/b	9.5	65	149-39	5.7-0.1	17.3-1.1	73.6-3.4	4.2-0.1	Stacey et al. (2008)
Organic	Sasobit	1.5 w/b	12.5	125	163-37	5.3±0	14.4±0	71.9±0	4.4-1.1	Hossain et al. (2009)
Organic	Sasobit	0.8 w/b	12.5	75	160-12	5.0±0	13.5+0.1	65.9+4.2	4.0±0.0	Liu et al. (2010)
Organic	Sasobit	1.5 w/b	12.5	75	150-20	5.9±0	17.0-1.8	77.5-4.2	4.0±0.0	Feipeng et al. (2011a, b)

WMA Technology	Additive	Dosage rate (%)	NMAS (mm)	No. of gyrations	Production temp. of WMA w.r.t HMA	Volumetric properties of WMA mix w.r.t Control HMA mix				References
						OAC (%)	VMA (%)	VFA (%)	VTM (%)	
Organic	Sasobit	3.0 w/b	19	75	150-40	5.4±0	18.3-3.7	77.5-5.0	4.0±0.0	Kunnawee et al. (2012)
Organic	Sasobit	1.5 w/b	12.5	80	160-30	5.8±0	17.5-0.2	76.0-1.0	4.0±0.0	Kavussi et al. (2012)
Organic	Sasobit	1.5 w/b	13.2	NA	173-20	4.6-0.1	14.6-0.6	74.2-0.1	4.0±0.0	Wang et al. (2013)
Organic(CRMB)	Sasobit	1.5 w/b	12.5	75	158-25	5.7±0	14.1+1.7	72.2+2.5	4.0±0.0	Akisetty, (2008)
Organic(RAP)	Sasobit	1.5 w/b	9.5	100	150-10	6.2±0	16.4-1.3	75.6-0.1	4.0-0.3	Bonaquist, (2011)
Organic(RAP)	Sasobit	1.5 w/b	9.5	70	150-20	6.7±0	15.3±0	73.7-0.4	4.0±0.0	Hill, (2011)
Organic(PMB)	Sasobit	1.5 w/b	12.5	75	150-10	5.1±0	13.9+1.4	72.6+1.7	4.0±0.0	Kim et al. (2012/2013)
Organic(SMA)	Sasobit	1.5 w/b	12.5	75	155-25	5.5+0.35	17.0+0.3	82.0-0.1	4.0±0.0	Punith et al. (2012)
Organic(RAP)	SonneWarmmix	1.0 w/b	12.5	75	150-17	7.7±0	22.0-1.9	73.3+3.3	3.9+0.9	Walaa et al. (2013)
Chemical	Evotherm	0.5 w/e	12.5	75	150-30	4.5+0.4	12.6+0.8	69.7+0.4	4.0±0.0	Kunnawee et al. (2012)
Chemical	Evotherm	0.5 w/e	12.5	125	149-19	5.1±0	15.0-0.9	70.8+4.5	4.4-0.9	Hurley et al. (2006a)
Chemical	Evotherm-DAT	0.5 w/e	13.2	NA	173-16	4.6-0.2	14.6-0.5	74.2+0.2	4.0±0.0	Wang et al. (2013)
Chemical(SMA)	Evotherm	0.5 w/e	12.5	75	155-20	5.5+0.35	17.0+0.3	82.0-2.0	4.0±0.0	Punith et al. (2012)
Chemical	Thiopave (SBS)	0.4 w/b	19.0	75	155-30	4.0±0	13.0±0	68.0±0	3.7±0.0	Samuel et al. (2011)

Note: w/m-by weight of total mix, w/b- by weight of bitumen, w/e-by weight of emulsion, RAP-recycled asphalt pavement, PMB-polymer modified bitumen, CRMB-crumb rubber modified bitumen, SMA-stone mastic asphalt, NA- not available

2.5 MOISTURE-INDUCED DAMAGE PROPERTIES OF WMA MIXTURES

Moisture-induced damage in asphalt mixture indicates the failure of adhesive bond between aggregate and asphalt and loss of cohesion/strength and stiffness due to the presence of moisture leading to pavement failure. Some of the test methods to evaluate moisture-induced damage include boiling water test, Static-immersion test, Modified Lottman test, and Immersion-Compression test (Martin 2014).

WMA technologies (foaming and some chemical additives) are more prone to moisture damage as they introduce moisture in the initial mixing process and due to lower production temperature (Kvasnak et al. 2009; Zaumanis 2010; Arabani et al. 2012). The lower production temperature of WMA mixtures, especially at mixing and compaction temperature lower than 130 °C and 110 °C, respectively, may not allow complete drying of aggregates. Therefore, the presence of moisture could prevent binder and aggregate bonding leading to moisture-induced damage (Bonaquist 2011; Punith et al. 2011; Xiao et al. 2013).

The moisture damage resistances of WMA mix with reference to the control HMA mix according to AASHTO T283/ ASTM D 4867/ EN 12697-12 was studied. In the present context, WMA technology, additive and their corresponding dosage rate, type of mix, binders, aggregate source with its water absorption, both dry and wet indirect tensile strength (ITS) value with corresponding TSR values are summarized in Table 2.3.

Most of the WMA technologies showed less resistance to moisture-induce damage than HMA but similar or better resistance was noticed with technologies such as Double barrel green system, Aquablack (foaming), tensoactive liquid additive (Chemical) and fatty polyamine with polymer wax-based (organic) additives (Middleton et al. 2008, Nathan et al. 2012; Franciso et al. 2012; Wenbin et al. 2012). Studies on Sasobit-modified WMA mixtures indicated lower or similar resistance to moisture-induce damage than HMA mixtures but Rediset-modified WMA mixtures either failed or marginally fulfilled the minimum TSR requirement (Ahmed et al. 2013; Malladi et al. 2015).

Dense-graded and open-graded (SMA & OGFC) WMA mixtures of NMAS (9.5, 12.5, 16.0 and 19.0 mm) were studied by the researchers to evaluate moisture-induced damage. These mixtures showed less resistance to moisture damage than the control HMA mixtures but showed better resistance with inclusion of RAP (Burak et al. 2013; Sheng et al. 2013; Shu et al. 2013).

Binders modified with WMA additives showed less resistance to moisture-induced damage but similar or better resistance was noticed with the addition of antistripping agents (Feipeng et al. 2010; Moer et al. 2011; Feipeng et al. 2013) and hydrated lime (Stacey et al. 2008; Jianchuan et al. 2011). Even it was true with modifiers like PMB and CRMB (Feipeng et al. 2010; Liu et al. 2011; Joel et al. 2012; Kim et al. 2012). In addition, proper conditioning of the WMA mix increased the resistance to moisture damage (Feipeng et al. 2013; Ahmed et al. 2013; Martin 2014).

Moisture-induced damage of WMA mixtures were significantly affected by type of aggregates. Studies on moisture damage of WMA mixtures with different aggregate source (granite, limestone, quartzite etc.) by many authors indicated that physical and engineering properties of aggregate have greater influence on the moisture damage and aggregates with high water absorption (> 1.0 %) are more prone to moisture damage and even fails to meet minimum TSR requirement (80%) (Feipeng et al. 2010; Feipeng et al. 2011; Akisetty et al. 2011; Feipeng et al. 2012; Ahmed et al. 2013). Zycotherm-modified WMA mixtures showed better resistance to moisture-induced damage with calcareous aggregates. Both HMA and Zycotherm-modified WMA mixtures with siliceous aggregate failed to fulfill the minimum TSR requirement (Mirzababaei 2016; Ziari et al. 2016). WMA mixtures made with moist aggregates exhibited lower resistance to moisture-induced damage than WMA mixtures made with dried aggregates (Punith et al. 2011; Xiao et al. 2013).

Field demonstration projects indicate that Sasobit and Aquablack TM-modified WMA mixtures that had a production temperature of more than 130 °C showed comparable resistance to moisture-induced damage than the HMA mixtures. While, Gencor and Water Injection modified WMA mixtures that had production temperatures less than 130 °C showed less resistance to moisture-induced damage than the HMA mixtures (Liu et al. 2011; Bower et al. 2012).

2.6 RUTTING PROPERTIES OF WMA MIXTURES

Rutting (permanent deformation) is defined as the accumulation of small amounts of unrecoverable strain resulting from applied wheel loads to the pavement resulting in reduction of useful service life and performance of pavement (Wenbin et al. 2012; Fereidoon et al. 2013). Some of the test methods to evaluate rutting properties include creep, repeated load, dynamic, simple shear and wheel-track tests. Factors, such as, binder grade, aggregate gradation, production temperature, and additives influences the rutting resistance.

Rutting properties of WMA mix with reference to HMA mix were evaluated by various authors as shown in Table 2.5. WMA technology and additive, type of equipment with test temperature, wheel load and contact pressure, air void of the mix, number of cycles and corresponding rut depth are summarized and it is seen that either number of cycles or rut depth is fixed.

Rutting potential of WMA mixtures using wheel-track test equipment's like Asphalt pavement analyzer (APA) according to AASHTO TP 63-03, Hamburg wheel tracking device (HWTD) according to AASHTO T 324/TEX 241-F, Wheel tracking test according to EN 12697-22, Immersion Wheel Tracking device according to T0719-1993 and Purdue University Laboratory Wheel Tracking Device (PUR Wheel) were used. These tests include casting of asphalt slab and subjected it to normal loading at a known rate of wheel passes per minute. The wheel load, contact pressure and testing temperature differ with equipment utilized.

All three WMA technologies studied showed less resistance to rutting than the conventional HMA mix. The use of ASA and hydrated lime improved rutting potential of these technologies to acceptable values but not with processes such as Double barrel green system, Aquablack (foaming), tensoactive liquid additive (Chemical) and fatty polyamine with polymer wax based (organic) additives (Middleton et al. 2008, Nathan et al. 2012; Franciso et al. 2012, Wenbin et al. 2012). Different types of binder are reported by authors to evaluate rutting potential of WMA mixtures. The binder with high grade showed less rut depth and use of modifiers like PMB and CRMB in WMA mix showed similar or better rutting potential (Feipeng et al. 2010; Joel et al. 2012; Liu et al. 2011; Kim et al. 2012).

Dense-graded and open-graded (SMA and OGFC) WMA mixtures were subjected to rutting by various authors. It was seen that, open graded WMA mixtures showed better resistance than the dense-graded WMA mixtures (Al-Qadi et al. 2012). In addition, SMA mix containing WMA additives and WMA mix containing RAP showed better resistance to rutting (Hill, 2011; Al-Qadi et al. 2012; Adriana et al. 2012; Jesse et al. 2013; Walaa et al. 2013; Sheng et al. 2013). The VTM of WMA mix subjected to rutting was found to be between 4.0±0.5 % and 7.0±0.5 %. The mix compacted at lower VTM showed less rut depth than the mix with higher VTM (Akisetty, 2008; Nathan et al. 2012; Ahmed et al. 2013). In addition, lower mixing and compaction temperatures result in less ageing of binder and reduces binder stiffness resulting in rutting problems (Xiao et al. 2009; Fakhri et al. 2012; Ziari et al. 2012; Vargas-Nordcbeck and Timm 2012; Zhao et al. 2012; Moghadas Nejad et al. 2014).

Table 2.2. Summary on moisture-induced damage properties

WMA Technology	WMA Additive	Dosage of additive (%)	Type of mix [NMAS(mm)]	Binder type	Aggregate type [Water absorption{%}]	Test Method of moisture-induced damage	ITS and TSR value of WMA mix w. r. t Control HMA mix			References
							Dry ITS(kPa)	Wet ITS (kPa)	TSR (%)	
Foaming	Asphamin	0.3 w/m	Dense graded(12.5)	PG 67-22	Limestone(1.5)	ASTM D 4867	2700-100	2300-600	82-10	John et al. (2013)
Foaming	Asphamin	0.3 w/m	Dense graded (19.0)	60/70	Siliceous aggregate(2.0)	AASHTO T283	1360-80	1200-260	88-16	Mansour et al. (2013)
Foaming	Asphamin	0.3 w/m	Open graded(12.5)	PG 76-22+CRMB	Granite(0.5)	AASHTO T283	1000-50	850-50	85-1	Punith et al. (2012)
Foaming	Asphamin	0.3 w/m	Dense graded (19.0)	PG 64-22+ASA	Schist(0.70)	AASHTO T283	1000-250	700-150	80+5	Feipeng et al. (2010)
Foaming	Asphamin	0.3 w/m	Open graded(12.5)	PG 64-22	Granite(0.5)	ASTM D 4867	620-120	470-135	76-9	Hurley et al. (2005a)
Foaming	Asphamin	0.3 w/m	Open graded (12.5)	PG70-34	Limestone	AASHTO T283	541±0	388-188	72-35	Nishant, (2010)
Foaming	Asphamin	0.3 w/m	Dense graded (12.5)	PG 64-22+CRMB	Granite(0.7)	AASHTO T283	920±0	900±0	96-1	Akisetty, (2008)
Foaming	Asphamin	0.3 w/m	Dense graded (12.5)	PG 64-22	Granite(0.7)	AASHTO T283	NA	NA	95+10	Gandhi, (2008/2010)
Foaming	Asphamin	0.3 w/m	Dense graded (12.5)	PG 64-22+ASA	Granite(0.5)	AASHTO T283	600+100	550+150	95+3	Feipeng et al. (2013c)
Foaming	Asphamin	0.3 w/m	Dense graded (12.5)	60/70	Siliceous aggregate(1.6)	AASHTO T283	830-10	750-100	92-10	Khodaii et al. (2012)
Foaming	Asphamin	0.3 w/m	Dense graded (12.5) + Hydrated lime	PG 64-22	Schist(0.70)	AASHTO T283	1020-40	850-40	84+2	Jianchuan et al. (2011)
Foaming	Asphamin	0.3 w/m	Dense graded (19.0) +RAP	50/70	Basalt	AASHTO T283	975±0	625+150	65+15	Burak et al. (2013)
Foaming	Asphamin	0.3 w/m	Dense graded (12.5)	PG 64-22	Synder Granite	AASHTO T283	765-91	622-81	89-12	Hossain et al. (2012)
Foaming	Asphamin	0.3 w/m	Dense graded (12.5)	PG 76-22+PMB	Granite(1.1)	SC-T-70	1200-190	1000-100	82+4	Kim et al. (2012a)
Foaming	Asphamin	0.3 w/m	Dense graded (19.0)	PG 64-22	Schist(0.70)	AASHTO T283	1000-200		--	Feipeng et al. (2013a)
Foaming	Free water system	0.25 w/m	Dense graded (9.5)	PG 58-34	NA	AASHTO T283	NA	NA	88+4	Mohd et al. (2013)

WMA Technology	WMA Additive	Dosage of additive (%)	Type of mix [NMAS(mm)]	Binder type	Aggregate type [Water absorption{%}]	Test Method of moisture-induced damage	ITS and TSR value of WMA mix w. r. t Control HMA mix			References
							Dry ITS(kPa)	Wet ITS (kPa)	TSR (%)	
Foaming	Advera	0.25 w/m	Dense graded (9.5)	PG 64-22	Limestone (Dolomitic)	AASHTO T283	1030-218	1359-203	76-6	Hill, (2008)
Foaming	Advera	0.25 w/m	Dense graded (12.5)	PG 64-28	Quartzite(0.45)	AASHTO T283	1162-333	1081-354	93-6	Ahmed et al. (2013)
Foaming	Advera	0.25 w/m	Dense graded (12.5)	PG 64-22+ASA	Synder Granite	AASHTO T283	678-11	603-89	89-12	Hossain et al. (2012)
Foaming	Synthetic Zeolite	0.3 w/m	Dense graded (16.0)	60/70	Ophite	EN 12697-12	NA	NA	85-2	Elsa et al. (2011/2012)
Foaming	Synthetic Zeolite	0.3 w/m	Dense graded 16.0)	PG 64-28	Limestone	AASHTO T283	NA	NA	78-4	Jun, (2010)
Foaming	Foam Bitumen	2.0 wc	Dense graded (12.5)	60/70	Siliceous aggregate	AASHTO T283	980-143	683-108	69-1	Kavussi et al. (2012)
Foaming	Foam Bitumen	2.0 wc	Dense graded (19.0) + RAP	PG 64-22	Limestone	AASHTO T283	NA	NA	85-5	Xiang et al. (2012)
Foaming	Foam WMA	3.0% w/b	Dense graded (12.5)	PG 64-22+ASA	Granite(0.5)	AASHTO T283	975-80	650+150	70+20	Feipeng et al. (2013b)
Foaming	Foam WMA	1.8% w/b	Dense graded (12.5)	PG 70-22	Limestone(1.5)	AASHTO T 283	1378-69	1206-69	84-3	Ayman et al. (2013)
Foaming	Foam WMA	NA	Dense graded (NA) +RAP	PG 64-22	NA	AASHTO T 283	NA	NA	95-10	Sheng et al. (2013)
Foaming	Double barrel green system	0.5 kg of water per metric ton of mix	Dense graded (NA) + RAP	PG 64-22	NA	AASHTO T283	807+178	625+193	78+6	Middleton et al. (2008)
Organic	Sasobit	1.5 w/b	Dense graded (14.0)	50/70	Granite(1.0)	EN 12697-12	NA	NA	47-5	Hugo et al. (2010)
Organic	Sasobit	1.5 w/b	Dense graded (12.5)	60/70	Siliceous aggregate(1.6)	AASHTO T283	830+20	750-50	92-7	Khodaii et al. (2012)
Organic	Sasobit	1.5 w/b	Dense graded (12.5)	PG 67-22	Limestone(1.5)	ASTM D 4867	2700-300	2300-600	82-7	John et al. (2013)
Organic	Sasobit	1.5 w/b	Dense graded (9.5)	PG 64-22	Limestone(NA)	AASHTO T283	1030-113	1355-123	76-2	Hill, (2008)
Organic	Sasobit	1.5 w/b	Dense graded (12.5)	PG 64-22	Granite(0.7)	AASHTO T283	NA	NA	95+15	Gandhi, (2008/2010)

WMA Technology	WMA Additive	Dosage of additive (%)	Type of mix [NMAS(mm)]	Binder type	Aggregate type [Water absorption{%}]	Test Method of moisture-induced damage	ITS and TSR value of WMA mix w. r. t Control HMA mix			References
							Dry ITS(kPa)	Wet ITS (kPa)	TSR (%)	
Organic	Sasobit	1.5 w/b	Open graded(12.5)	PG 76-22+CRMB	Granite(0.5)	AASHTO T283	1000-100	850-50	85+3	Punith et al. (2012)
Organic	Sasobit	0.8 w/m	Open graded(12.5)	PG 64-22	Granite(0.5)	ASTM D 4867	620-252	470-208	76-5	Hurley et al. (2005b)
Organic	Sasobit	1.5 w/b	Dense graded (16.0)	PG 64-28	Limestone	AASHTO T283	NA	NA	78-1	Jun, (2010
Organic	Sasobit	1.5 w/b	Dense graded (12.5)	60/70	Siliceous aggregate(1.6)	AASHTO T283	1360-160	1200-160	88-3	Mansour et al. (2013)
Organic	Sasobit	1.5 w/b	Dense graded (12.5)	PG 64-22	Steel slag+ Limestone	AASHTO T283	891+98	825+110	93+2	Mahmoud et al. (2013)
Organic	Sasobit	1.5 w/b	Dense graded (9.5) + Hydrated lime	PG 64-22	Limestone	AASHTO T283	1265-204	1490-313	85+5	Stacey et al. (2008)
Organic	Sasobit	1.5 w/b	Dense graded (12.5)	60/70	Limestone(1.4)	AASHTO T283	730-20	620-70	85-8	Ebrahim et al. (2012)
Organic	Sasobit	1.5 w/b	Open graded (12.5)	60/70+ASA	Granite	ASTM D 4867	NA	NA	81+3	Meor et al. (2011)
Organic	Sasobit	1.5 w/b	Dense graded (12.5)	PG 64-22	Synder Granite	AASHTO T283	668-160	595-162	89-6	Hossain et al. (2011)
Organic	Sasobit	1.5 w/b	Dense grade(12.5) +RAP	60/70	Granite	ASTM D 4867	NA	NA	87-6	Fereidoon et al. (2014)
Organic	Sasobit	1.5 w/b	Dense graded (12.5) +RAP	PG 64-28	Limestone(1.5)	AASHTO T283	714-102	NA	--	Bonaquist, (2011)
Organic	Sasobit	0.8 w/m	Dense grade (12.5) + Hydrated lime	PG 64-22	Schist(1.1)	AASHTO T283	1020-120	850-100	84+8	Jianchuan et al. (2011)
Organic	Sasobit	1.5 w/b	Dense graded (12.5)	PG 64-22	Limestone(2.2)	AASHTO T283	1100-100	NA	--	Ziari et al. (2013)
Organic	Sasobit	1.5 w/b	Dense graded (12.5)	PG 64-22+ASA	Synder Granite	AASHTO T283	765-322	622-217	89-6	Hossain et al. (2009)
Organic	Syn. Wax	3.0 w/b	Dense graded (19.0)	80/100	Granite(0.12)	ASTM D 4123-82	444+141	NA	NA	Arun et al. (2013)
Organic	Sasobit	1.5 w/b	Dense graded (12.5)	PG 64-22	Granite(0.7)	AASHTO T283	920-20	900-10	96.4-4	Akisetty, (2008)
Organic	Sasobit	1.5 w/b	Dense graded (12.5)	PG 76-22+PMB	Granite(1.1)	AASHTO T283	1200-250	1000-50	82+14	Kim et al. (2012)

WMA Technology	WMA Additive	Dosage of additive (%)	Type of mix [NMAS(mm)]	Binder type	Aggregate type [Water absorption{%}]	Test Method of moisture-induced damage	ITS and TSR value of WMA mix w. r. t Control HMA mix			References
							Dry ITS(kPa)	Wet ITS (kPa)	TSR (%)	
Organic	Sasobit	1.5 w/b	Dense graded (19.0) +RAP	22+CRMB 50/70	Basalt	AASHTO T283	975+225	625+275	65+10	Burak et al. (2013)
Organic	Sasobit	1.5 w/b	Dense graded (12.5)	Bitumen Emulsion	NA	AASHTO T283	NA	NA	98±0	Dinis-Almeida et al. (2012)
Chemical	Evotherm	0.5% w/e	Dense graded (9.5)	PG 64-22	Dolomitic-Limestone	AASHTO T283	1030+22	1355-137	76+10	Hill, (2008)
Chemical	Evotherm	0.5% w/e	Dense graded (NA) +RAP	PG 64-22	NA	AASHTO T 283	NA	NA	95-15	Sheng et al. (2013)
Chemical	Evotherm	0.5% w/e	Dense graded (16.0)	PG 64-28	Limestone	AASHTO T283	NA	NA	78.2-8	Jun, (2010)
Chemical	Evotherm	0.5% w/e	Open graded (12.5)	PG 64-22	Granite(0.5)	ASTM D 4867	673-175	470-261	97-13	Hurley et al. (2006a)
Chemical	Evotherm	0.5% w/e	Dense graded (12.5)	PG 64-28	Quartzite(0.45)	AASHTO T283	1162-415	1081-469	93-9	Ahmed et al. (2013)
Chemical	Evotherm	0.5% w/e	Dense grade (12.5) + Hydrated lime	PG 64-22	Schist(1.1)	AASHTO T283	1020-60	850+10	84+6	Jianchuan et al. (2011)
Chemical	Rediset WMX	2.0 w/b	Dense graded (19.0)	50/70	Basalt	AASHTO T283	975+150	625+75	65-3	Burak et al. (2013)
Chemical	Rediset WMX	2.0 w/b	Dense graded (12.5)	PG 67-22	NA	ASTM D 4867	2700-500	2300-900	82-12	John et al. (2013)
Chemical	Cecabase RT	0.2 w/b	Open graded (19.0)	PG 76-22	Limestone	AASHTO T283	541-36	388-143	72-23	Nishant, (2010)
Chemical	Cecabase RT	0.2 w/b	Open graded (19.0)	PG 64-28	NA	AASHTO T283	658+55	436+19	66-2	Elie et al. (2011)
Chemical	Cecabase RT	0.2 w/b	Open graded (NA)+RAP	PG 58-34	NA	AASHTO T283	750-140	650-70	91+3	Shu et al. (2013)
Chemical	Cecabase RT	0.2 w/b	Dense graded (19.0) +RAP	50/70	Granite(1.0)	EN 12697-12	2750-100	2400+100	81+2	Joel et al. (2012)
Chemical	Cecabase RT	0.2 w/b	Dense graded (14.0)	50/70+ CRMB	Granite(1.0)	EN 12697-12	1300+50	1100+100	73-2	Joel et al. (2013)
Chemical	Thiopave (SBS)	0.4 w/b	Dense graded (19.0)	PG 64-22	Limestone	AASHTO T283	NA	NA	81+6	Samuel et al. (2011)

Note: ASA-antisripping agents, RAP-recycled asphalt pavement, PMB-polymer modified bitumen, CRMB-crumb rubber modified bitumen, NA- not available

Table 2.3. Summary on rutting properties

WMA Technology	WMA Additive	Test method	Type of test equipment	Wheel load (Kg)	Contact Pressure (kPa)	Test-temperature (°C)	Air void Content (%)	No. of cycles w.r.t Control mix	Rut depth (mm) of WMA mix w.r.t Control mix	Reference
Foaming	Asphamin	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	7.0±0.5	10,000-4500	12.5±0.0	Zelelam et al. (2012)
Foaming	Asphamin	AASHTO TP 63-03	Asphalt Pavement Analyzer	54.4	815	64	7.0±0.5	8,000±0.0	7.5+3.5	Hurley et al. (2005a)
Foaming	Asphamin(ASA)	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	7.0±0.5	10,300±0.0	12.5±0.0	Hossain et al. (2009)
Foaming	Asphamin	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	58	7.0±0.5	8,050±0.0	4.9+1.0	Gandhi, (2008)
Foaming(RAP)	Asphamin	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	7.0±0.5	10,000±0.0	6.2-0.2	Sheng et al. (2013)
Foaming(PMA)	Asphamin	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	64	4.5±0.5	8,000±0.0	1.0+0.1	Kim et al. (2012)
Foaming(RAP)	Asphamin	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	58	7.0±0.5	8,000±0.0	3.0+0.8	Adriana et al. (2012)
Foaming	Advera	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	7.0±0.5	10,300-1,200	12.5±0.0	Hossain et al. (2012)
Foaming	Advera	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	7.0±0.5	5900-2200	12.5±0.0	Hill, (2011)
Foaming	Advera	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	64	4.5±0.5	8,000±0.0	3.8+1.3	Ahmed et al. (2013)
Foaming	Advera	TEX 241-F	Hamburg Wheel-Track Test	71.7	NA	50	4.0±0.5	9500-5500	12.5±0.0	Estakhri et al. (2010)
Foaming	Foam WMA	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	700±35	64	7.0±0.5	8,050±0.0	7.0+1.5	Feipeng et al. (2013b)
Foaming	Foam WMA	AASHTO T 340	Asphalt Pavement Analyzer	52.1	690	49	7.0±0.5	8,000±0.0	1.5+0.5	Ayman et al. (2013)
Foaming(SMA)	Foam WMA	AASHTO T324	Hamburg Wheel-Track Test	75.25	NA	30	7.0±0.5	20,000±0.0	3.5-0.5	Al-Qadi et al. (2012)
Foaming	Foam Bitumen+ Hydrated Lime	EN 12697-22	Wheel Tracking Test	NA	NA	60	4.3±0.0	10,000±0.0	3.6-0.5	Kavussi et al. (2012)
Foaming	Foam Bitumen+ Hydrated Lime	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	50	7.0±0.5	10,000±0.0	7.5-3.0	Xiang et al. (2012)
Foaming	Foam WMA (ASA+Lime)	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	700±35	64	7.0±0.5	8,050±0.0	3.0-0.5	Feipeng et al. (2013b)
Foaming	Double barrel green system	AASHTO TP 63-03	Asphalt Pavement Analyzer	NA	NA	58	7.0±0.5	8,000±0.0	7.9-0.8	Middleton et al. (2008)
Foaming	Aquablack	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	2.6±0.0	10,000±0.0	3.6-0.4	Nathan et al. (2012)
Organic	Sasobit	TEX 241-F	Hamburg Wheel-Track Test	71.7	NA	50	4.0±0.5	9500-4500	12.5±0.0	Estakhri et al. (2010)
Organic(RAP)	Sasobit	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	7.0±0.5	5900+600	12.5±0.0	Hill, (2011)
Organic	Sasobit	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	58	7.0±0.5	8,000±0.0	4.9±0.0	Gandhi, (2008)
Organic	Sasobit(ASA)	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	7.0±0.5	10,300+1300	12.5±0.0	Hossain et al. (2009)

WMA Technology	WMA Additive	Test method	Type of test equipment	Wheel load (Kg)	Contact Pressure (kPa)	Test-temperature (^{0}C)	Air void Content (%)	No. of cycles w.r.t Control mix	Rut depth (mm) of WMA mix w.r.t Control mix	Reference
Organic	Sasobit	AASHTO TP 63-03	Asphalt Pavement Analyzer	54.4	815	64	7.0±0.5	8,000±0.0	7.1+0.1	Hurley et al. (2005b)
Organic	Sasobit	EN 12697-22	Wheel Tracking Test	NA	NA	50	4.0±0.5	10,000±0.0	6.0+2.0	Hugo et al. (2010a)
Organic	Sasobit	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	4.7±0.0	10,000±0.0	1.8+0.1	Nathan et al. (2012)
Organic	Sasobit	EN 12697-22	Wheel Tracking Test	NA	NA	50	3.0±0.5	10,000±0.0	8.0+2.0	Hugo et al. (2010b)
Organic	Sasobit	AASHTO T324	Hamburg Wheel-Track	71.7	NA	50	7.0±0.5	10,000-62,50	12.5±0.0	Zelelam et al. (2012)
Organic	Sasobit(ASA)	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	7.4-0.3	10,000±0.0	2.4-0.3	Stacey et al. (2008)
Organic	Sasobit	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	64	4.0±0.5	8,000±0.0	1.1+0.4	Akisetty, (2008)
Organic(PMA)	Sasobit	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	64	4.5±0.5	8,000±0.0	1.0-0.4	Kim et al. (2012)
Organic(PMA)	Sasobit	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	58	7.0±0.5	8,000±0.0	4.2-1.3	Liu et al. (2011)
Organic(SMA)	Sasobit	AASHTO T324	Hamburg Wheel-Track Test	75.25	NA	30	7.0±0.5	10,000±0.0	3.5-1.5	Al-Qadi et al. (2012)
Organic(RAP)	Sasobit	NA	Purdue University Laboratory Wheel Tracking Device (PURWheel)	178.4	630	64	6.0±0.5	10,000±0.0	7.7-3.4	Jesse et al. (2013)
Organic(RAP)	Sonnewarmix	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	7.0±0.5	10,000±0.0	1.1-0.4	Walaa et al. (2013)
Organic	Synthetic wax	NA	Wheel Tracking Test	53	NA	50	4.0±0.5	10,000±0.0	10.4-3.0	Arun et al. (2013)
Organic	Synthetic wax	EN 12697-22	Wheel Tracking Test	NA	1380	60	7.0±0.5	10,000±0.0	3.0+0.5	Kai et al. (2009)
Organic	Fatty polyamines+ Polymer wax	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	700±35	58	7.0±0.5	8,000±0.0	7.1-2.0	Wenbin et al. (2012)
Chemical(RAP)	Evotherm	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	64	7.0±0.5	8,000±0.0	11.5-2.5	Sheng et al. (2013)
Chemical	Evotherm	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	64	4.0±0.5	8,000±0.0	2.5±0.0	Jun, (2010)
Chemical	Evotherm	AASHTO TP 63-03	Asphalt Pavement Analyzer	54.4	815	64	7.0±0.5	8,000±0.0	4.0+0.5	Hurley et al. (2006a)
Chemical	Evotherm	TEX 241-F	Hamburg Wheel-Track Test	71.7	NA	50	4.0±0.5	9500-6000	12.5±0.0	Estakhri et al. (2010)
Chemical	Evotherm	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	7.0±0.5	5900-2700	12.5±0.0	Hill, (2011)
Chemical	Evotherm	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	64	4.5±0.5	8,000±0.0	3.8+0.2	Ahmed et al. (2013)
Chemical(SMA)	Evotherm	AASHTO T324	Hamburg Wheel-Track Test	75.25	NA	30	7.0±0.5	20,000±0.0	3.5+0.4	Al-Qadi et al. (2012)

WMA Technology	WMA Additive	Test method	Type of test equipment	Wheel load (Kg)	Contact Pressure (kPa)	Test-temperature (^{0}C)	Air void Content (%)	No. of cycles w.r.t Control mix	Rut depth (mm) of WMA mix w.r.t Control mix	Reference
Chemical	Rediset WMX	T0719-1993	Immersion Wheel Tracking Test	NA	700	60	4.0±0.5	8,000±0.0	2.0+6.0	Liantong et al. (2012)
Chemical	Rediset WMX	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	7.0±0.5	10,000-1500	12.5±0.0	Zelelam et al. (2012)
Chemical	Tensoactive-liquid	UEN 12697-22	Wheel Tracking Test	71.9	NA	60	7.0±0.5	10,000±0.0	4.0-1.0	Franciso et al. (2012)
Chemical (RAP+CRMB)	Surfactant based	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	50	4.0±0.5	8,000±0.0	5.0-1.0	Joel et al. (2012)
Chemical(CRMB)	Surfactant based	EN 12697-22	Wheel Tracking Test	NA	NA	50	4.0±0.5	10,000±0.0	1.6-0.4	Joel et al. (2013)
Chemical	Cecabase RT	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	690	58	7.0±0.5	8,000±0.0	3.5+0.5	Shu et al. (2013)
Chemical	Thiopave (SBS)	AASHTO T324	Hamburg Wheel-Track Test	71.7	NA	50	7.0±0.5	10,000±0.0	4.0+2.0	Samuel et al. (2011)
Chemical	Polymer+ fatty acid amine	AASHTO TP 63-03	Asphalt Pavement Analyzer	45.4	700±35	58	7.0±0.5	8,000±0.0	7.1-0.2	Wenbin et al. (2012)

Note: ASA-antisripping agents, RAP-recycled asphalt pavement, PMB-polymer modified binder, CRMB-crumb rubber modified bitumen, SMA- stone mastic asphalt, NA- not available

Studies on Sasobit modified WMA mixtures using HWTD showed lower rutting resistance than HMA mixtures but rut depth were within limits after 10,000 loading cycles. While, studies conducted using APA showed that Sasobit modified WMA mixtures exhibited similar rutting resistance of HMA mixtures after 8,000 loading cycles (Mo et al. 2012; Jamshidi et al. 2013; Malladi et al. 2015). Rediset modified WMA mixtures compacted at 110 °C exhibited lower rutting resistance than HMA mixtures compacted at 130 °C (Bennert et al. 2011).

WMA mixtures made with moist aggregates exhibited lower resistance to rutting than WMA mixtures made with dried aggregates (Punith et al. 2011; Xiao et al. 2013). Field demonstration projects indicate that Sasobit and Aquablack TM modified WMA mixtures that had a production temperature of more than 130 °C showed comparable resistance to rutting damage than HMA mixtures. While, Gencor and Water Injection modified WMA mixtures that had production temperatures less than 130 °C showed less resistance to rutting than HMA mixtures (Liu et al. 2011; Bower et al. 2012).

2.7 FATIGUE PROPERTIES OF WMA MIXTURES

Fatigue life of asphalt mix is its ability to withstand repeated load application without fracture and expressed as relationship between the initial stresses or strain (Mansour et al. 2013). It can be determined by knowing number of cycles to failure using repeated flexure or indirect tensile tests performed at several stress or strain levels.

Fatigue resistance of WMA mixtures based on number of cycles to failure evaluated by various authors is presented in Table 2.5. In the present context, WMA technology, additive, type of equipment, method of testing along with test temperature, air void content of mix, applied strain/stress level and air voids of the mix is reported. Most of the authors evaluated fatigue life of WMA mixtures using Beam fatigue testing machine (strain or stress controlled) and repeated load indirect tensile test with 50% reduction in beam stiffness as the fatigue failure criteria. Usually beams and cylindrical specimens are tested to know the fatigue life of the asphalt mix at VTM between 4.0±0.5 % and 7.0±0.5 % (Xiao et al. 2009, Fakhri et al. 2012; Ziari et al .2012).

Most of the WMA processes exhibit high fatigue damage than the control mix with exception of the mixtures from processes such as free water system (Mohd et al. 2013), Rheofalt LT70 (Ziari et al. 2013), Artificial wax (Emanuele et al. 2013) and synthetic wax (Kai et al. 2009). Studies on Sasobit modified WMA mixtures evaluated using beam fatigue testing machine (strain controlled) showed high fatigue damage than the HMA mixtures (Diefenderfer and Hearon 2008, Xiao et al. 2009, Ziari et al .2012). Even it was true with repeated load indirect tensile test (Fakhri et al. 2013). D'Angelo et al. (2008) found that both Sasobit and Aspha-min WMA pavements exhibit equivalent fatigue cracking to that in traditional HMA mixtures based on field performance data in France, Germany and Norway.

Modified binders with WMA additives showed better resistance to fatigue (Joel et al. 2012; Kim et al. 2012; Mansour et al. 2012). Furthermore, better resistance to fatigue damage was reported with open graded mixtures such as SMA mixtures modified with WMA additives (Al-Qadi et al. 2013). Fatigue resistance of WMA mixtures is also influenced by the applied stress/strain levels during testing. More fatigue damage was seen at low stress/strain levels but at high stress/strain levels similar or less fatigue damage was reported (Feipeng et al. 2009; Mansour et al. 2013; Ahmed et al. 2013).

Table 2.4. Summary on fatigue properties

WMA Technology	WMA Additive	Device used	Specimen description	Method of testing (temperature, ^{0}C)	Air voids (%)	Strain/ Stress Level (με/kPa)	Fatigue Life of WMA mix w.r.t control HMA mix * 10^6(Nf)	References
Foaming	Foam WMA	Bending fatigue testing machine	380*63*50 mm^3	0.1s loading, no rest period (7)	5.0±0.5	300	0.25±0.0	Sheng et al. (2013)
Foaming	Free water system	Strain controlled fatigue testing machine	NA	four point beam fatigue test (20)	5.0±0.5	400	0.65-0.10	Mohd et al. (2013)
Foaming	Advera	Strain controlled fatigue testing machine	NA	four point beam fatigue test (20)	5.0±0.5	400	0.65+1.25	Mohd et al. (2013)
Foaming(PMB)	Asphamin	Strain controlled fatigue testing machine	381*63.5*50 mm^3	0.1s loading, no rest period (20)	7.0±0.5	300	0.52-0.27	Mansour et al. (2013)
Foaming	Asphamin	Strain controlled fatigue testing machine	381*63.5*50 mm^3	four point beam fatigue test (20)	7.0±0.5	500	0.012+0.0	Feipeng et al. (2009)
Foaming	Asphamin	Repeated load indirect tensile test apparatus	Cylindrical specimen	Repeated loading 025s loading, 1s rest period	4.0±0.5	300	0.18+0.06	Mansour et al. (2013)
Foaming(PMB)	Asphamin	Repeated load indirect tensile test apparatus	Cylindrical specimen	Repeated loading 025s loading, 1s rest period	4.0±0.5	600	0.12-0.05	Mansour et al. (2013)
Foaming	Advera	Strain controlled fatigue testing machine	NA	four point beam fatigue test (21)	7.0±0.5	300	0.23+0.16	Ahmed et al. (2013)
Foaming	Advera	Strain controlled fatigue testing machine	NA	four point beam fatigue test (21)	7.0±0.5	700	0.016-0.004	Ahmed et al. (2013)
Organic	Synthetic wax	Strain controlled fatigue testing machine	300*40*40 mm^3	four point beam fatigue test (20)	7.0±0.5	400	0.27-0.01	Kai et al. (2009)
Organic	Artificial wax	Strain controlled fatigue testing machine	500*260*50 mm^3	four point beam fatigue test (20)	4.0±0.5	400	0.45-0.2	Emanuele et al. (2013)
Organic	Sasobit	Strain controlled fatigue testing machine	381*63.5*50 mm^3	four point beam fatigue test (20)	7.0±0.5	500	0.012+0.023	Feipeng et al. (2009)

WMA Technology	WMA Additive	Device used	Specimen description	Method of testing (temperature, ^{0}C)	Air voids (%)	Strain/ Stress Level (με/kPa)	Fatigue Life of WMA mix w.r.t control HMA mix * 10^{6}(Nf)	References
Organic	Sasobit	Strain controlled fatigue testing machine	385*63.5*50 mm^3	four point beam fatigue test (21)	7.0±0.5	400	0.80+0.15	Ziari et al. (2013)
Organic	Rheofalt L T70	Strain controlled fatigue testing machine	385*63.5*50 mm^3	four point beam fatigue test (21)	7.0±0.5	400	0.80-0.20	Ziari et al. (2013)
Organic	Synthetic wax	Strain controlled fatigue testing machine	NA	four point beam fatigue test (20)	7.0±0.5	300	1.87-0.11	Hugo et al. (2010)
Organic	Sasobit	Strain controlled fatigue testing machine	381*63.5*50 mm^3	four point beam fatigue test (20)	7.0±0.5	400	0.09+0.02	Stacey et al. (2008)
Organic	Sasobit	Repeated load indirect tensile test apparatus	Cylindrical specimen	Repeated loading 025s loading, 1s rest period	4.0±0.5	300	0.18+0.12	Mansour et al. (2013)
Organic (PMB)	Sasobit	Repeated load indirect tensile test apparatus	Cylindrical specimen	Repeated loading 025s loading, 1s rest period	4.0±0.5	600	0.12-0.03	Mansour et al. (2013)
Chemical	Thiopave (SBS)	Strain controlled fatigue testing machine	381*63.5*50.8 mm^3	four point beam fatigue test (20)	7.0±0.5	500	0.12+0.23	Samuel et al. (2011)
Chemical	Cecabase RT	Strain controlled fatigue testing machine	NA	four point beam fatigue test (20)	7.0±0.5	400	0.1+1.9	Shu et al. (2013)
Chemical(RAP)	Cecabase RT	Strain controlled fatigue testing machine	NA	four point beam fatigue test (20)	7.0±0.5	400	1.30-0.33	Joel et al. (2012)
Chemical	Cecabase RT	Strain controlled fatigue testing machine	381*51*51 mm^3	four point beam fatigue test (20)	7.0±0.5	400	0.50+1.50	Elie et al. (2011)
Chemical	Evotherm	Bending fatigue testing machine	380*63*50 mm^3	0.1s loading, no rest period (7)	5.0±0.5	300	0.10+0.25	Sheng et al. (2013)
Chemical	Evotherm	Strain controlled fatigue testing machine	NA	four point beam fatigue test (21)	7.0±0.5	300	0.23+1.37	Ahmed et al. (2013)
Chemical	Evotherm	Strain controlled fatigue testing machine	NA	four point beam fatigue test (21)	7.0±0.5	700	0.016-0.015	Ahmed et al. (2013)

Note: RAP-recycled asphalt pavement, PMB-polymer modified binder, CRMB-crumb rubber modified bitumen, NA- not available

2.8 SUMMARY

WMA is the broad term which is typically used to refer technologies that reduce greenhouse gas emissions and energy consumption by lowering the temperature at which asphalt mixtures are produced and placed. Recent global experiences (Hurley et al. 2006; D' Angelo et al. 2008; Stacey et al. 2008; Bonaquist 2011) suggest, WMA has the potential to replace HMA technology and has many benefits when compared to HMA due to lower production temperature. Hence, many highway agencies and DOTs all over the world are working to develop suitable specifications based on its performance. However, despite the benefits, it is more prone to moisture-induced damage due to varying physical and chemical properties of the aggregates and rutting due to less aging of binder and sometimes lower air voids as it is produced at lower mixing and compaction temperature.

Different working temperatures (mixing and compaction) were adopted by researchers worldwide for evaluation of the properties of WMA mixtures. Laboratory performance of WMA mixtures at lower working temperatures below 90 °C is rather unclear. While, the effect of mixing and compaction temperatures were addressed upto 130 °C and 110 °C, respectively, and the margin between these temperatures were not larger than 20 °C (Kanitpong et al. 2007; Akisetty et al. 2009; Lee et al. 2012; Xiao et al. 2013; Jamshidi et al. 2013).

Reviews of research findings summarize mix design, mechanical and workability properties of asphalt mixtures adopting various WMA additives available world-wide (D'Angelo et al. 2008; Carmen et al. 2012; Behnam et al. 2013). WMA additives namely Rediset LQ, Sasobit and Zycotherm are commercially available in the Indian market. The effect of these WMA additives on properties of WMA mixtures have not been addressed by researchers in the Indian Subcontinent.

From review of literature, it is also evident that the N_{des} adopted by various authors and road agencies for the design of WMA mixtures were not the same for selected NMAS (Hurley et al. 2005; Hurley et al. 2006; Liu et al. 2010; Xiao et al. 2011; Kanitpong et al. 2012; Kavussi et al. 2014; Ahmed et al. 2013).

Laboratory evaluation of mix design and mechanical properties of WMA mixtures are necessary during the design process. Subsequently the ability to quantify compactability of WMA mixtures would be very much helpful. Significant research was carried out with conventional HMA for defining compaction characteristics of asphalt mixtures using different methods while compaction characteristics of WMA mixtures were carried out only using the Bahia method (Kanitpong et al. 2007; Hanz et al. 2010; Sanchez-Alonso et al. 2011; Mo et al. 2012) and Locking point method has not been addressed.

Hence there is a need for study of effect of lower mixing and compaction (working) temperatures on mix design, workability and mechanical properties of WMA mixtures. This will provide wider margin between mixing and compaction temperatures that can ensure WMA mixtures for longer hauling time and better laboratory performance.

3.0 MATERIALS AND METHODOLOGY

3.1 GENERAL

This chapter provides a brief description of the materials used in this study, tests conducted and experimental design plan to accomplish the objectives of the present research.

3.2 MATERIALS

Straight-run (plain) binder, granite aggregate source and three non-foaming WMA additives were used in the study. Crushed stone dust is used as the mineral filler with 100% passing 0.6 mm sieve.

3.2.1 Aggregate and mineral filler

Granite stones crushed into coarser and finer particles were used as aggregates to meet the required gradation. The general aggregate properties of the same are tabulated in Table 3.1. The mineral filler used in the study is crushed stone dust from same aggregate source. The percentage of mineral filler for both 26.5mm and 19mm NMAS gradation is 5%. The filler was graded within the limits indicated in the Table 3.2.

Table 3.1. Properties of aggregate

Particulars of physical properties	Test method	Results	Requirement
LA Abrasion Value (%)	IS 2386 P4	22.0	≤ 30
Aggregate impact Value (%)	IS 2386 P4	21.0	≤ 24
Water Absorption (%)	IS 2386 P3	0.12	≤ 2
Combined Elongation and Flakiness Indices (%)	IS 2386 P1	29.0	≤ 35
Soundness, magnesium sulphate solution (%)	IS 2386 P5	0.20	≤ 18

Table 3.2. Grading requirements of mineral filler (MoRTH, 2013)

IS Sieve (mm)	Cumulative % passing by weight of total aggregate
0.600	100
0.300	95-100
0.075	85-100

3.2.2 WMA additives

Non-foaming WMA additives available in Indian market Rediset® LQ, Sasobit® and Zycotherm®, were procured from M/s KPL International Limited, M/s Spectrum Chemicals, and M/s Zydex Industries, respectively. The dosage rate of Rediset LQ, Sasobit and Zycotherm were 0.5%, 3.0% and 0.1% by weight of binder. The physical and chemical properties of these additives are presented in Table 3.3. Fig. 3.1 shows WMA additives (a) Rediset® LQ, (b) Sasobit® and (c) Zycotherm®.

3.2.3 Asphalt Binder

Plain asphalt binder of viscosity grade (VG-30) provided by Mangalore Refinery and Petrochemicals Limited (MRPL) was used. The properties of neat binder, Rediset-modified binder, Sasobit-modified binder, and Zycotherm-modified binder are presented in Table 3.3.

3.3 SELECTION OF AGGREGATE GRADATIONS

The first step in the selection of aggregate gradations was to fix the sieve sets for dense graded mix. To meet this requirement, the set of sieves was fixed by selecting the commonly used Indian Standard (IS) sieves, designated as 26.5mm, 19.0 mm, 13.2 mm, 9.5 mm, 4.75 mm, 2.36 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.15 mm and 0.075 mm. The sieve sizes given vide British Standards (BS: 410) and American Society for Testing Materials (ASTM E 11) are same as those specified in Indian Standard (IS: 460) (MoRTH 2013). Asphalt structural layers, Dense Bituminous Macadam grading-II

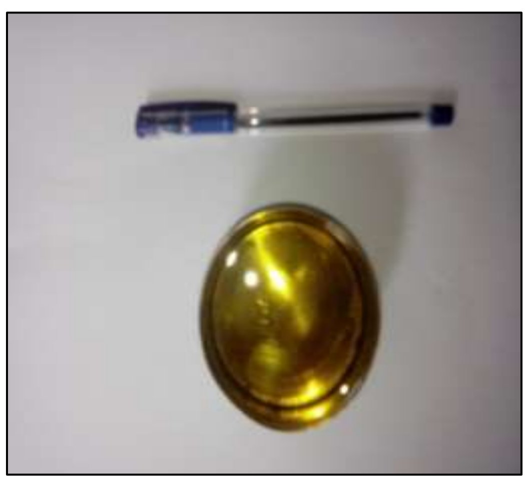
(NMAS26.5) and Bituminous concrete grading-I (NMAS19) conforming to the requirements of MoRTH, Government of India are presented in Table 3.5.

Table 3.3. Properties of WMA additives used [Source: Manufacturers]

Properties	Rediset® LQ	Sasobit®	Zycotherm®
Ingredients	Fatty polyamines, polymer and non-ionic components	Solid saturated hydrocarbons	Benzyl alcohol, Ethylene alcohol and Hydroxyalkyl-alkoxyl-alkylsilyl compounds
Physical state	Dark Liquid	Pastilles, flakes	Liquid
Colour	Pale yellow	Off-white to pale brown	Pale yellow
Odour	Amine like	Practically odorless	--
Density	0.55 g/cc	1.03 g/cc	1.01 g/cc
PH values	--	Neutral	10% solution in water neutral or slightly acidic
Freeze point	5 °C	--	5 °C
Flashpoint	>150 °C	Around 290 °C	>80 °C
Solubility in water	Soluble	Insoluble	Soluble

(a)

(b)



(c)

Fig. 3.1. WMA additives (a) Rediset® LQ, (b) Sasobit® and (c) Zycotherm®

Table 3.4. Properties of asphalt binder

Properties	Test method	NB	RMB	SMB	ZMB	Requirement
Penetration at 25 °C , 100 g, 5 s, 0.1 mm	IS 1203	67	73	38	70	60-70
Softening point, °C	IS 1205	58	60	70	56	≥ 46
Flash point, °C	IS 1209	310	313	317	316	≥ 230
Absolute viscosity at 60 °C, mPa·s	IS 1206 P2	2920	3900	4800	3110	2400-3600
Kinematic viscosity at 135 °C, mPa·s	IS 1206 P3	352	375	393	366	≥ 350
Specific gravity at 27 °C	--	1.02	1.01	1.05	1.00	--
Retained Penetration, % after thin-film oven test, %	IS 1203	54	76	32	72	>52
Ductility Test at 25 °C , 5 cm/min, cm after thin-film oven test	IS 1208	65	60	53	58	≥ 50

NB-Neat binder (VG-30), RMB-Rediset modified binder, SMB-Sasobit modified binder, ZMB-Zycotherm modified binder

3.4 TESTS CONDUCTED

3.4.1 Mix design method

The asphalt mixture design is done as per Superpave mix design (SP-2) using SGC (Fig 3.2) with short term oven ageing (STOA) for two hours at their respective compaction temperature. The Superpave specimens of diameter 150 mm (NMAS26.5) and 100 mm (NMAS19) were prepared using the SGC. The diameter of specimen was adopted based on NMAS requirements as recommend in Superpave series No. 2 (SP-02) (The Asphalt Institute, 2001).

Table 3.5. Aggregate Composition of asphalt structural layers (MoRTH, 2013)

Designation	DBM grading-2(NMAS26.5)		BC grading-1(NMAS19)	
NMAS (mm)	26.5		19	
Layer thickness(mm)	50 – 75		50	
IS sieve (mm)	Cumulative % by weight of total aggregate passing			
	Specified Limits	Adopted	Specified Limits	Adopted
37.5	100	100	--	--
26.5	90-100	95	100	100
19.0	71-95	83	79-100	90
13.2	56-80	68	59-79	69
9.5	--	--	52-72	62
4.75	38-54	46	35-55	45
2.36	28-42	35	28-44	36
1.18	--	--	20-34	27
0.6	--	--	15-27	21
0.3	7-21	14	10-20	15
0.15	--	--	5-13	9
0.075	2-8	5	2-8	5
Binder content (%)	Min 4.5 w/m		Min 5.2 w/m	

Note: w/m-weight by total mix

The compaction efforts criteria for the present study were adopted based on SUPERPAVE (Superior Performing Pavements) HMA mix design method for varying traffic levels with N_{des} of 75 (medium traffic level) , 100 (medium to high traffic level), and 125 (high traffic level) gyrations. Design asphalt content of each mixture was arrived based on the requirements of Voids in Total Mixtures (VTM), Voids in Mineral Aggregate (VMA), and Voids Filled with Asphalt (VFA) (MoRTH, 2013).

3.4.2 Rutting test

Rutting resistance of asphalt mixtures was evaluated using WRT as shown in Fig. 3.3(a). Asphalt mixtures were evaluated in dry condition at a testing temperature of 60 °C. Wheel load was 750N and contact pressure was 700 kPa, the test was run at a rate of 42 passes per minute. Asphalt slabs are compacted to required air voids and density in a size of 300mm×300mm×50mm using the wheel rut shaper (WRS) (Fig.3.3b). The number of loading cycles to 6mm rut depth was recorded. From the measured rut depth, dynamic stability (mm/minute), the number of load repetitions to generate 1-mm rutting during the last 15-min of one-hour testing, was calculated by the following formula:

$$\text{Dynamic Stability} = \frac{N_{15}}{d_{60} - d_{45}} \tag{3.1}$$

Where, N_{15} = loading cycles in 15 minutes, cycles; d_{60} = rut depth at the 60 minutes, mm; and d_{45} = rut depth at 45 minutes, mm.

Fig.3.2. Superpave gyratory compactor

3.4.3 Repeated load test

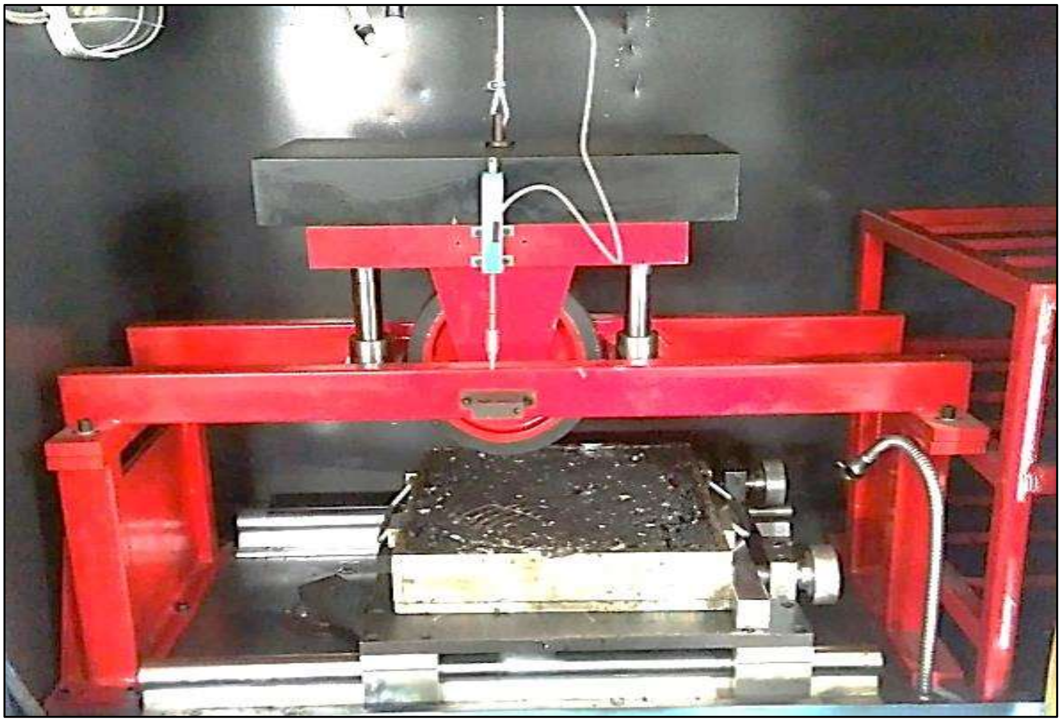
Flexural fatigue properties of asphalt mixtures were evaluated using the repeated load test (RLT) (Fig. 3.4a). The controlled stress mode test was conducted at a frequency of 5Hz and rest period of 0.1 seconds at a testing temperature of 23±2 °C. Fatigue beam specimens were compacted to required air voids and density to a size of 380mm×77mm×75mm. Beams were prepared by applying 30 kN load using compression testing machine through rectangular compaction plunger of dimension 400mm×75mm. The beam was tested under four point loading, as shown in Fig. 3.4(b) so that the failure is localized in the central portion of the beam where the shear is zero. The failure load of the mixtures was measured by applying a static load using RLT. The number of fatigue cycles to failure (initial 5mm cracking) by applying 10% of failure load of the mixtures was measured. Flexural strength of the asphalt mixtures was calculated by the following formula:

$$\text{Flexural strength} = \frac{\rho l}{bd^2} \qquad \textbf{(3.2)}$$

Where, ρ = failure load (kN); *l* = length of the fatigue beam (mm); b = breadth of the fatigue beam (mm); and d = depth of the fatigue beam (mm).

3.4.4 Moisture-induced damage test

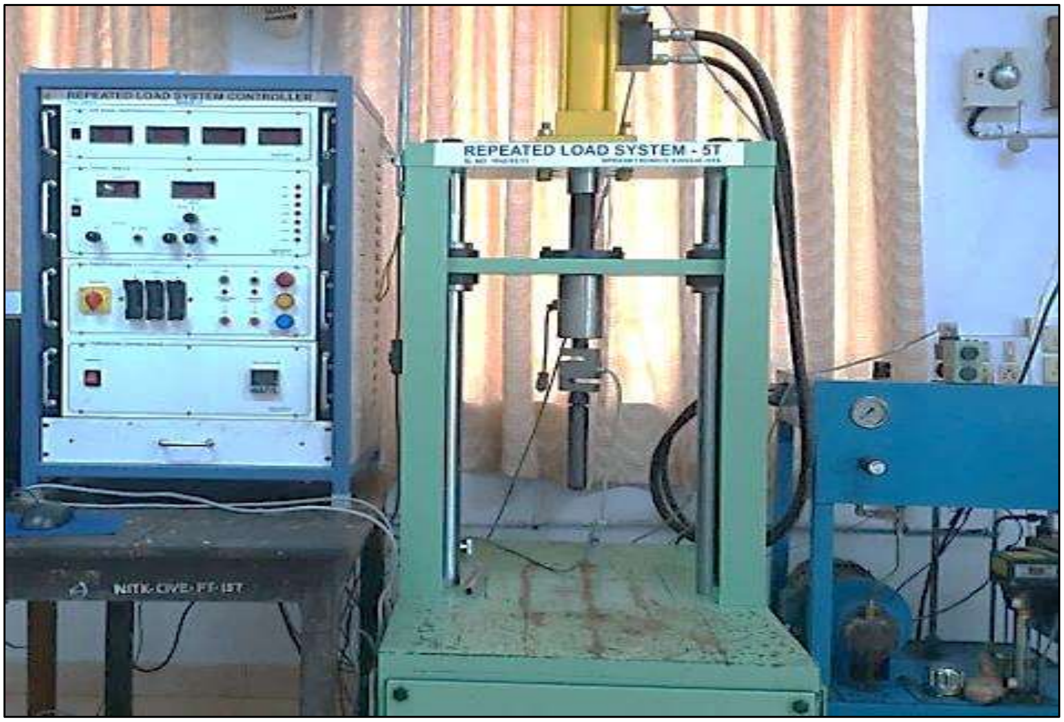
The moisture- induced damage in asphalt mixtures is determined as a loss of strength due to moisture in terms of TSR. TSR is defined as a ratio of ITS value of a conditioned specimen to that of an unconditioned specimen. Fig. 3.5 represents the indirect tensile strength test setup used to evaluate the ITS values of conditioned and unconditioned specimens. This method covers preparation of compacted asphalt mixtures and the measurement of the change of diametral tensile strength resulting from the effects of water saturation and laboratory accelerated stripping phenomenon with a freeze-thaw cycle.



(a)

(b)

Fig. 3.3. (a) Wheel rut tester and (b) Wheel rut shaper



(a)

(b)

Fig. 3.4. (a) Repeated load testing machine and (b) Fatigue beam setup

Fig. 3.5. Indirect tensile strength test setup

3.5 EXPERIMENTAL DESIGN

The experimental design includes evaluation of mix design, workability, and mechanical properties of dense asphalt mixtures for varying working temperatures and NMAS as presented in Table 3.7. To accomplish the objective of the present study, two NMAS, four types of mix, and three working temperatures were selected as shown in Fig. 3.6. Dense asphalt mixtures (NMAS19 and NMAS26.5) modified by non-foaming WMA additives Rediset LQ (W-R), Sasobit (W-S), and Zycotherm (W-Z) and the control asphalt mixtures (CM), which are prepared without any additive were four type of mixtures studied. Three working (mixing/compaction) temperatures adopted were 150-165 °C/130 °C (MoRTH, 2013), 120-135 °C/90 °C (IRC SP-11, 2014), and 110-120 °C/70 °C (adopted for the study). These working temperatures were selected to provide wider gap between mixing and compaction temperatures that can ensure WMA mixtures for longer hauling time and were not based on the viscosity of binders.

Asphalt mix design was done by the Superpave method of mix design using the SGC. The Superpave specimens of diameter 150 mm (NMAS26.5) and 100 mm (NMAS19) were prepared using the SGC. The diameter of specimen was adopted based on NMAS requirements as recommend in Superpave series No. 2 (SP-02) (The Asphalt Institute, 2001). The compaction efforts criteria for the present study were adopted based on SUPERPAVE (Superior Performing Pavements) HMA mix design method for varying traffic levels with N_{des} of 75 (medium traffic level) , 100 (medium to high traffic level) and 125 (high traffic level) gyrations. Mix design properties of four types of mix (CM, W-R, W-S and W-Z) were evaluated at (N_{des}) of 75, 100 and 125 gyrations using three binder contents (5.5, 6.0, and 6.5) % for NMAS19 and (4.5, 5.0, and 5.5) % for NMAS26 at three working temperatures. Design asphalt content of each mixture was arrived based on the requirements of MoRTH specifications (MoRTH, 2013).

In order to evaluate the workability and mechanical properties of control and WMA mixtures, design asphalt content was selected based on Table 4.2. Workability properties in terms of SGC densification indices using Bahia and Locking point method were evaluated. In order to evaluate workability properties, the Superpave specimens of diameter 150 mm (NMAS26.5) and 100 mm (NMAS19) were prepared using the SGC by subjecting loose mixtures to 225 gyrations (Bahia et al. 1998; Mohammad and Al-Shamsi 2007). Gyrations at aggregate locking point and 92% G_{mm} along with CDI and TDI were calculated by adopting Bahia and Locking point method.

Mechanical properties such as resistance to moisture-induced damage of asphalt mixtures were evaluated according to AASHTO T-283 (Modified Lottman test), rutting resistance by laboratory wheel tracking test using WRT, and flexural fatigue resistance by fourth point bending using Repeated Load Testing machine. In present study two aggregate conditions, oven dry and surface saturated dry aggregates were evaluated for moisture-induced damage properties of the asphalt mixtures (ASTM C125-15). Prior to preparation of asphalt mixtures both aggregates were subjected to oven drying for one hour corresponding to their mixing temperature. Furthermore all mixtures were prepared at their design asphalt content and were subjected to Short Term Oven Aging (STOA) for two hours corresponding to their compaction temperature (Bonaquist et al. 2011; Martin et al. 2014). Subsequently the mixtures were compacted into cylindrical specimens using the SGC with a VTM of 7.0±0.1%. The ITS test was performed on these specimens to determine the resistance to moisture-induced damage of asphalt mixtures. Three specimens were tested under controlled normal condition and three were tested after conditioning. The conditioning consisted of 70–80% saturation of the specimens followed by a freeze–thaw cycling at (-18 °C) for 16 hours. Subsequently, a warm-water soaking cycle at 60 °C was applied for 24 hours. The specimens were then tested at 25 °C and ratios of ITS values of the conditioned specimens to those of unconditioned specimens were determined as TSR.

Wheel Rut Shaper (WRS), an asphalt mixture compaction device, was used to fabricate the asphalt slab specimen for the rutting resistance test. Slab specimens of dimension 300mm×300mm×50mm were fabricated with a VTM of 7.0±0.1% at their respective design asphalt contents. Prior to slab compaction, all the asphalt mixtures were subjected to STOA for two hours corresponding to their compaction temperature to simulate binder aging and absorption during asphalt pavement construction (Bonaquist et al. 2011; Martin et al. 2014). These were then placed in an environmental chamber for 6 hours at 60 °C before testing (Kandhal and Alen, 2003). WRT is a small size wheel tracking test device was used to evaluate the rutting resistance of the asphalt mixtures according to EN 12697-22 in dry condition at a testing temperature of 60 °C. Wheel load was 750N, contact pressure was 700 kPa, and at a rate of 42 passes per minute. The number of rut passes to 6 mm rut depth (failure criteria as per NCHRP 508, 2003) and dynamic stability was noted (Kandhal and Alen, 2003).

Table 3.6. Mixing and compaction temperatures adopted in the study

Mixing temperature (°C)	Compaction temperature (°C)
150-165	130
120-135	90
100-110	70

Table 3.7. Experimental design of mix design, workability and mechanical properties

Response properties		Source of variance					
		NMAS	N_{des}	Type of mixture	Working temperature	Binder content	Number of specimens
Mix design properties		2	3	4	3	3	3X72=648
Workability properties	Bahia method	2	1	4	3	1	3X24=72
	Locking point	2	1	4	3	1	3X24=72
Moisture-induced damage properties	Oven dry aggregates	2	1	4	3	1	6X24=144
	Surface saturated dry aggregates	2	1	4	3	1	6X24=144
Rutting properties		2	1	4	3	1	3X24=72
Fatigue properties		2	1	4	3	1	3X24=72

Note: NMAS (NMAS19 and NMAS26.5); N_{des} (75,100,125); Type of mixture (CM,W-R,W-S,W-Z); Binder content [NMAS19 (5.5,6.0,6.5)% and NMAS26.5 (4.5,5.0,5.5)%]; AC_{des}-Design asphalt content

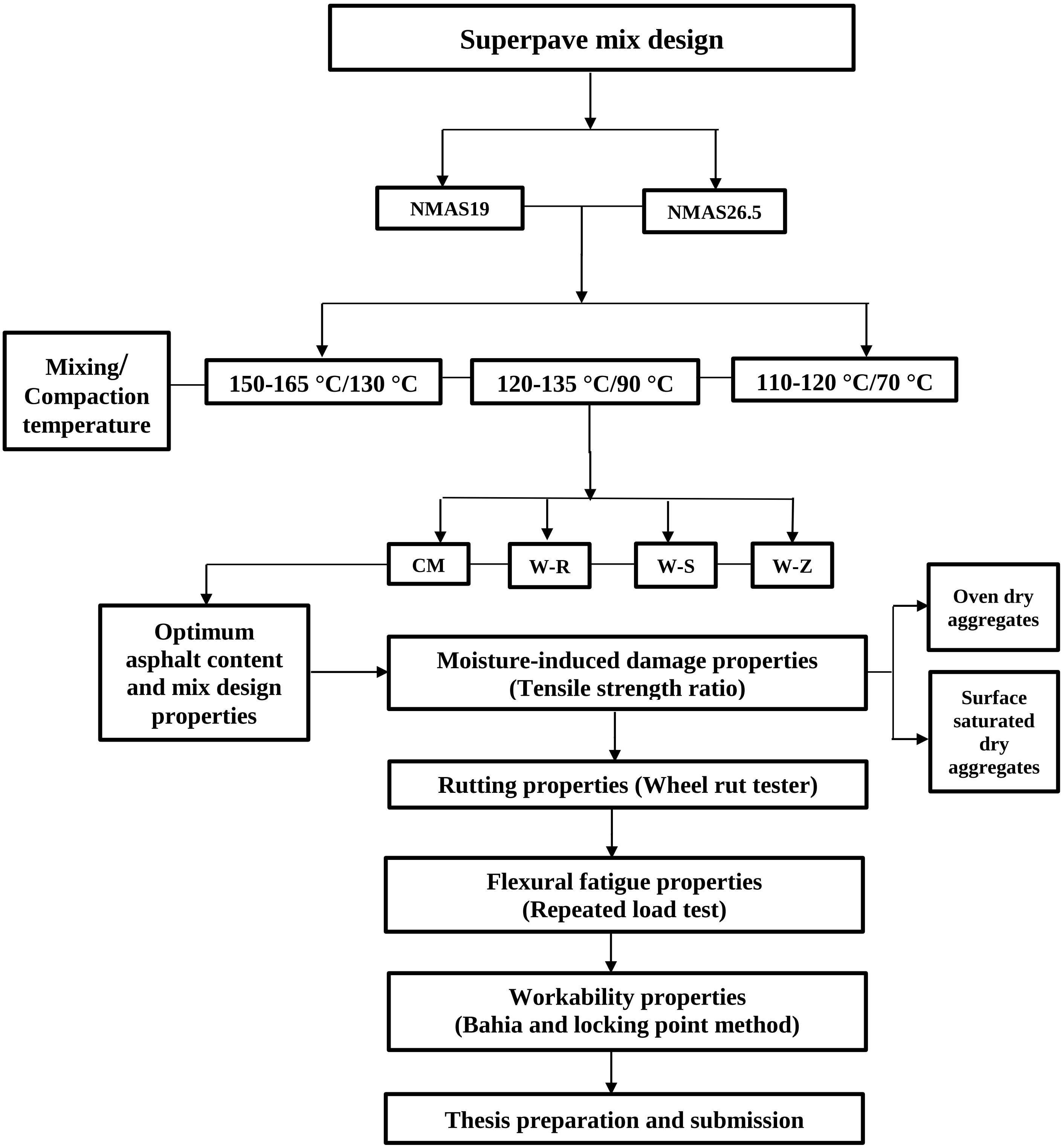


Fig. 3.6. Experimental design

Flexural fatigue beam specimens of dimension 400mm×75mm×75mm were compacted by applying 30 kN load using a compression testing machine with a VTM of 4.0±0.1% at their respective design asphalt contents. Prior to compaction, all asphalt mixtures were subjected to STOA for two hours to simulate binder aging and absorption during asphalt pavement construction (Bonaquist et al. 2011; Martin et al. 2014). Flexural fatigue characteristics of the mixtures were evaluated by using RLT at a testing temperature of 23±2 °C. The controlled stress mode test was conducted at a frequency of 5Hz and a loading period of 0.1 second. The beam was tested under four point bending, so that the failure is localized in the central portion of the beam where the bending moment is constant. The failure load of the mixtures was measured by applying static load using RLT and flexural strength was calculated. The number of fatigue cycles to the failure of the asphalt mixtures was measured by applying 10% of failure load upto initial 5mm cracking measured using a linear variable displacement transducer (LVDT).

3.6 STATISTICAL ANALYSIS

In order to determine the level of significance of main effects of each treatment factor, the experimented results are subjected to the analysis of variance test (Montgomery 2004). In this study, the test results were statistically analyzed using one-way analysis of variance (ANOVA) test with a significance level (α= 0.05). The ANOVA was conducted using MINITAB (Release 17, trial version) to examine the significance of NMAS, N_{des}, binder content, working temperature and type of mixture on the mix design parameters, and NMAS, working temperature and type of mixture on mixture workability and mechanical properties.

4.0 RESULTS AND DISCUSSIONS

4.1 GENERAL

This chapter provides results and discussions of mix design, workability, rutting, flexural fatigue and moisture-induced damage properties of asphalt mixtures with and without WMA additives for varying working temperatures and NMAS.

4.2 SUPERPAVE MIX DESIGN PROPERTIES

Superpave mix design properties, such as, bulk specific gravity of compacted mixtures (G_{mb}), VTM, VMA and VFA of asphalt mixtures were evaluated at different gyrations of 75, 100, and 125. In addition, three binder contents (5.5-6.5) % and (4.5-5.5) % for NMAS19 and NMAS26.5 mixtures, respectively, four type of mixes (CM, W-R, W-S, and W-Z) and three mixing and compaction (working) temperatures (150-165 °C/130 °C, 120-135 °C/90 °C, and 110-120 °C/70 °C were used. The compactions efforts criteria in the mix design of HMA in addition to the design number of gyrations (N_{des}) recommended in Superpave mix design method and adopted in this study are presented in Table 4.1.

Reduction in working temperature resulted in increase of VTM and VMA, and decrease in VFA values of asphalt mixtures. Higher N_{des} resulted in lower VTM and VMA, and higher VFA values of asphalt mixtures. Similar findings were noticed in the studies conducted by Kanitpong et al. (2007), Akisetty et al. (2009), Lee et al. (2012), Toraldo et al. (2013), Jamshidi et al. (2013) on WMA mixtures compacted upto 110 °C.

According to the specifications of MoRTH (2013), to design VTM requirement for dense asphalt mixtures is 4±1%. Fig. 4.1 and 4.2 depict the variation in VTM values with binder content, type of mixture, working temperature, and N_{des} of NMAS19 and NMAS26.5 mixtures, respectively. Control mixtures compacted at 130 °C and 90 °C achieved the required VTM at N_{75} and N_{100}, respectively, while WMA mixtures compacted at 130 °C and 90 °C achieved the required VTM at N_{75}. WMA mixtures compacted at 70 °C achieved required VTM at N_{100}, while control mixtures achieved at N_{125}.

The minimum VMA requirement corresponding to NMAS19 and NMAS26.5 mixtures is 13% and 12%, respectively and VFA requirement should be in the range of 65% to 75% (MoRTH, 2013). Fig. 4.3 and 4.4 depict the variation in VMA values with binder content, type of mixture, working temperature, and N_{des} of NMAS19 and NMAS26.5 mixtures, respectively. WMA and control mixtures corresponding to both NMAS fulfilled the minimum VMA requirement for all working temperature, binder content and N_{des}. Figs. 4.5 and 4.6 depict the variation in VFA values with binder content, type of mixture, working temperature, and N_{des} of NMAS19 and NMAS26.5 mixtures, respectively. WMA mixtures compacted at 90 °C and 70 °C fulfilled the VFA requirement at N_{75}, N_{100} and N_{125} but it was not true for control mixtures.

Table 4.1. Superpave gyratory compaction efforts (ASTM D 6925, 2006)

Design traffic	Compaction parameters		
(ESAL x 10^6)	$N_{initial}$	N_{design}	$N_{maximum}$
< 0.3	6	50	75
0.3 to < 3	7	75	115
3 to < 30	8	100	160
> 30	9	125	205

$N_{initial}$ - Number of initial gyrations: This parameter indicates a tender mix during field compaction, caused by either an inappropriate gradation or excessive asphalt content. It is undesirable for the mix to achieve a high degree of compaction at a low number of gyrations.

N_{design} - Design number of gyrations: It is required to produce a density in the mix that is equivalent to the expected density in the field after the indicated amount of traffic.

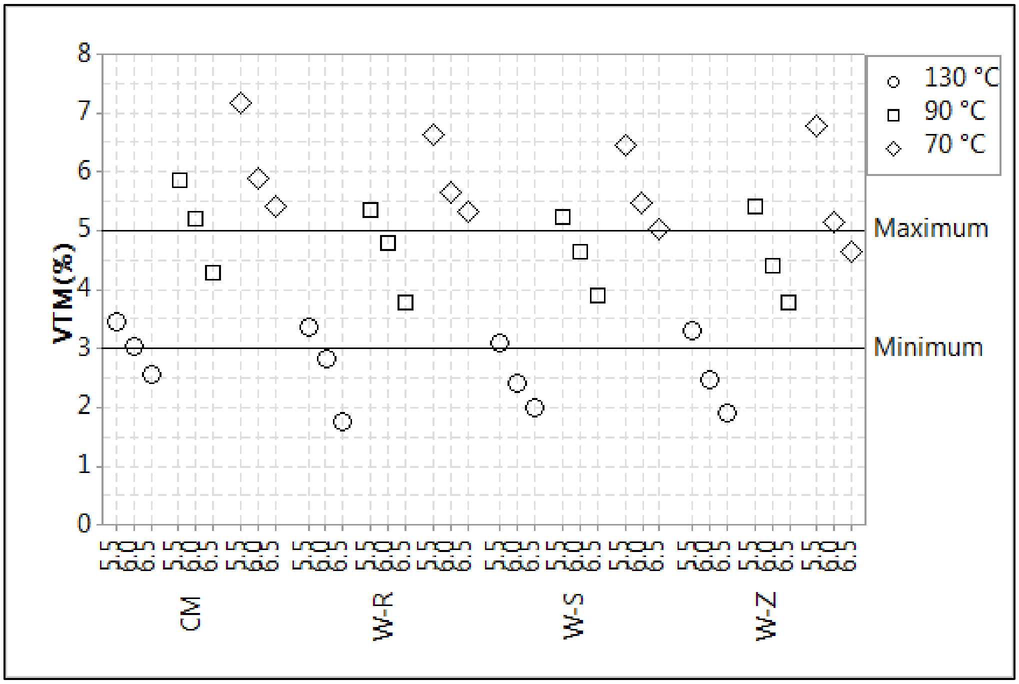
$N_{maximum}$ - Final number of gyrations: It is the number of gyrations required to produce a density in the laboratory that should absolutely never be exceeded in the field. It is undesirable for the mix to obtain less than 2% air voids at this point as this would indicate long-term instability under traffic.

Results also indicated that reduction in working temperature led to problems in densification of the mix, resulting in lower G_{mb}. Figs. 4.7 and 4.8 depict the variation in G_{mb} values due to binder content, type of mixture, working temperature, and N_{des} of NMAS19 and NMAS26.5 mixtures respectively. Further, it is seen that, there is no significant difference between the G_{mb} values among the mixtures with different binder contents while higher G_{mb} values were obtained at higher N_{des}.

For selected working temperature and NMAS, VFA and VMA values of the W-S mixtures were found to be higher than those of CM, W-R, and W-Z mixtures. Subsequently, G_{mb} values of W-R mixtures were found to be higher than those of CM, W-S and W-Z mixtures. These results are consistent with findings of previous studies (Lee and Kim, 2009; Zhaoxing et al. 2014 and Hamzah et al. 2015).

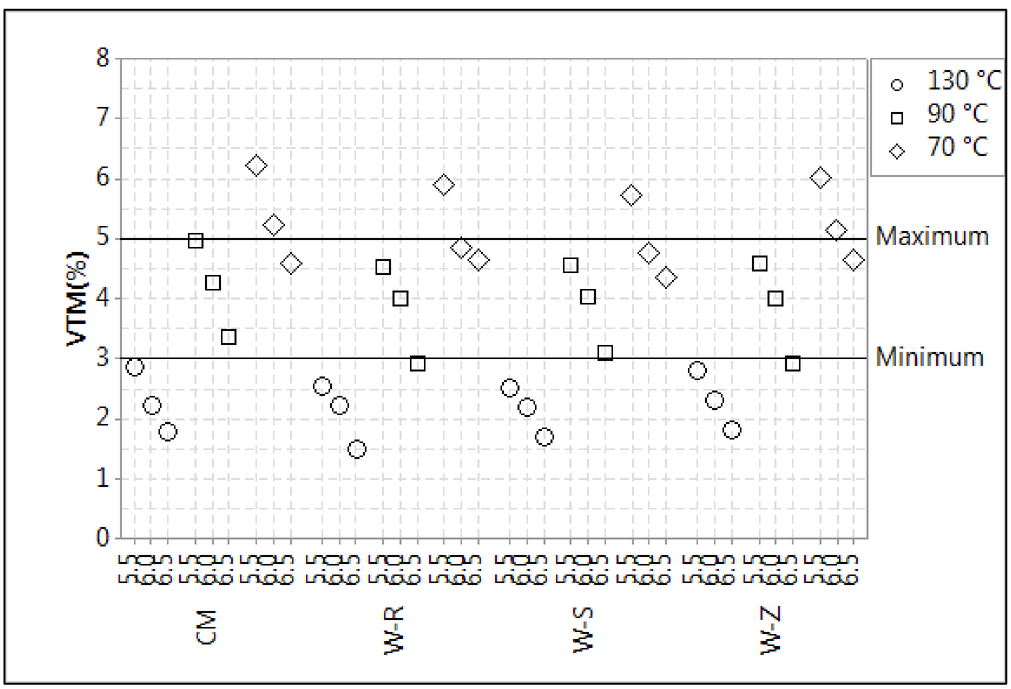
Design asphalt contents of NMAS19 and NMAS26.5 mixtures were arrived at based on the requirements of MoRTH (2013) in Table 5.2. From Table 5.2, it is clearly evident that asphalt mixtures compacted at 130 °C are suitable for traffic levels 0.3 to <3 million ESALs, while asphalt mixtures compacted at 90 °C and 70 °C were suitable for higher traffic levels of 3 to <30 and ≥30 million ESALs, respectively. However, design asphalt content of WMA mixtures were lower than the control mixtures but there is no much variation in mix design properties and were well within the requirements (MoRTH, 2013).

The effect of N_{des}, working temperature, type of mixture and binder content on mix design properties of control and WMA mixtures were statistically analyzed using one way ANOVA test as presented in Table 4.3. It can be noticed that N_{des}, working temperature, type of mixture and binder content had significant effects on mix design properties. Working temperature had the most significant effect on mix design properties, as it had the highest F value followed by N_{des} and type of mixture. Furthermore, binder content was not found significant for G_{mb} values.



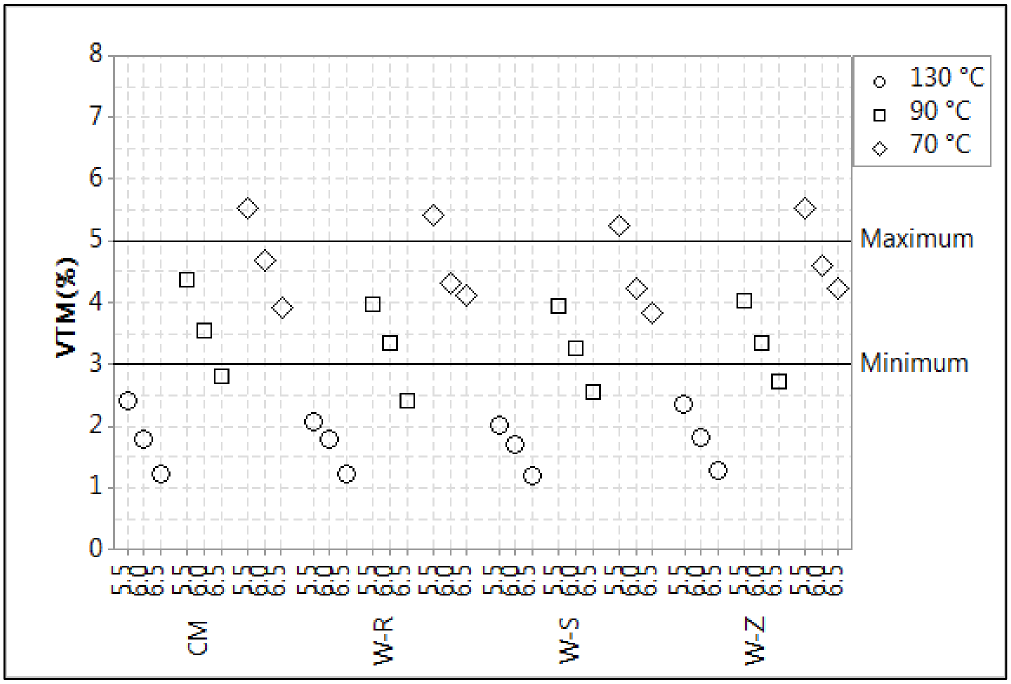
VTM(%)
130 °C
90 °C
70 °C
Maximum
Minimum
CM
W-R
W-S
W-Z

(a)



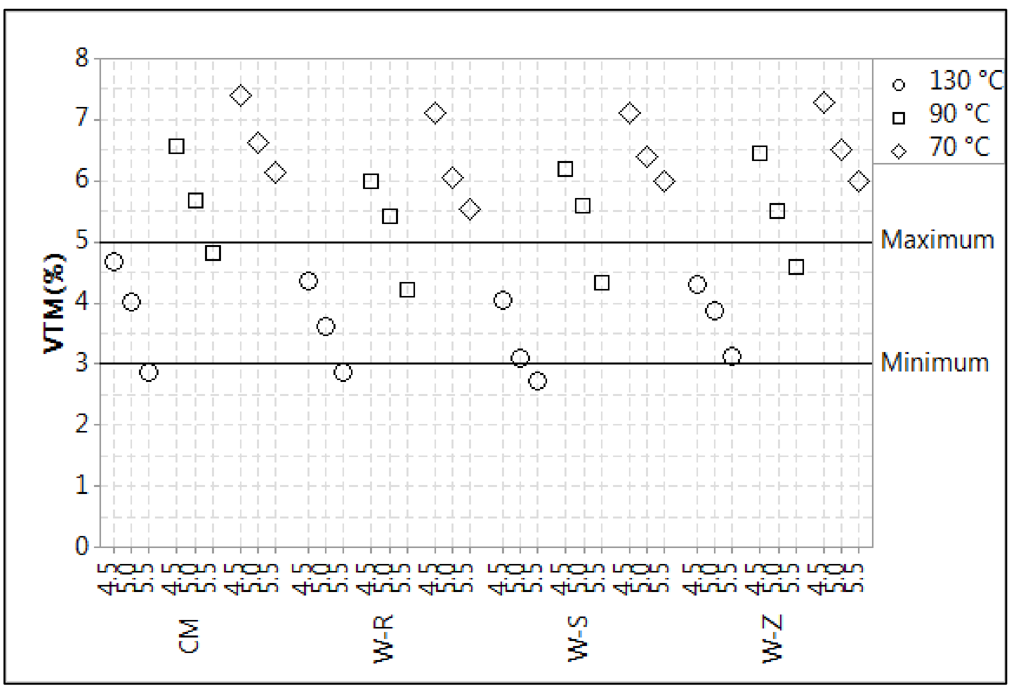
VTM(%)
130 °C
90 °C
70 °C
Maximum
Minimum
CM
W-R
W-S
W-Z

(b)

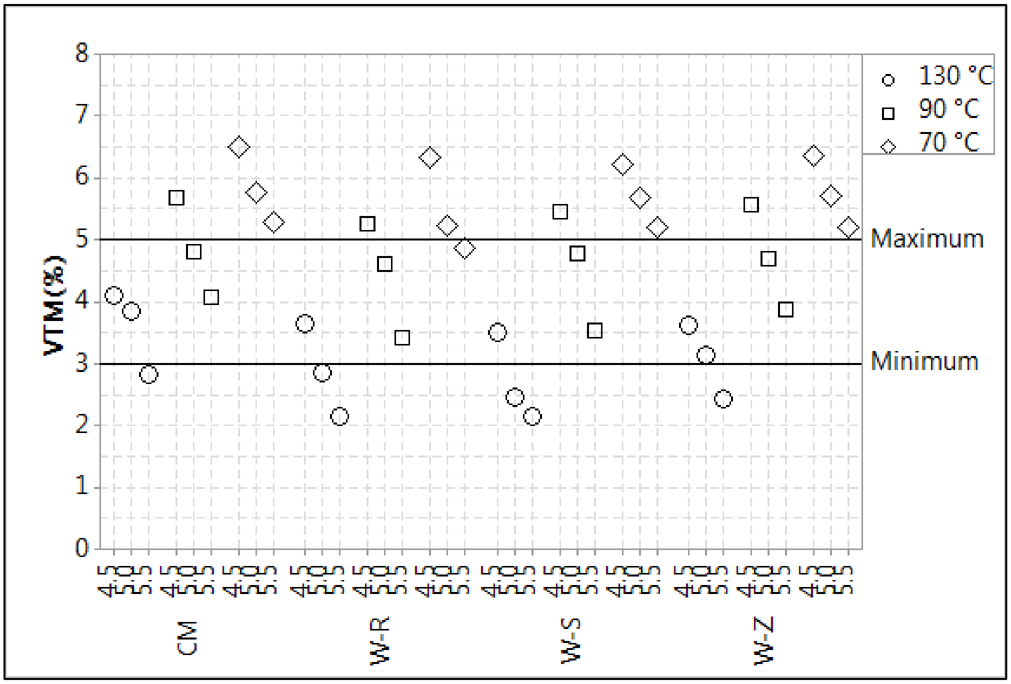


(c)

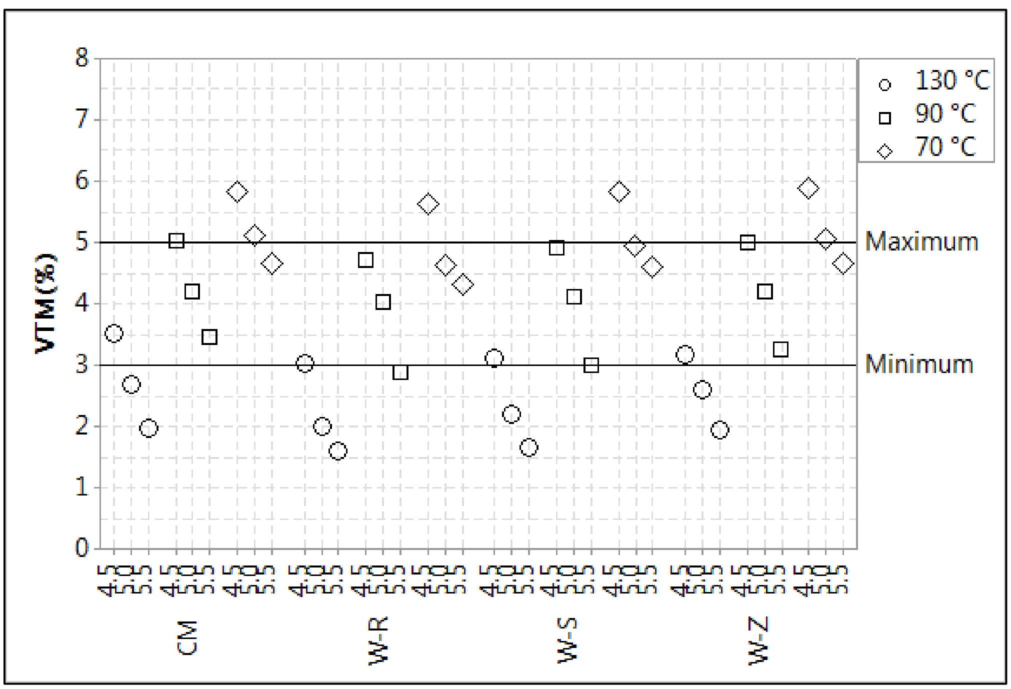
Fig. 4.1. Variation in VTM due to binder content, type of mixture, and working temperature of NMAS19 mixtures (a) 75 gyration (b) 100 gyration and (c) 125 gyration



(a)

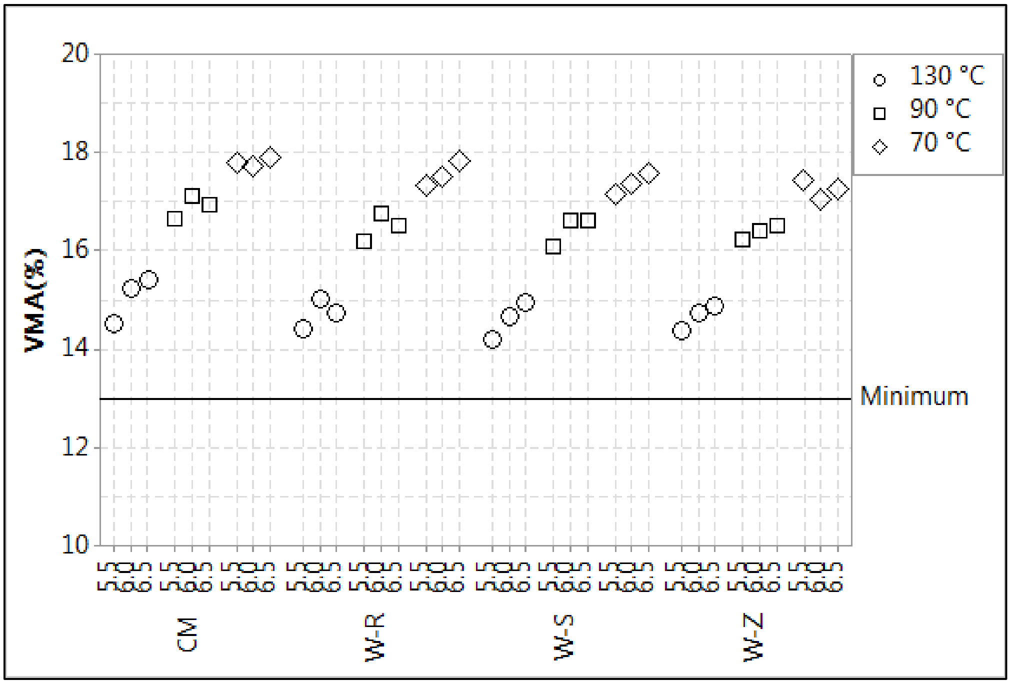


(b)



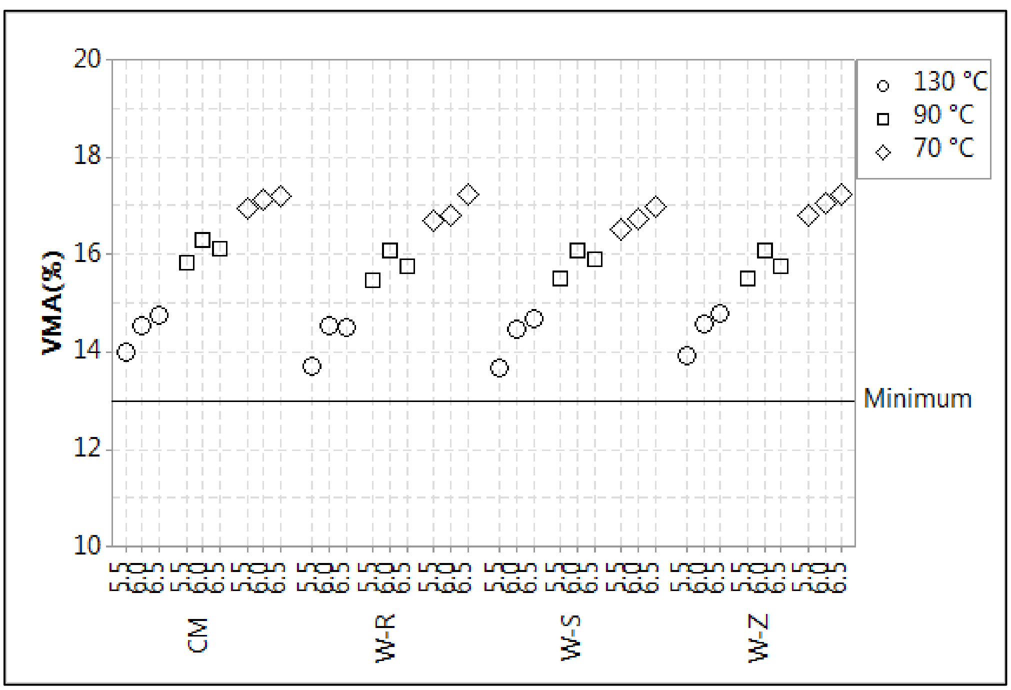
(c)

Fig. 4.2. Variation in VTM due to binder content, type of mixture, and working temperature of NMAS26.5 mixtures (a) 75 gyration (b) 100 gyration and (c) 125 gyration



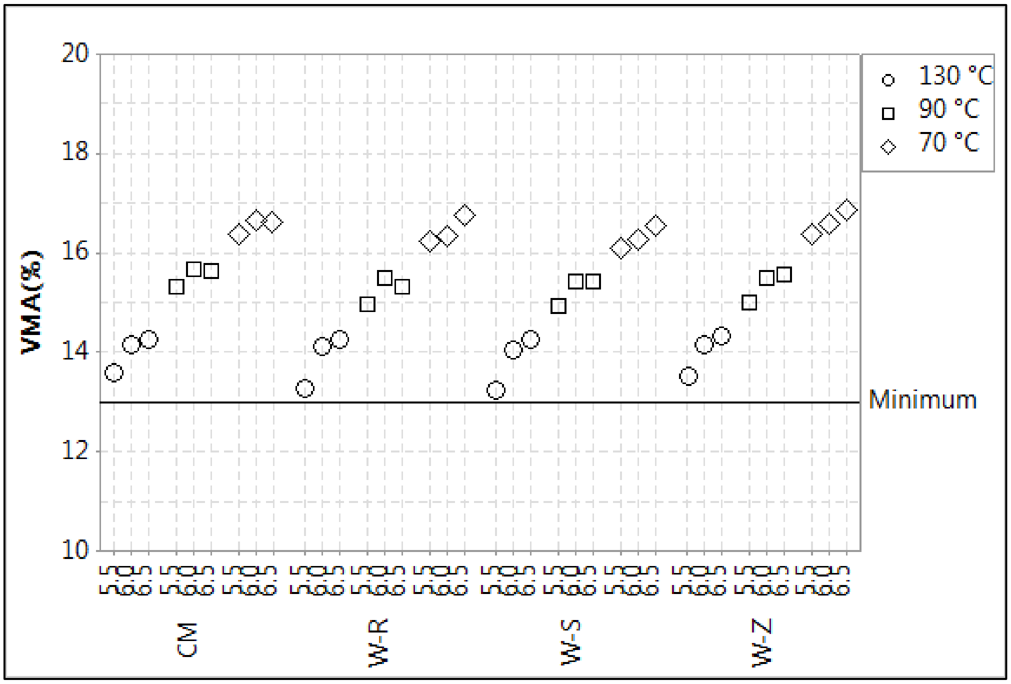
VMA(%)
20
18
16
14
12
10
130 °C
90 °C
70 °C
Minimum
CM
W-R
W-S
W-Z

(a)



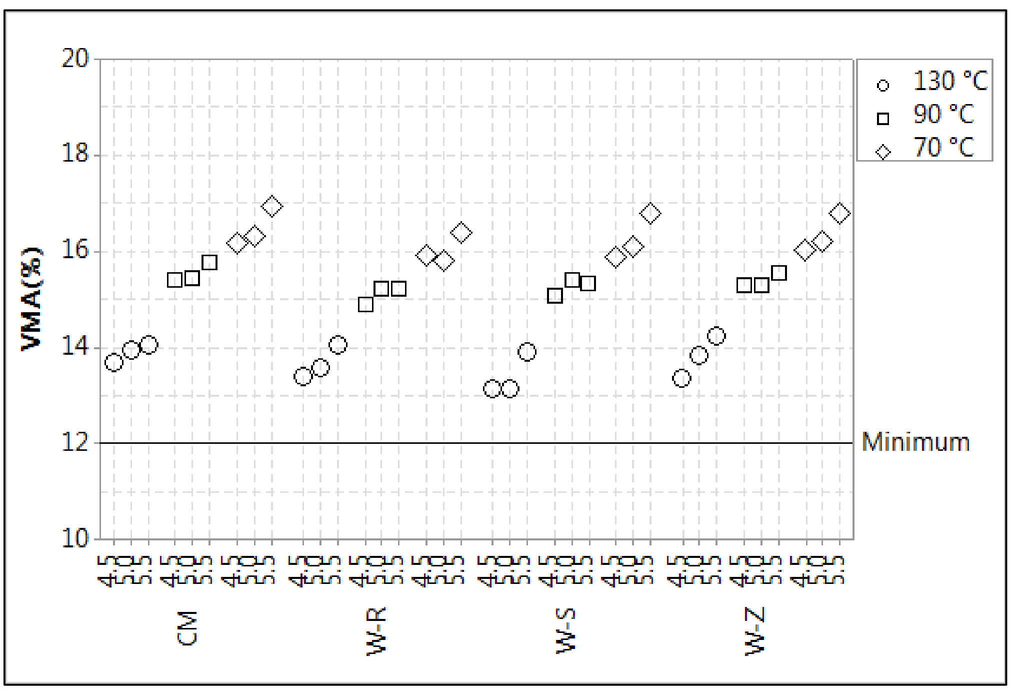
VMA(%)
20
18
16
14
12
10
130 °C
90 °C
70 °C
Minimum
CM
W-R
W-S
W-Z

(b)

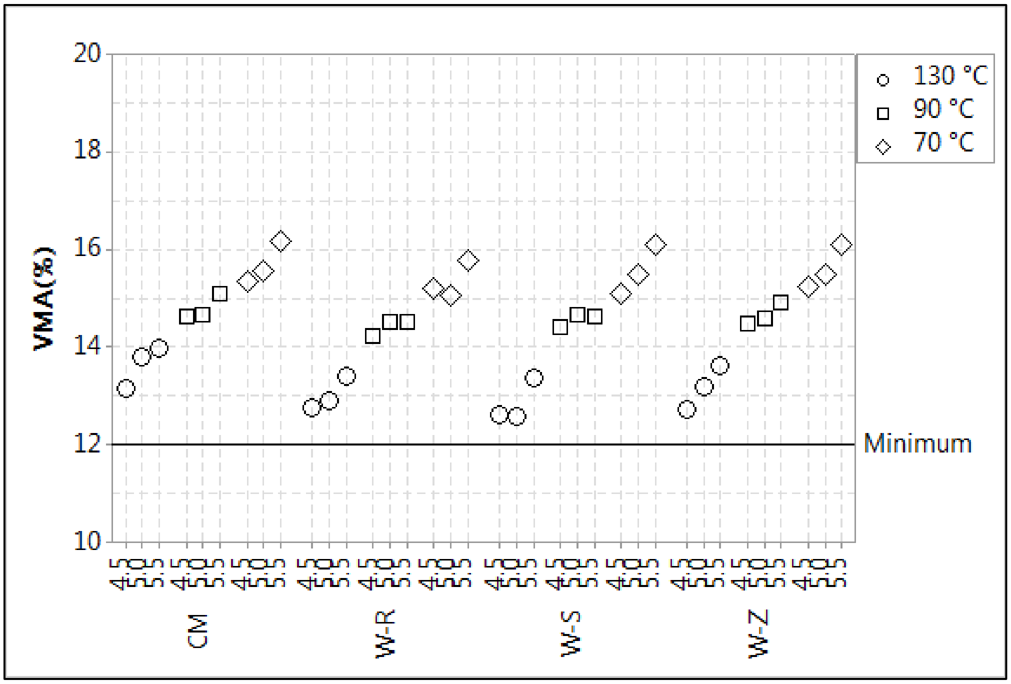


(c)

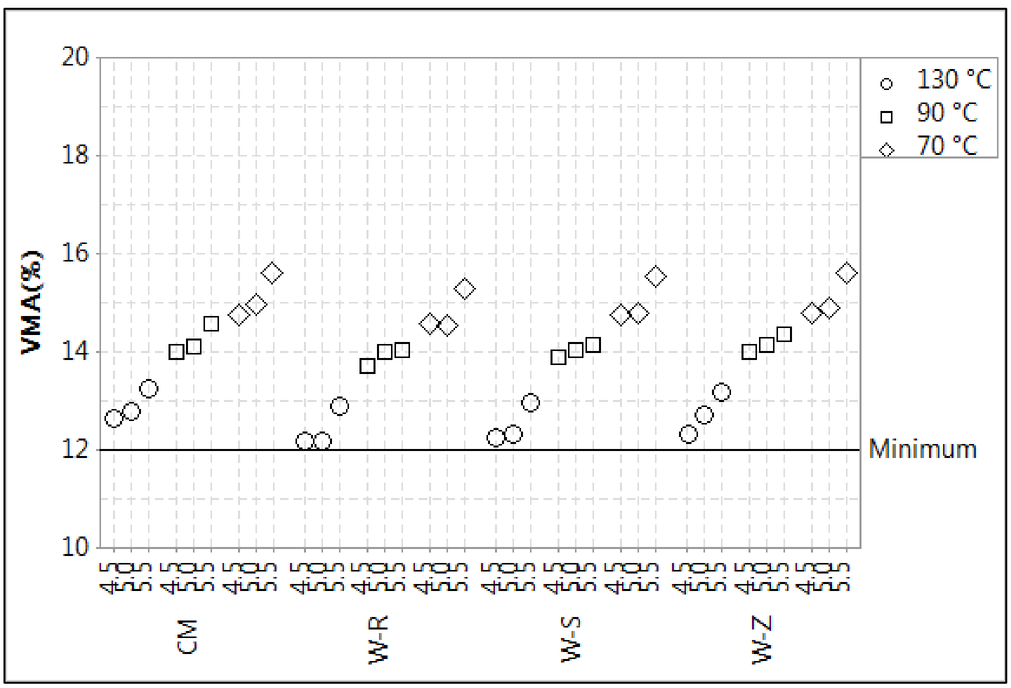
Fig. 4.3. Variation in VMA due to binder content, type of mixture, and working temperature of NMAS19 mixtures (a) 75 gyration (b) 100 gyration and (c) 125 gyration



(a)

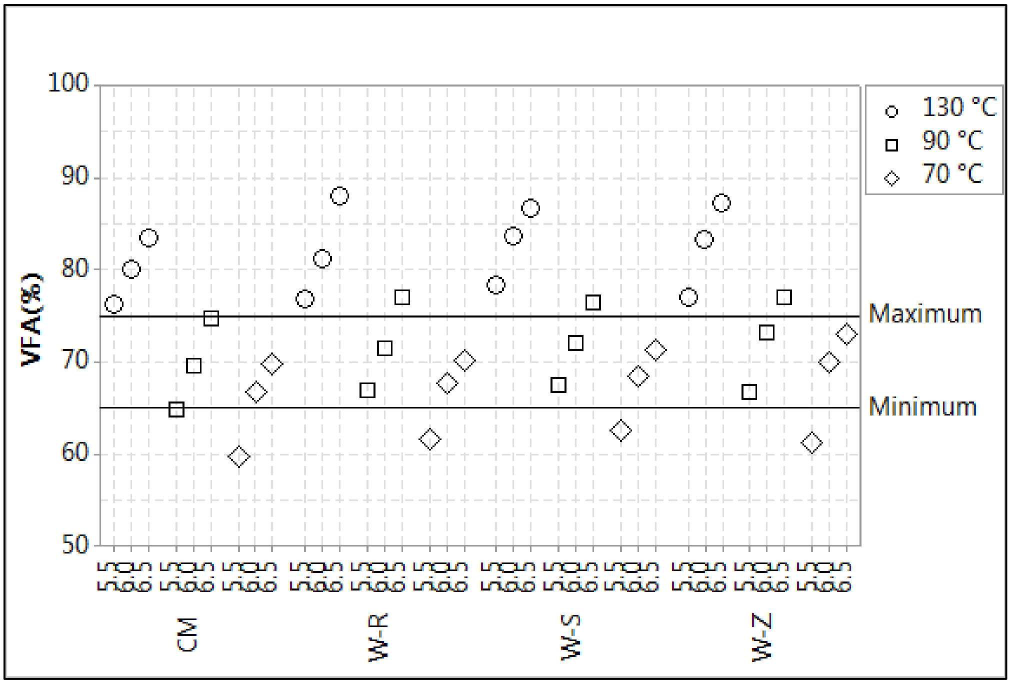


(b)



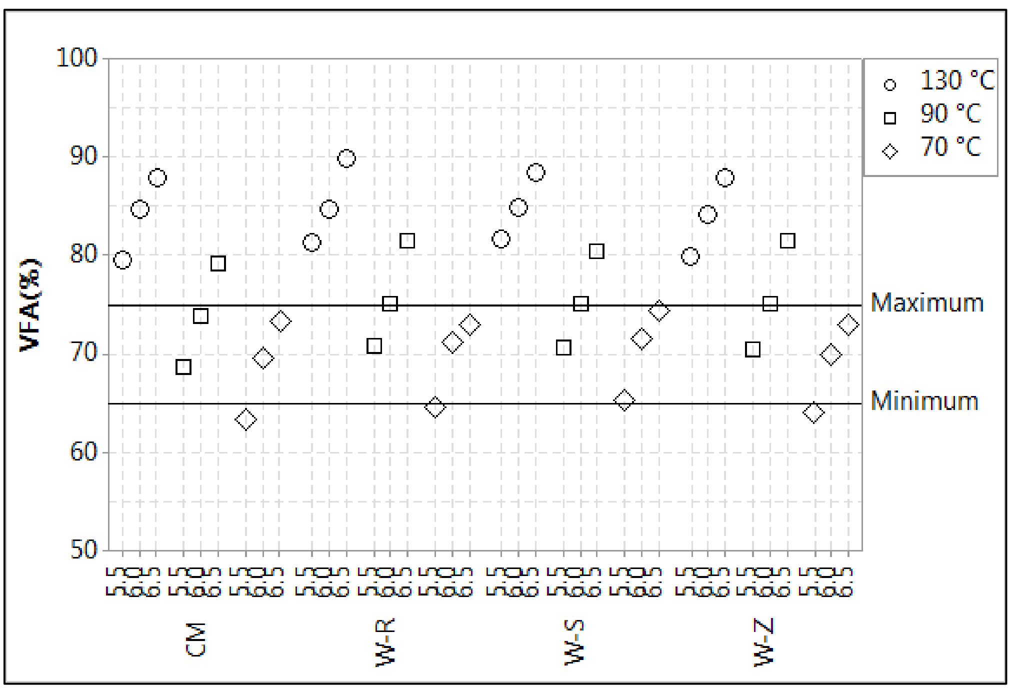
(c)

Fig. 4.4. Variation in VMA due to binder content, type of mixture, and working temperature of NMAS26.5 mixtures (a) 75 gyration (b) 100 gyration and (c) 125 gyration



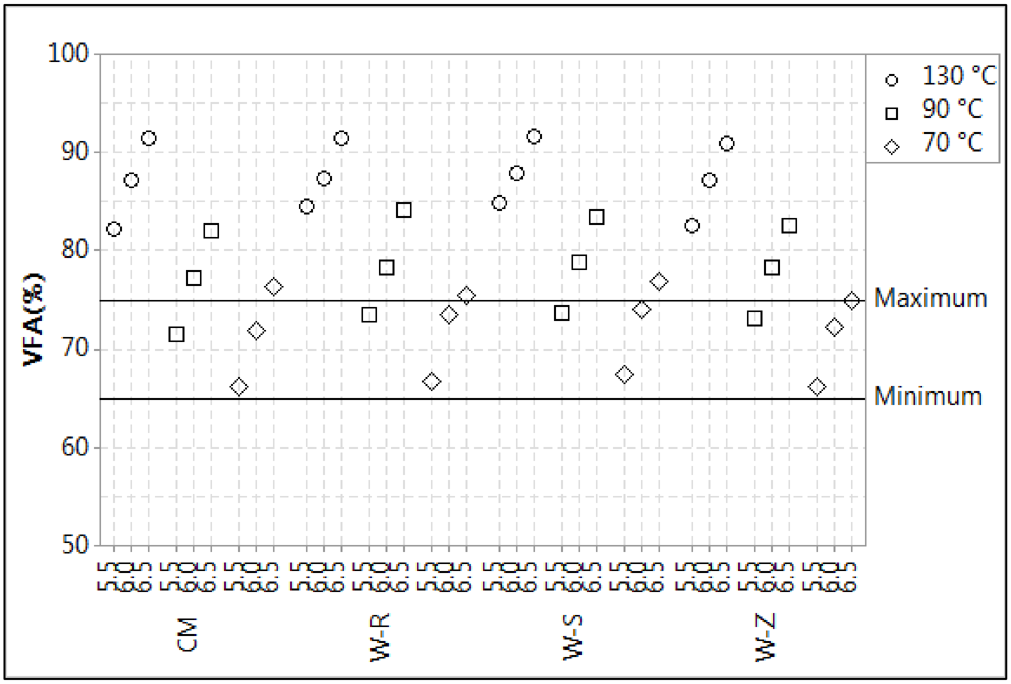
100
90
80
70
60
50
VFA(%)
130 °C
90 °C
70 °C
Maximum
Minimum
CM
W-R
W-S
W-Z

(a)



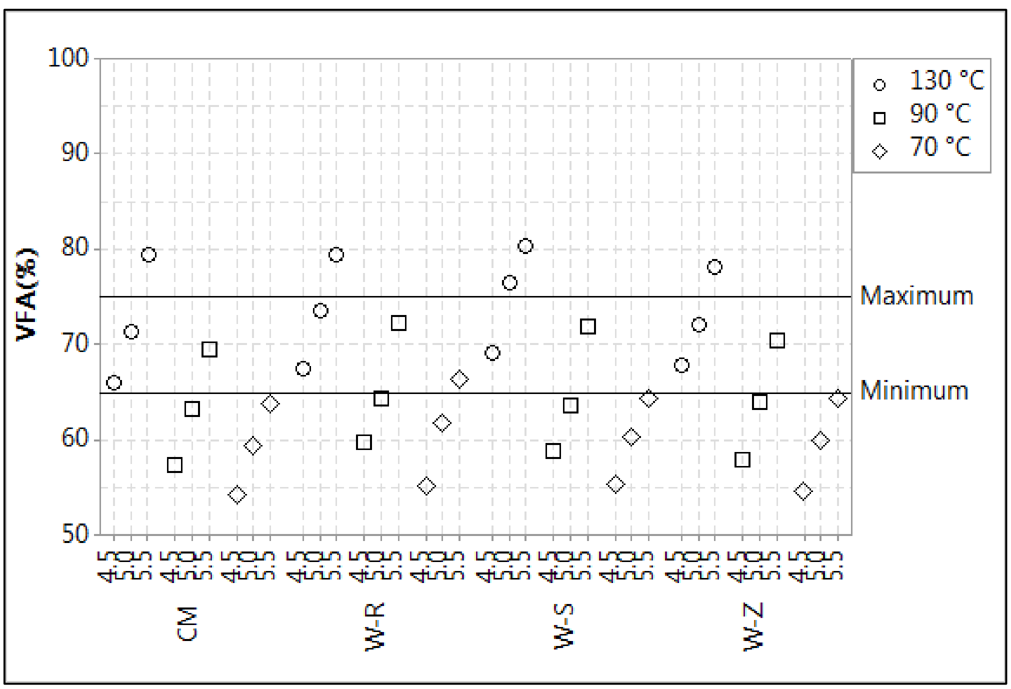
100
90
80
70
60
50
VFA(%)
130 °C
90 °C
70 °C
Maximum
Minimum
CM
W-R
W-S
W-Z

(b)

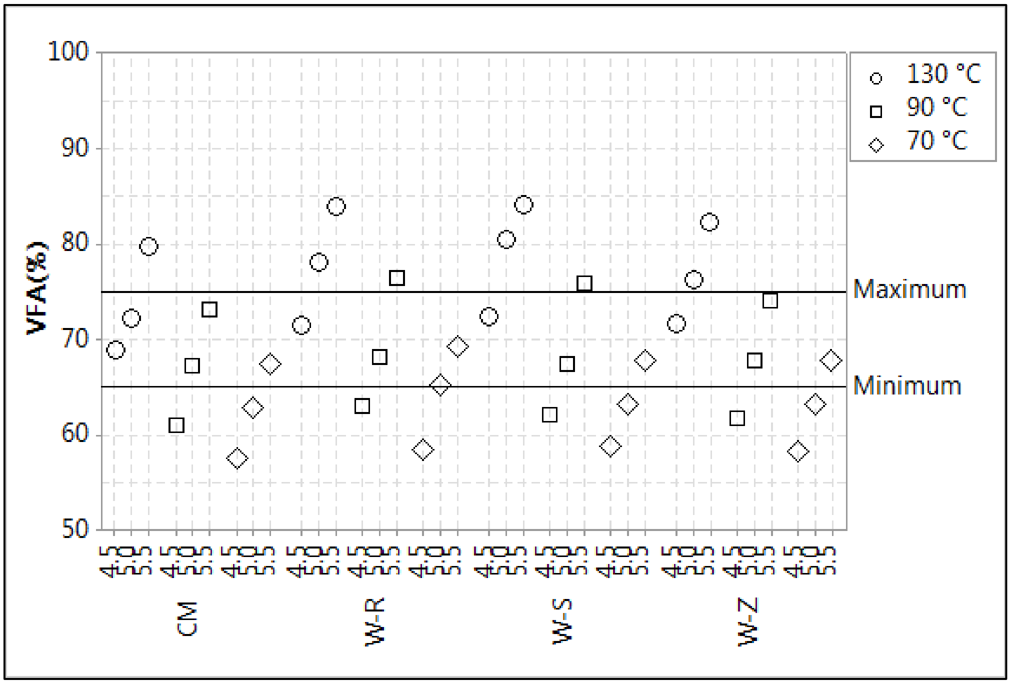


(c)

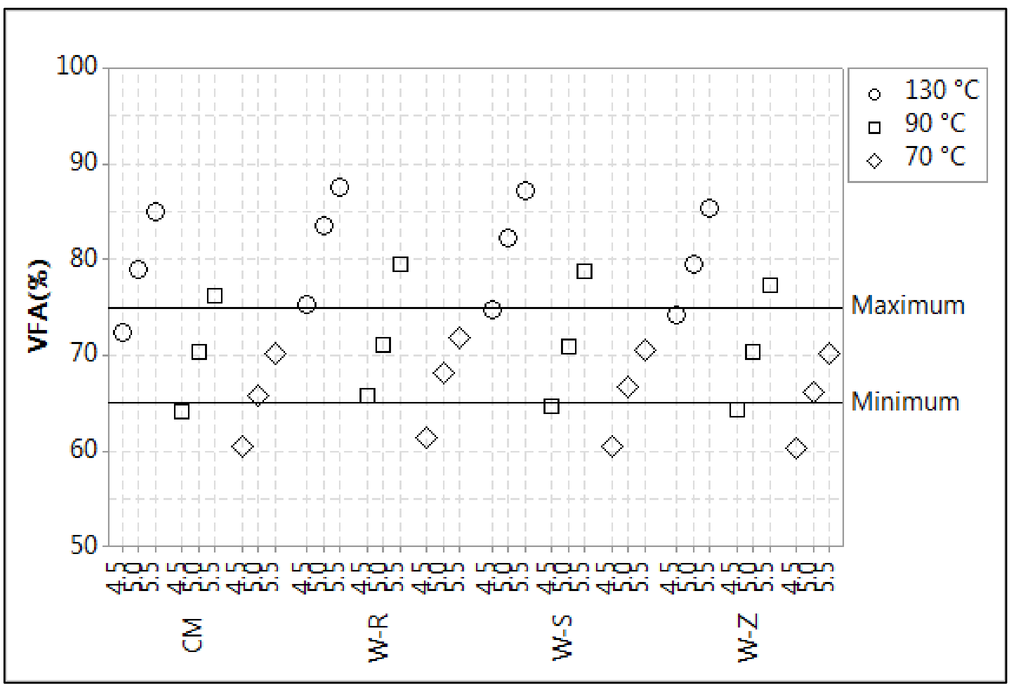
Fig. 4.5. Variation in VFA due to binder content, type of mixture, and working temperature of NMAS19 mixtures (a) 75 gyration (b) 100 gyration and (c) 125 gyration



(a)

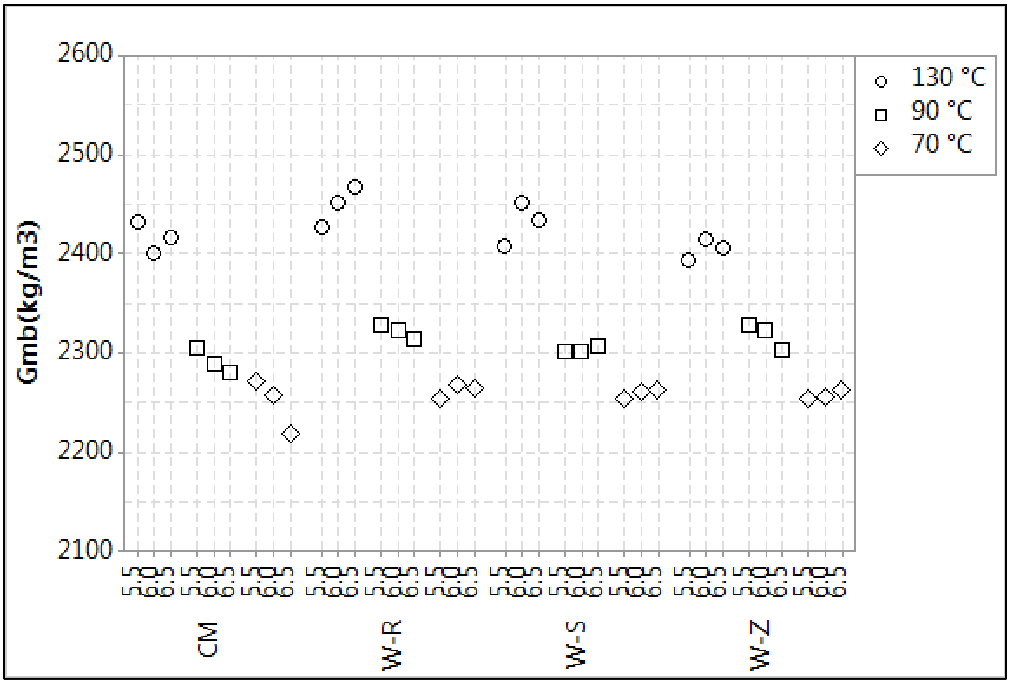


(b)

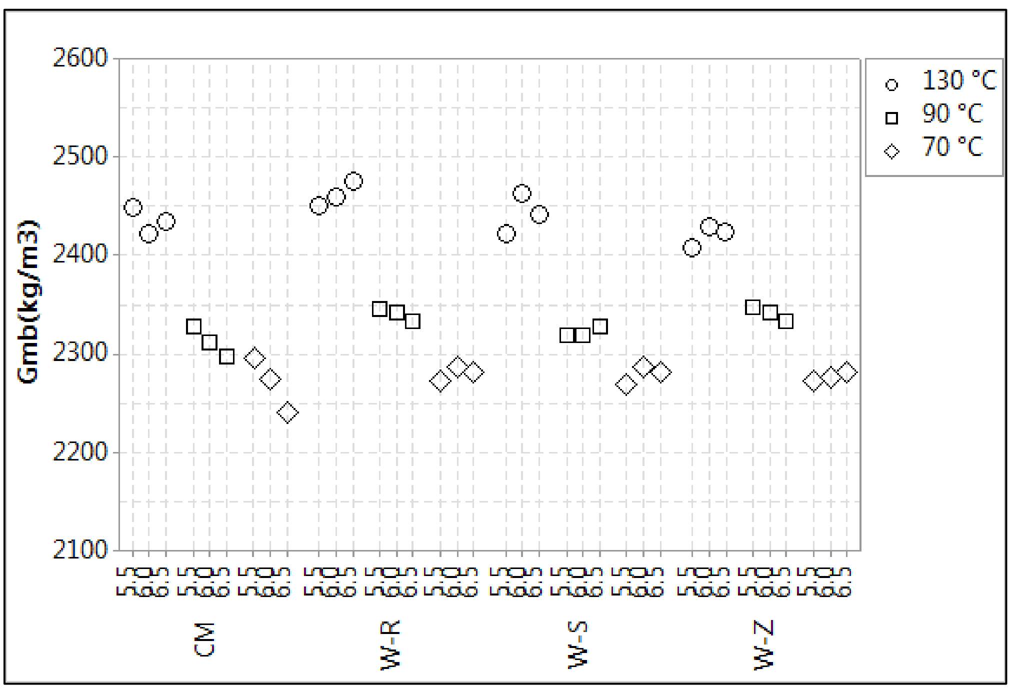


(c)

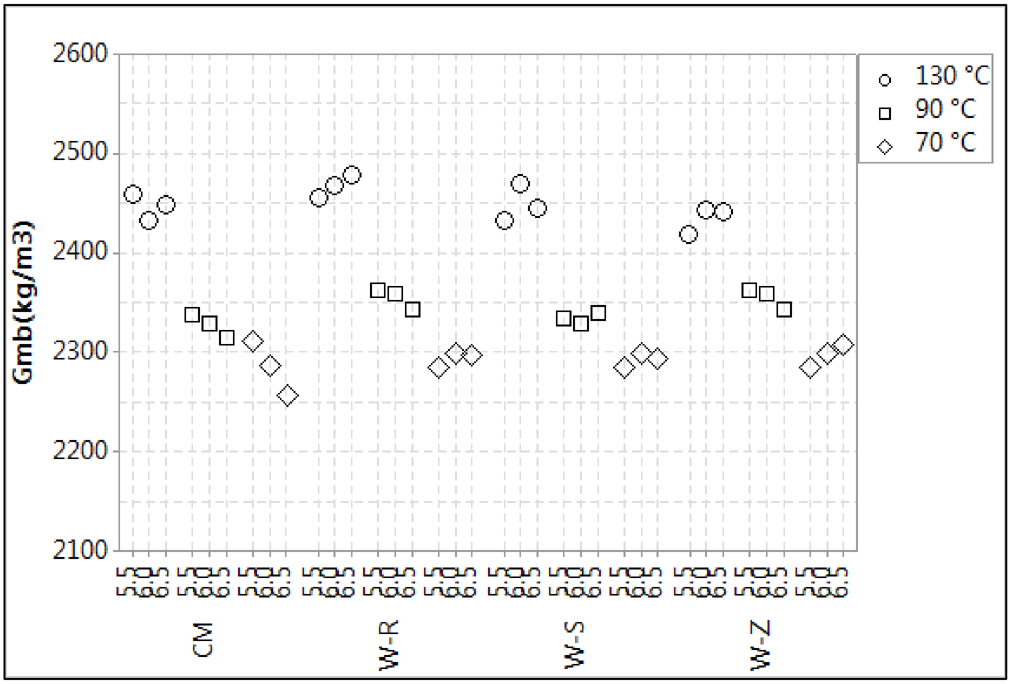
Fig. 4.6. Variation in VFA due to binder content, type of mixture, and working temperature of NMAS26.5 mixtures (a) 75 gyration (b) 100 gyration and (c) 125 gyration


Gmb(kg/m3)
2600
2500
2400
2300
2200
2100
130 °C
90 °C
70 °C
CM
W-R
W-S
W-Z

(a)

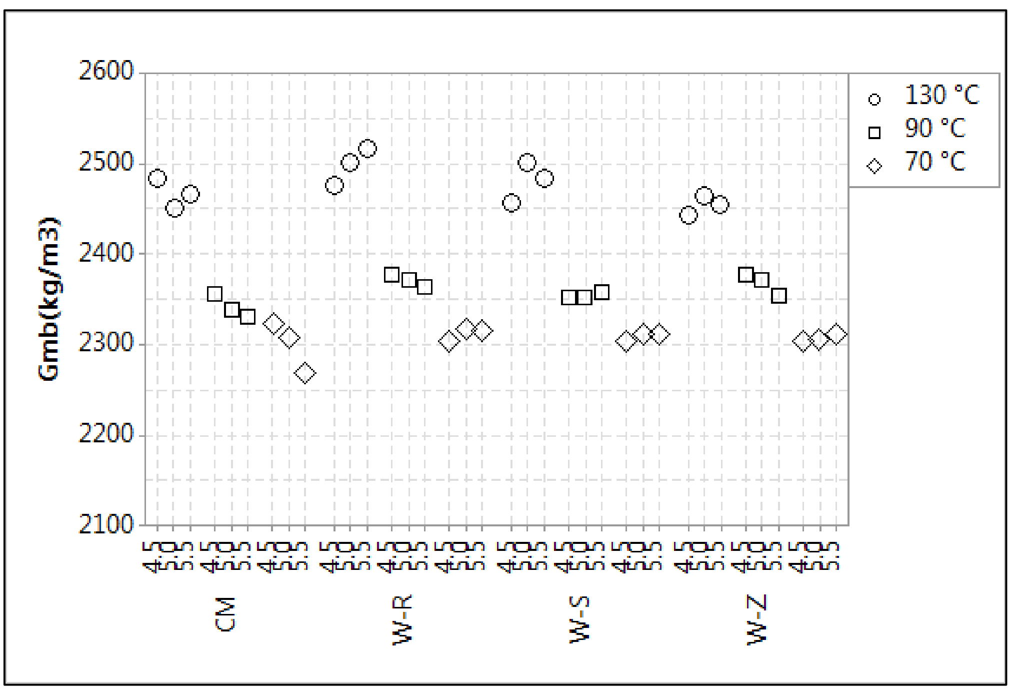

Gmb(kg/m3)
2600
2500
2400
2300
2200
2100
130 °C
90 °C
70 °C
CM
W-R
W-S
W-Z

(b)

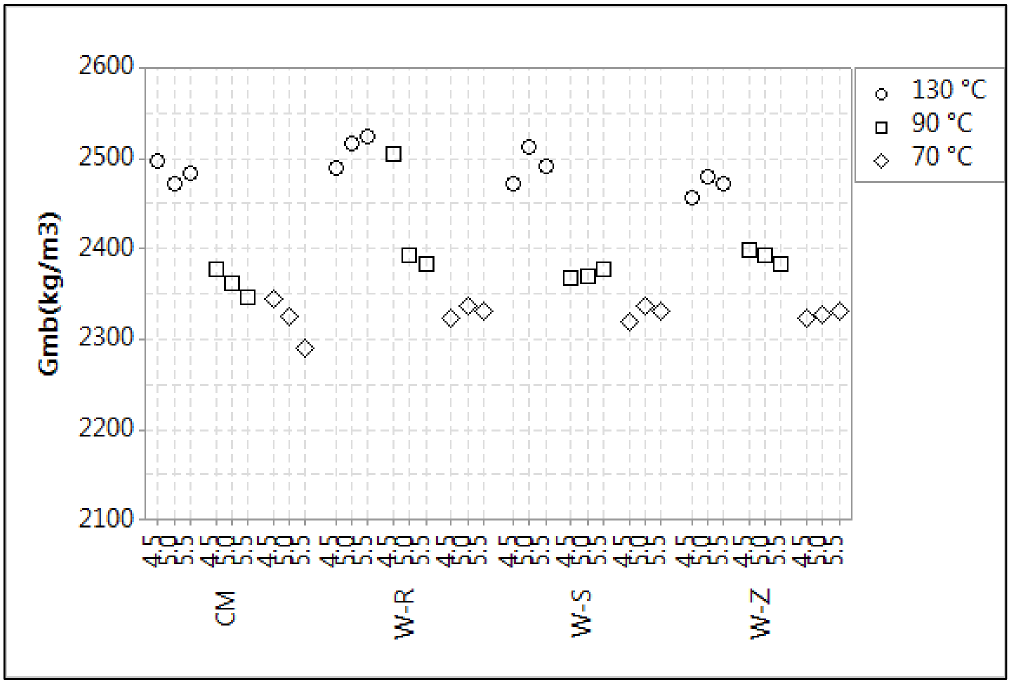


(c)

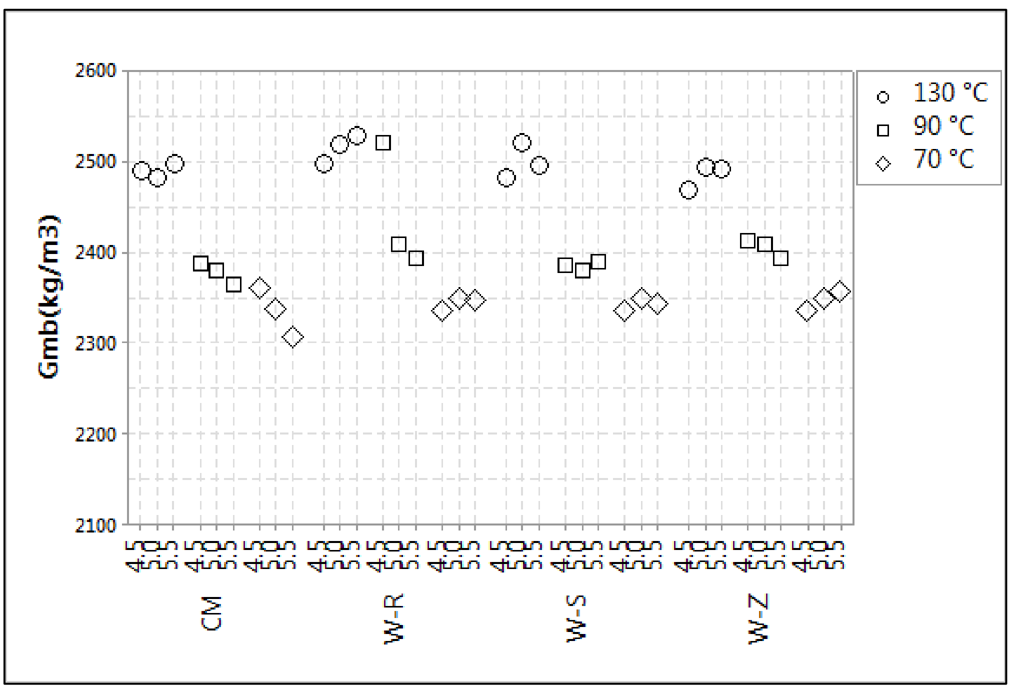
Fig. 4.7. Variation in G_{mb} due to binder content, type of mixture, and working temperature of NMAS19 mixtures (a) 75 gyration (b) 100 gyration and (c) 125 gyration



(a)



(b)



(c)

Fig. 4.8. Variation in G_{mb} due to binder content, type of mixture, and working temperature of NMAS26.5 mixtures (a) 75 gyration (b) 100 gyration and (c) 125 gyration

Table 4.2. Results of asphalt mix design properties

Mixing/Compaction temperature (° C)	Properties	NMAS19					NMAS26.5				
		CM	W-R	W-S	W-Z	Requirement[a]	CM	W-R	W-S	W-Z	Requirement[a]
150-165/130	N_{des}	75	75	75	75	--	75	75	75	75	--
	AC_{des} (%)	6.0	5.5	5.5	5.5	5.2 (minimum)	5.0	4.5	4.5	4.5	4.5 (minimum)
	G_{mb} (kg/m^3)	2401	2446	2407	2393	--	2451	2496	2457	2453	--
	VTM (%)	3.05	3.35	3.08	3.30	3-5	4.00	4.36	4.05	4.3	3-5
	VMA (%)	15.2	14.42	14.8	14.37	13 (minimum)	13.95	13.4	13.72	13.35	12 (minimum)
	VFA (%)	79.9	74.76	74.96	74.04	65-75	71.33	67.47	69.14	67.79	65-75
120-135/90	N_{des}	100	100	100	100	--	100	100	100	100	--
	AC_{des} (%)	6.0	5.5	5.5	5.5	5.2 (minimum)	5.5	5.0	5.0	5.0	4.5 (minimum)
	G_{mb} (kg/m^3)	2312	2345	2318	2340	--	2347	2392	2369	2362	--
	VTM (%)	4.25	4.52	4.56	4.00	3-5	4.07	4.62	4.78	4.7	3-5
	VMA (%)	16.28	15.45	15.49	16.10	13 (minimum)	15.09	14.51	14.65	14.58	12 (minimum)
	VFA (%)	73.90	70.75	70.56	74.10	65-75	73.03	68.15	67.37	67.76	65-75
110-120/70	N_{des}	125	125	125	125	--	125	125	125	125	--
	AC_{des} (%)	6.5	6.0	6.0	6.0	5.2 (minimum)	5.5	5.0	5.0	5.0	4.5 (minimum)
	G_{mb} (kg/m^3)	2256	2299	2282	2280	--	2306	2359	2339	2340	--
	VTM (%)	3.92	4.32	4.22	4.60	3-5	4.67	4.64	4.93	4.95	3-5
	VMA (%)	16.61	16.34	16.26	16.59	13 (minimum)	15.62	14.53	14.79	14.89	12 (minimum)
	VFA (%)	74.04	73.57	74.04	72.27	65-75	70.1	68.06	66.66	68.09	65-75

Note: N_{des}- Design gyrations, AC_{des}-Design asphalt content (%), G_{mb}-bulk specific gravity of compacted mixes, VTM-air voids in total mix, VMA-voids in mineral aggregates, VFA-voids filled with asphalt, [a]MoRTH (2013)

Table 4.3. Results of one way ANOVA test for mix design properties

Response factor	Properties	Source of variation									
		NMAS		Design gyration		Binder content		Type of mixture		Working temperature	
		F	Pr	F	Pr	F	Pr	F	Pr	F	Pr
Mix design properties	VTM	201.44	0.000	602.12	0.000	393.56	0.000	32.84	0.000	3243.96	0.000
	VMA	179.82	0.000	603.10	0.000	86.60	0.000	32.94	0.000	3240.10	0.000
	VFA	197.81	0.000	593.21	0.000	854.84	0.000	34.08	0.000	3381.96	0.000
	G_{mb}	13.71	0.000	17.36	0.000	1.95	0.070*	14.87	0.000	240.41	0.000

Note: F-critical value, Pr-probability value, *Pr-not significant.

4.3 WORKABILITY PROPERTIES

Workability of the asphalt mixtures was evaluated in terms of compactibility which is defined as the effort required for achieving consolidation of asphalt mixtures and is critical for effective long-term performance in the field. During the design process, evaluation of mix design and mechanical properties of asphalt mixtures are necessary to asses subsequent the ability to quantify compactibility (Kanitpong et al. 2007; Sanchez-Alonso et al. 2011; Mo et al. 2012).

Workability properties in terms of SGC densification indices using Bahia and Locking point method were evaluated. In order to evaluate workability properties, the Superpave specimens of diameter 150 mm (NMAS26.5) and 100 mm (NMAS19) were prepared using SGC by subjecting loose mixtures to 225 gyrations (Bahia et al. 1998; Mohammad and Al-Shamsi 2007).

Gyrations at aggregate locking point and 92% G_{mm} along with CDI and TDI calculated using Locking point and Bahia method are presented in Table 4.4. Gyrations at aggregate locking point were found to vary between 44-63 and 69-86 for NMAS19 and NMAS26.5 mixtures, respectively. Similarly, Gyrations at aggregate locking point and 92% G_{mm} were found to vary between 19-39 and 24-49 for NMAS19 and NMAS26.5 mixtures, respectively. It clearly indicates that NMAS19 mixtures undergo aggregate degradation at lower traffic level as compared to NMAS26.5 mixtures. Fig. 4.9 clearly indicates that the variations in the gyration at aggregate locking point and 92% G_{mm} were statistically significant in relation to type of mixture, and working temperature.

CDI values calculated using Locking point method was found to vary between 335.7-663.9 and 435.7-817.6 for NMAS19 and NMAS26.5 mixtures respectively. Similarly, CDI values calculated using Bahia method were found to vary between 26.3-112.8 and 56.3-146.3 for NMAS19 and NMAS26.5 mixtures, respectively. Results indicated that NMAS19 mixtures are more workable as compared to NMAS26.5

mixtures. Fig. 4.10 indicates CDI take more energy to compact the specimens at lower working temperature. Variations in the CDI calculated using Locking point and Bahia method clearly indicate it is statistically significant in relation to type of mixture, and working temperature. W-S mixtures compacted at 90 °C and 70 °C showed lower CDI values which indicate that it will take less energy for densification due to higher VFA values. Similar findings were noticed in studies conducted on effect of NMAS on workability properties (Stakston et al. 2002; Mohammad and Al-Shamsi 2007; Leiva et al. 2008).

TDI values calculated using Locking point method were found to vary between 159.4-252.9 and 299.1-416.7 for NMAS19 and NMAS26.5 mixtures, respectively. Similarly, TDI values calculated using Bahia method were found to vary between 405.9-709.9 and 515.9-815.9 for NMAS19 and NMAS26.5 mixtures respectively. TDI values are lower compared to CDI values for Locking point method while it was vice versa for Bahia method. Fig. 4.11 indicates that TDI values are lower compared to CDI values for Locking point method and higher compared to CDI values for Bahia method. Variations in the TDI calculated using Locking point and Bahia method clearly indicate it is statistically significant in relation to type of mixture, and working temperature. Subsequently, W-S mixtures compacted at 90 °C and 70 °C showed higher TDI values due to higher VMA values compared to CM, W-R and W-Z mixtures indicated increase in resistance to traffic loading. However, WMA mixtures compacted at 90 °C and 70 °C showed lower workability properties than control mixtures compacted at 130 °C. Similar results were also noticed in the studies conducted by Kanitpong et al. (2007), Sanchez-Alonso et al. (2011), and Mo et al. (2012) using Bahia method upto a compaction temperature of 110 °C.

Gyration at aggregate locking point and 92% G_{mm}, CDI and TDI values calculated using Bahia method and Locking point method clearly indicate it is statistically significant in relation to NMAS, type of mixture, and working temperature as noticed in

Table 4.5. Results indicated that NMAS19 mixtures are more workable and less resistance to traffic loading as compared to NMAS26.5 mixtures. Similar findings were noticed in studies conducted on effect of NMAS on workability properties (Stakston et al. 2002; Mohammad and Al-Shamsi 2007; Leiva et al. 2008).

Table 4.4. Results of workability properties

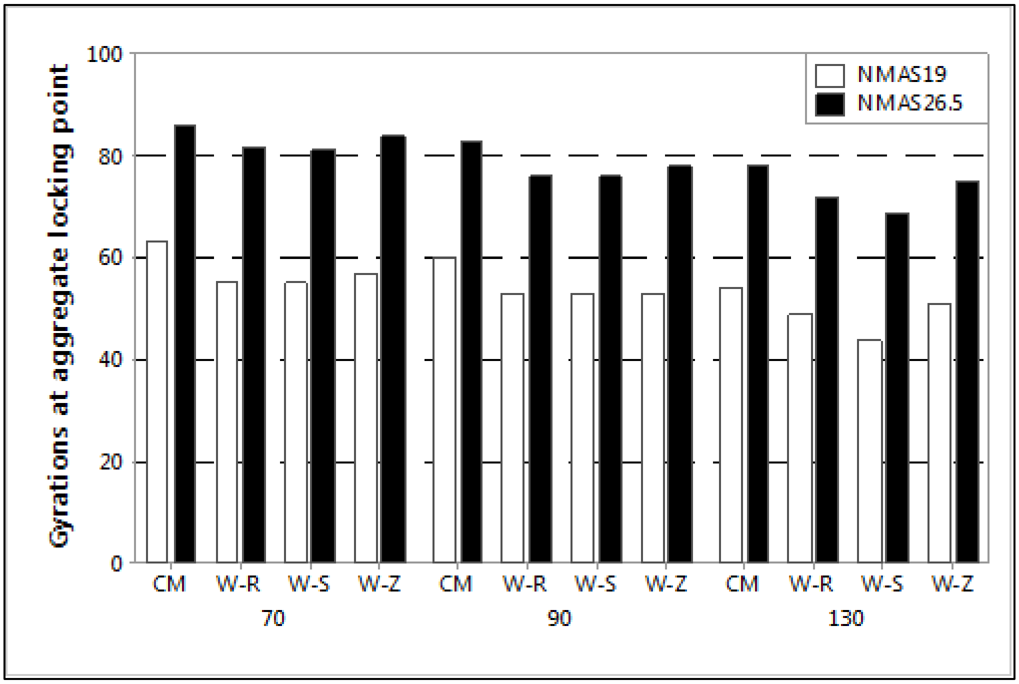
Mixing/ Compaction temperature(°C)	Type of mixture	Bahia method			Locking point method		
		$G_{92\%}$	CDI	TDI	G_{LP}	CDI	TDI
NMAS19							
150-165/130	CM	23	39.6	637.8	54	450.7	228.8
	W-R	20	28.6	808.5	49	429.3	247.9
	W-S	19	26.3	709.9	44	335.7	252.9
	W-Z	21	39.9	708.4	51	439.3	232.9
120-135/90	CM	34	98.4	536.0	60	484.4	218.4
	W-R	27	52.7	658.0	53	449.0	220.8
	W-S	22	30.2	675.8	53	359.0	239.8
	W-Z	28	52.2	640.7	53	444.5	219.5
110-120/70	CM	39	112.8	405.9	63	663.9	159.4
	W-R	34	87.6	444.6	55	512.8	209.9
	W-S	34	83.0	588.0	55	430.5	218.4
	W-Z	37	103.3	443.2	57	560.7	173.8
NMAS26.5							
150-165/130	CM	26	69.9	775.8	78	653.9	328.8
	W-R	23	58.6	808.5	72	512.2	347.9
	W-S	24	56.3	815.9	69	435.7	352.9
	W-Z	28	69.6	808.4	75	526.0	332.9
120-135/90	CM	42	142.8	688.0	83	767.8	318.4
	W-R	32	82.7	740.7	76	650.0	320.8
	W-S	27	60.2	758.0	76	532.5	339.8
	W-Z	33	82.2	737.8	78	670.0	319.5
110-120/70	CM	49	146.3	515.9	86	817.6	259.4
	W-R	39	117.6	680.6	82	697.8	309.9
	W-S	39	113.0	636.0	81	692.3	318.4
	W-Z	44	133.3	544.6	84	707.8	273.8

Note: $G_{92\%}$-Gyrations at 92% G_{mm}, G_{LP}-Gyrations at locking point

Table 4.5. Results of one way ANOVA test for workability properties

Aggregate condition	Response properties	Source of variation					
		NMAS		Type of mixture		Working temperature	
		F	Pr	F	Pr	F	Pr
Bahia method	Gyrations at 92% G_{mm}	22.30	0.000	7.90	0.002	57.27	0.000
	CDI	28.47	0.000	8.42	0.001	36.51	0.000
	TDI	7.88	0.012	14.10	0.003	13.76	0.000
Locking point method	Gyrations at locking point	183.81	0.000	4.68	0.005	12.52	0.004
	CDI	30.71	0.000	6.33	0.006	5.96	0.008
	TDI	90.24	0.000	5.73	0.017	14.41	0.018

Note: F-critical value, Pr-probability value, *Pr-not significant.



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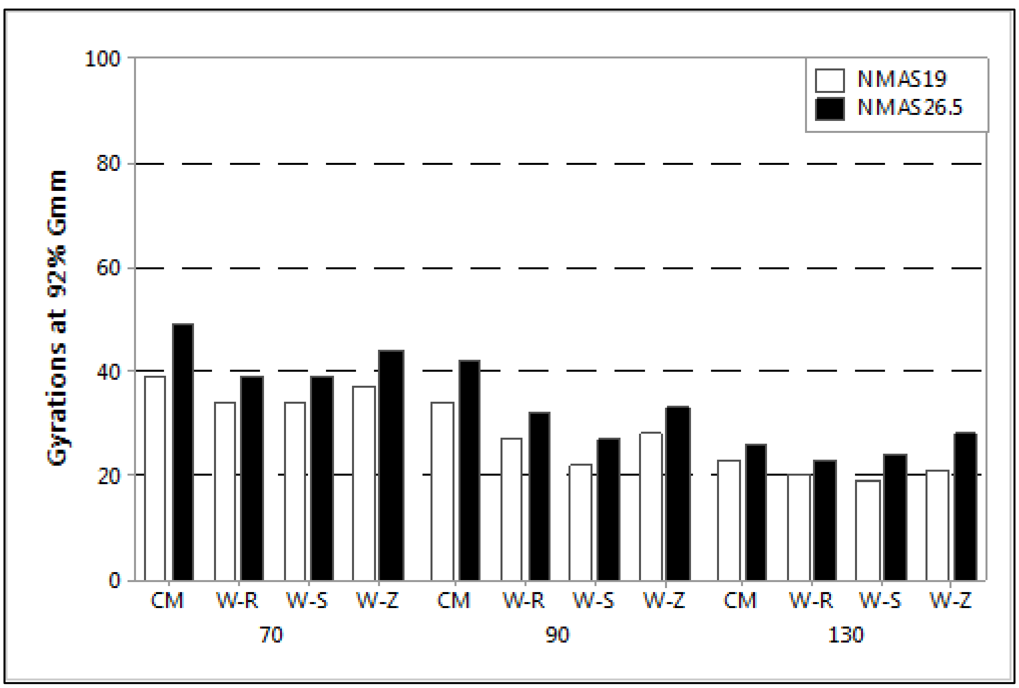
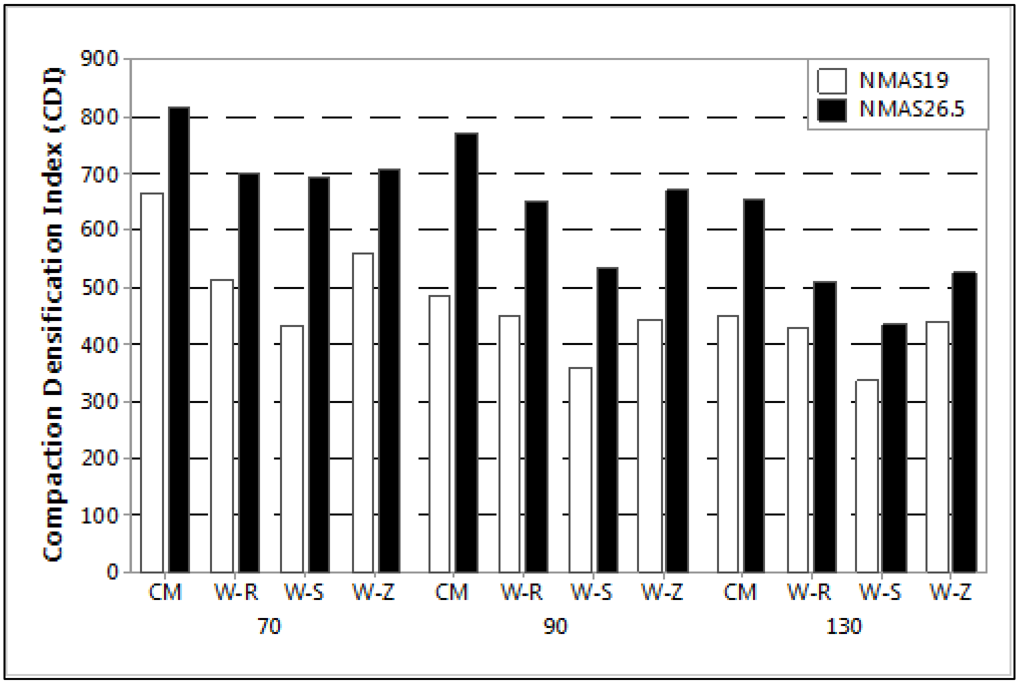


(b)

Fig. 4.9. Gyrations at aggregate locking point and 92% G_{mm}



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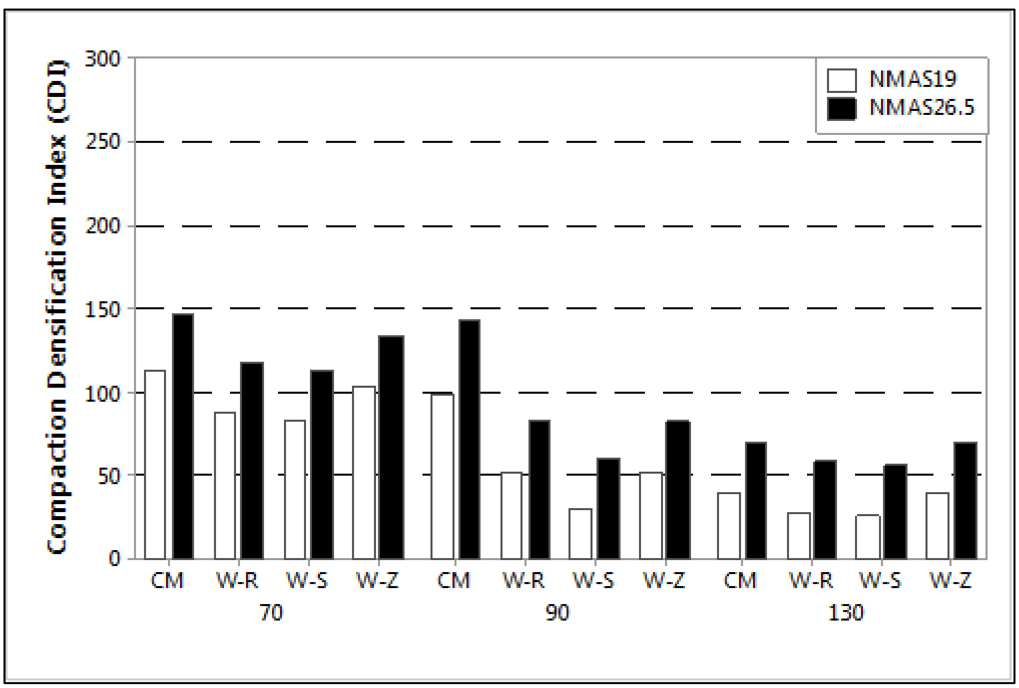

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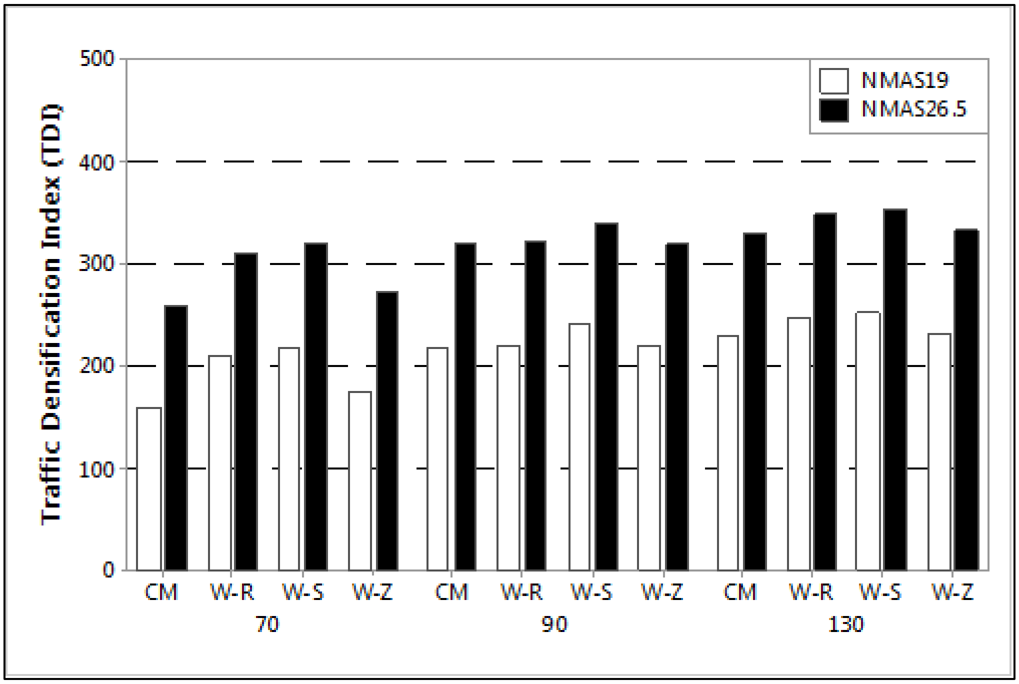
Fig. 4.10. Variation in CDI values (a) Locking point method (b) Bahia method



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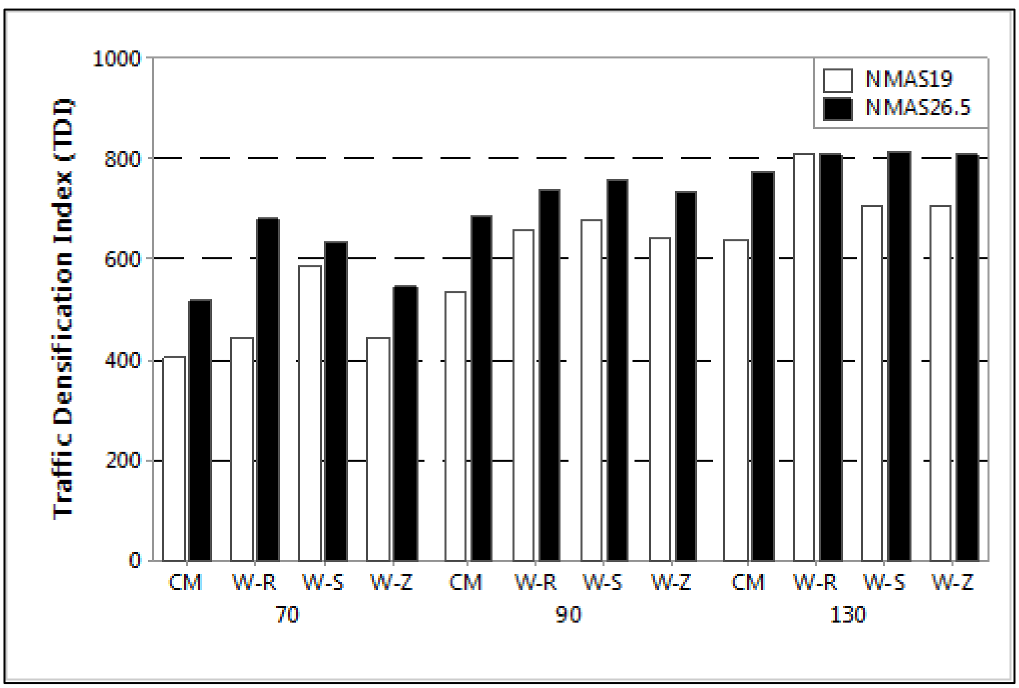


(b)

Fig. 4.11. Variation in TDI values (a) Locking point method (b) Bahia method

4.3 RUTTING PROPERTIES

Rutting (permanent deformation) is defined as the accumulation of small amounts of unrecoverable strain resulting from applied wheel loads to the pavement resulting in reduction of useful service life and performance of pavement (Wenbin et al. 2012; Fereidoon et al. 2013). A typical curve showing rut depth versus number of cycles of wheel tracking test (WTT) is shown in Fig. 4.12. The post-compaction consolidation is the deformation in millimeters at 1000 wheel passes and occurs rapidly during the first few minutes of the test. The creep slope is the inverse of the deformation rate within the linear region of the deformation curve after post compaction and prior to stripping (if stripping occurs) which measures rutting susceptibility. The stripping slope is the inverse of the deformation rate within the linear deformation of the deformation curve, after the stripping which measures the accumulation of permanent deformation due to moisture damage. The stripping inflection point is the number of wheel passes corresponding to the intersection of the creep slope and the stripping slope (Kandhal and Allen 2003).

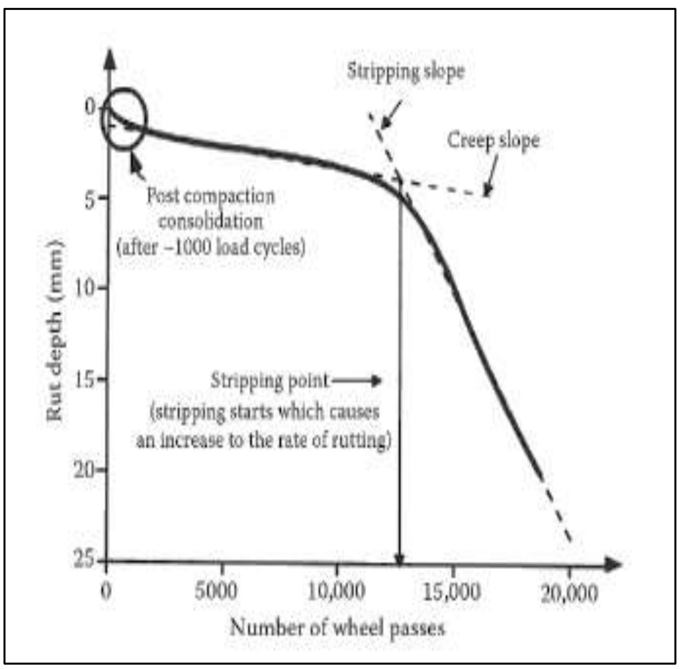


Fig 4.12. Typical curve showing rut depth versus number of wheel passes of WTT

Number of rut passes to 6mm rut depth (failure criteria as per NCHRP 508, 2003) along with dynamic stability of asphalt mixtures in dry condition at testing temperature of 60 °C were measured and presented in Table 4.6. Figs. 4.13 and 4.14 depict rut passes and dynamic stability of asphalt mixtures in relation to NMAS, type of mixture and working temperature. Rut passes were found to be in the range of 6050-12050, and 7200-14900 for NMAS19 and NMAS26.5 mixtures, respectively. Dynamic stability was found to be in the range of 1850-3190, mm/min and 2009-3610, mm/min for NMAS19 and NMAS26.5, respectively. Rut resistance of NMAS26.5 mixtures were found significantly higher than NMAS19 mixtures. Similar findings were noticed by Bennert et al. (2010), Punith et al. 2011, Zhao et al. (2012), Xiao et al. 2013, and Ali et al. 2013 with WMA mixtures compacted upto 110 °C.

Rut passes and dynamic stability of asphalt mixtures significantly reduced with the reduction in working temperature. Rutting resistance of W-S mixtures compacted at 90 °C and 70 °C were found higher than those of CM, W-R and W-Z mixtures. However, WMA mixtures compacted at 90 °C and 70 °C showed lower rutting resistance than control mixtures compacted at 130 °C. The main reason might be that the mixtures were subjected to a short term ageing at a higher working temperature that resulted in a stiffer mixture having higher rut resistance mixtures.

The rut results were also analyzed using TDI, obtained from both Bahia and Locking point method as shown in Figs. 4.15 and 4.16 for NMAS19 and NMAS26.5 mixtures, respectively. It is evident that, higher TDI values indicated lower rut passes and higher dynamic stability. These results provide an indication of better mixture stability to traffic loading. The rut results have reasonable correlation with TDI values with an R^2 of 0.65-0.72 for NMAS19 and good correlation with TDI values with an R^2 of 0.72-0.79 for NMAS26.5 mixtures. The trend also indicates that there might be optimum TDI values for the WMA mixtures corresponding to better rutting resistance. Statistical analysis results tabulated in Table 4.7 indicate that NMAS, working temperature and type of mixture had significant effects on rutting properties. Working temperature had the most significant effect on rutting resistance as it has the highest F value, followed by NMAS and type of mixture.

Table 4.6. Results of rutting properties

Mixing/ Compaction temperature(°C)	Type of mixture	NMAS19		NMAS26.5	
		Rut passes	Dynamic stability (mm/min)	Rut passes	Dynamic stability (mm/min)
150-165/130	CM	11290	3055	13850	3404
	W-R	11540	3105	14200	3524
	W-S	12050	3190	14900	3610
	W-Z	11410	3095	14050	3490
120-135/90	CM	7000	1932	8117	2287
	W-R	8100	2296	10483	2839
	W-S	9370	2680	12350	3216
	W-Z	7770	2202	9290	2607
110-120/70	CM	6050	1850	7200	2009
	W-R	7500	2101	8200	2324
	W-S	8070	2400	10100	2754
	W-Z	7250	2029	7900	2234

Table 4.7. Results of one way ANOVA test for rutting properties

Response Properties	Source of variation					
	NMAS		Type of mixture		Working temperature	
	F	Pr	F	Pr	F	Pr
Rut passes	52.49	0.000	12.11	0.000	132.96	0.000
Dynamic stability	40.87	0.000	16.31	0.000	132.69	0.000

Note: F-critical value, Pr-probability value, *Pr-not significant.

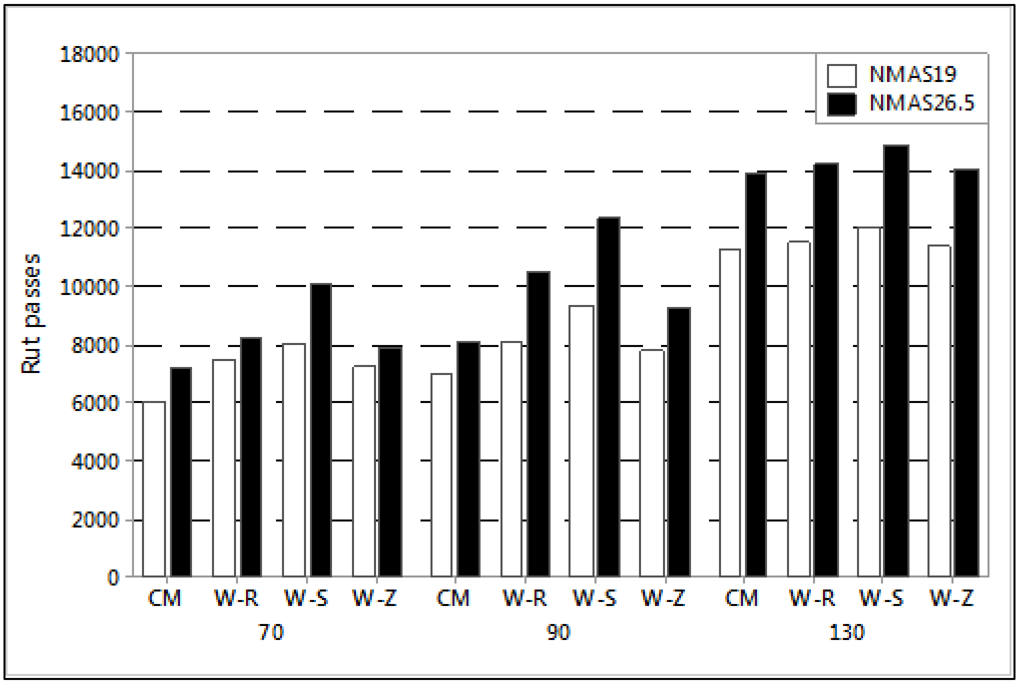


Fig. 4.13. Rut passes results of asphalt mixtures

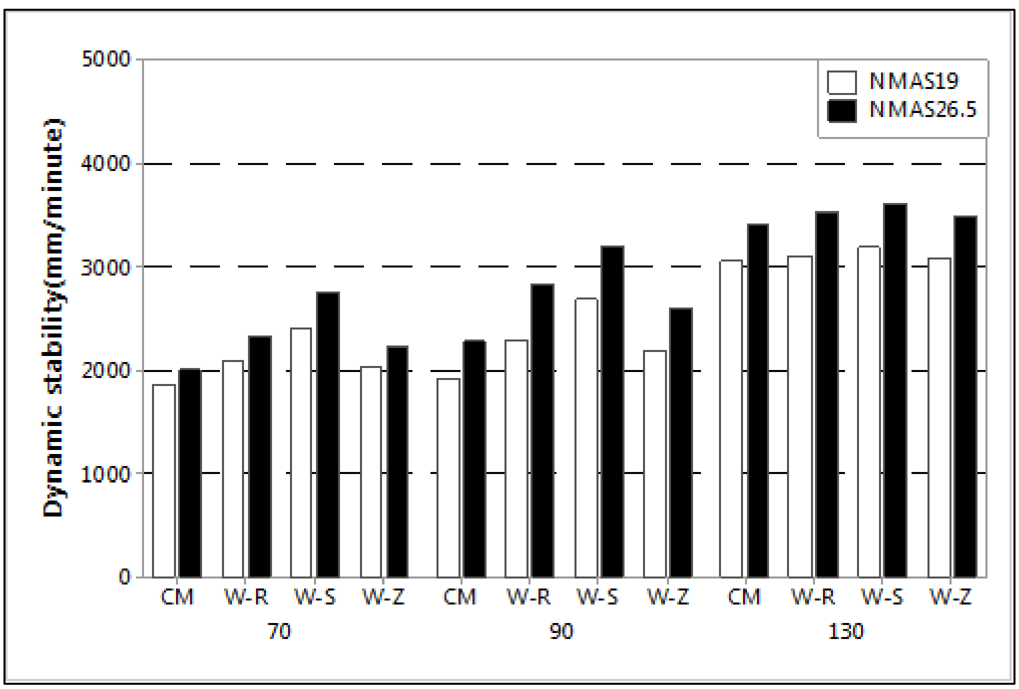
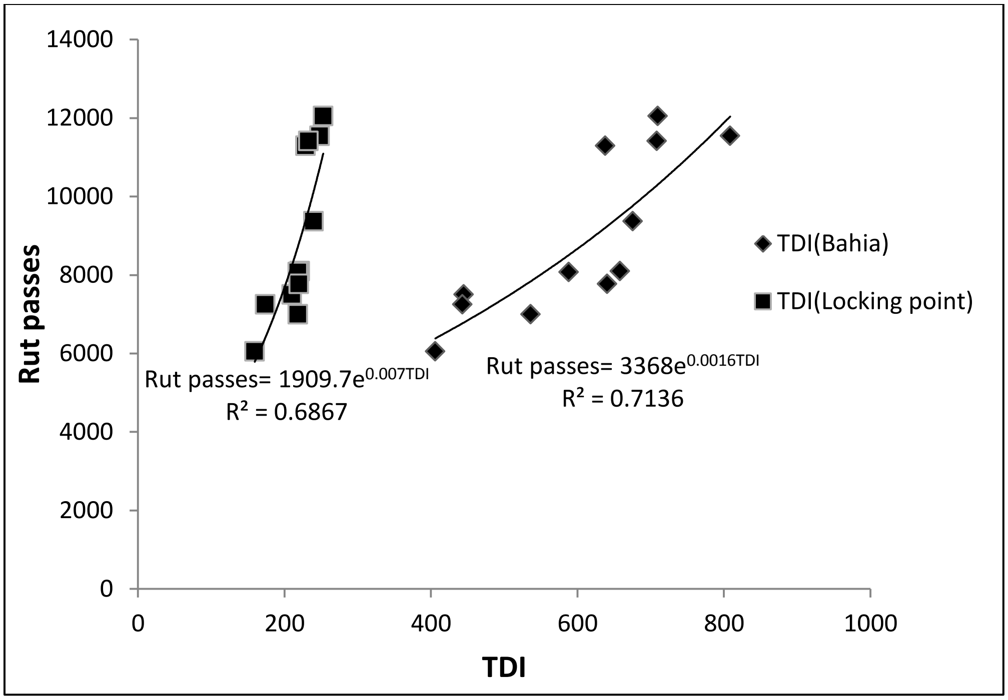


Fig. 4.14. Dynamic stability results of asphalt mixtures



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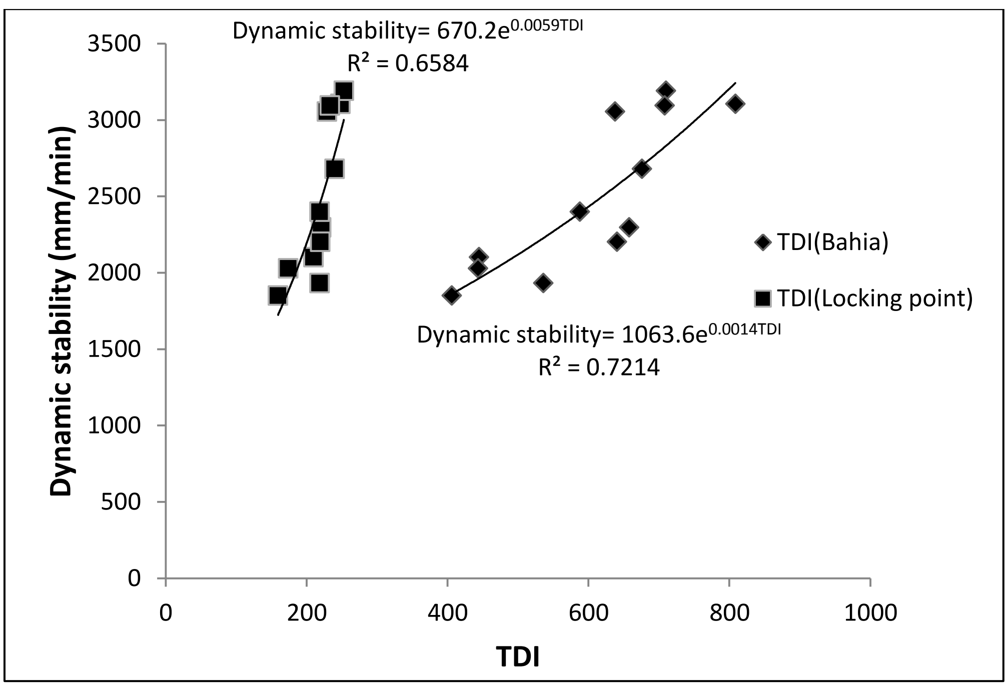
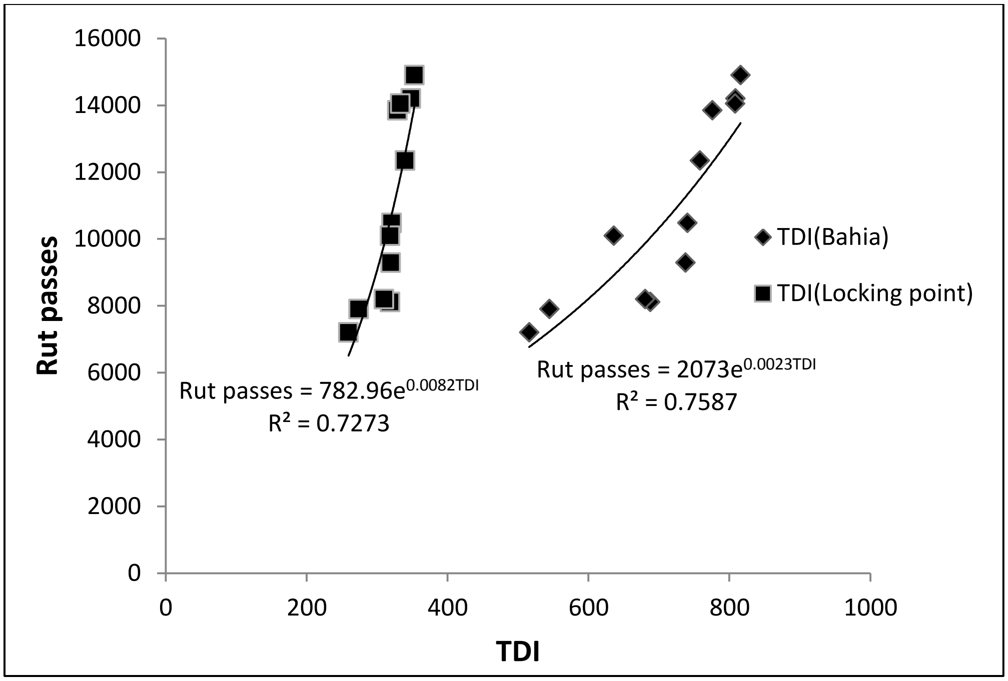
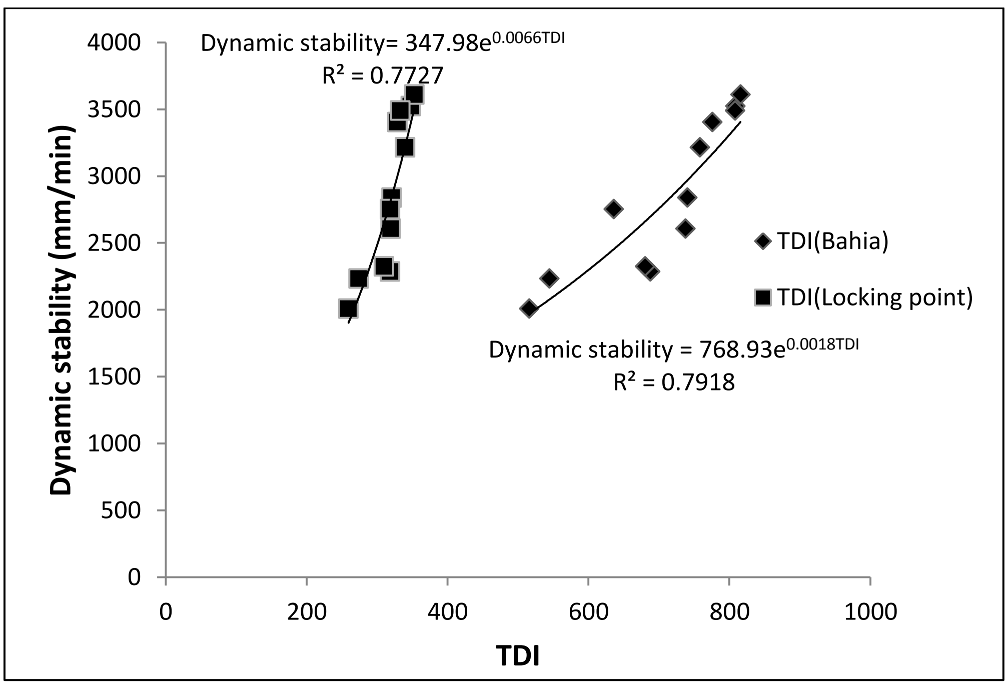


(b)

Fig. 4.15. Regression analysis of rutting properties of NMAS19 mixtures (a) rut passes v/s TDI (b) dynamic stability v/s TDI



(a)



(b)

Fig. 4.16. Regression analysis of rutting properties of NMAS26.5 mixtures (a) rut passes v/s TDI (b) dynamic stability v/s TDI

4.4 FLEXURAL FATIGUE PROPERTIES

Fatigue cracking is one of the major pavement failures due to the accumulation of damage under repeated load applications. Fatigue life of asphalt mix is its ability to withstand repeated load application without fracture and expressed as relationship between the initial stresses or strain. It can be determined by knowing number of cycles to failure using repeated flexure or indirect tensile tests performed at several stress or strain levels (Mansour et al. 2013). In repeated flexure fatigue test, beam is tested under four point loading setup, as shown in Fig. 4.17 so that the failure is localized in the central portion of the beam where the bending moment is constant (Ajay et al. 2007).

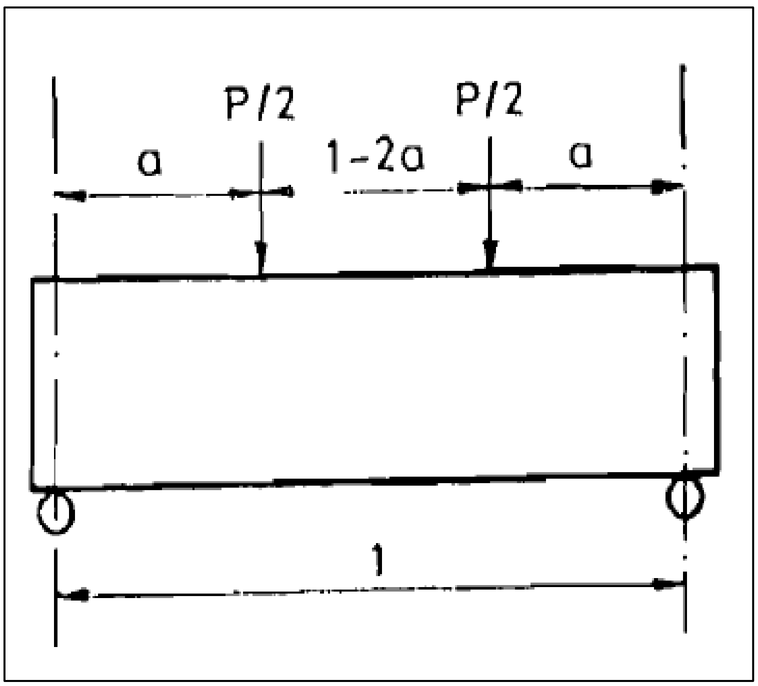


Fig. 4.17 Four point loading

Fatigue cycles and flexural strength of NMAS19 and NMAS26.5 mixtures are presented in Table 4.8. The applied stresses (10% of failure load) were in the range of 0.08-0.24kN and 0.25-0.45kN for NMAS19 and NMAS26.5 mixtures, respectively. Figs. 4.18 and 4.19 depict flexural strength and fatigue cycles of asphalt mixtures in relation to NMAS, type of mixture and working temperature. Fatigue cycles were found to be in the range of 2175-10500 and 3503-12920 for NMAS19 and NMAS26.5 mixtures, respectively. Similarly, flexural strength was found to be in the range of 0.5-1.5 kPa and 1.6-2.8 kPa for NMAS19 and NMAS26.5 mixtures respectively.

Flexural fatigue resistances of NMAS26.5 mixtures were found to be significantly higher than NMAS19 mixtures as per the statistical results in Table 4.9. Fatigue cycles and flexural strength of asphalt mixtures significantly reduced with the reduction in working temperature. Flexural fatigue resistance of W-S mixtures compacted at 90 ^{0}C and 70 °C were found significantly higher than those of CM, W-R and W-Z mixtures. However, WMA mixtures compacted at 90 °C and 70 °C showed lower fatigue resistance than control mixtures compacted at 130 °C. Similar findings were noticed in the studies conducted by Diefenderfer and Hearon (2008), Xiao et al. (2009), Ziari et al. (2012), Fakhri et al. (2013) on WMA mixtures compacted at 110 °C.

Statistical analysis was conducted to evaluate the effect of the NMAS, type of mixture and working temperature on fatigue resistance of WMA mixtures as presented in Table 4.9. It is clearly evident from statistical analysis that NMAS, working temperature, and type of mixture had significant effects on fatigue properties. Working temperature had the most significant effect due to highest F value, followed by the NMAS and type of mixture.

Table 4.8. Results of fatigue properties

Mixing/ Compaction temperature(°C)	Type of mixture	NMAS19		NMAS26.5	
		Fatigue cycles	Flexural strength (kPa)	Fatigue cycles	Flexural strength (kPa)
150-165/130	CM	9850	1.3	12063	2.6
	W-R	10200	1.4	12400	2.7
	W-S	10500	1.5	12920	2.8
	W-Z	9950	1.4	12190	2.7
120-135/90	CM	4350	0.7	6503	1.8
	W-R	6330	1	9392	2.3
	W-S	7558	1.2	10443	2.4
	W-Z	5040	0.9	8283	2
110-120/70	CM	2175	0.5	3503	1.6
	W-R	3165	0.8	6392	2.1
	W-S	3742	0.9	7443	2.3
	W-Z	2520	0.7	5283	1.9

Table 4.9. Results of one way ANOVA test for fatigue properties

Response Properties	Source of variation					
	NMAS		Type of mixture		Working temperature	
	F	Pr	F	Pr	F	Pr
Fatigue cycles	83.91	0.000	7.9	0.003	146.67	0.000
Flexural strength	1211.91	0.000	26.18	0.000	135.87	0.000

Note: F-critical value, Pr-probability value, *Pr-not significant.

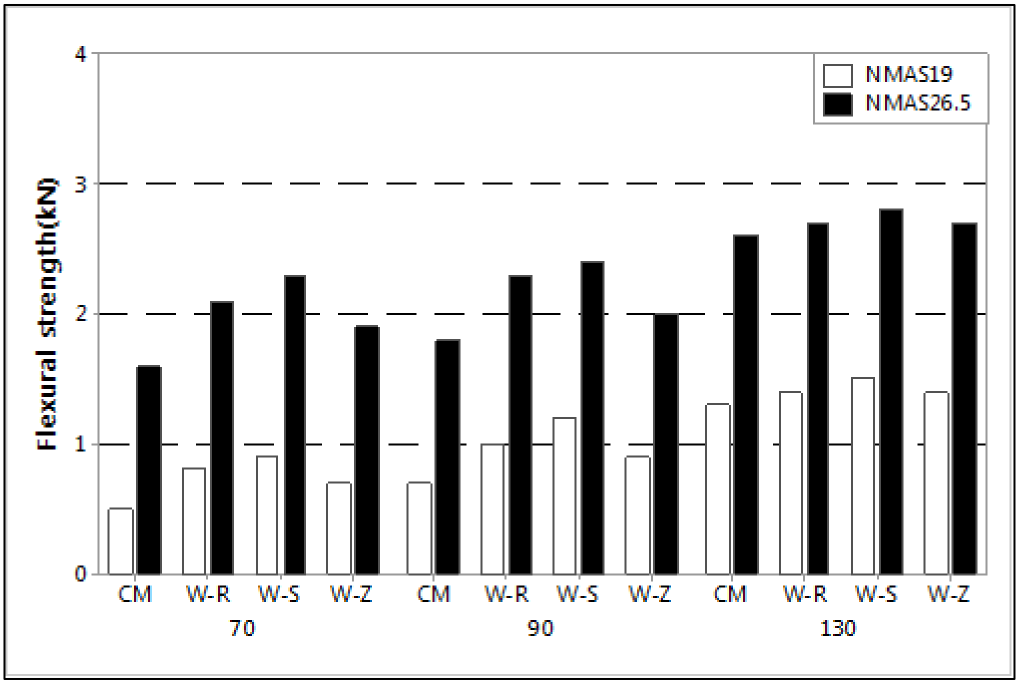


Fig. 4.18. Flexural strength results of asphalt mixtures

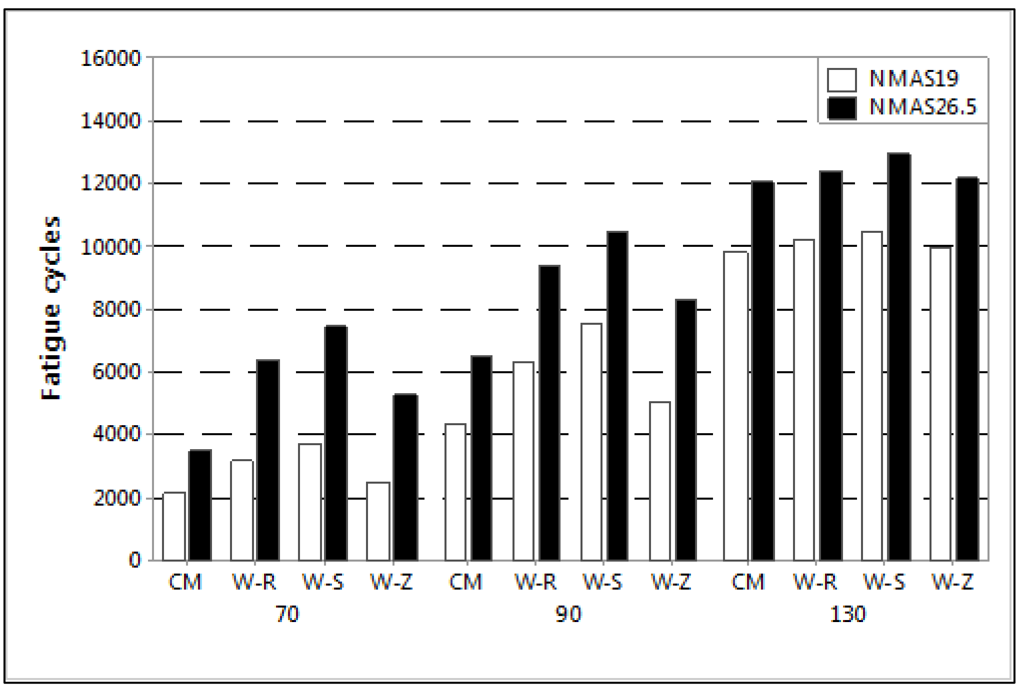


Fig. 4.19. Fatigue cycles to failure results of asphalt mixtures

4.5 MOISTURE-INDUCED DAMAGE PROPERTIES

The moisture damage in asphalt mixtures is determined as a loss of strength due to the presence of moisture in terms of a tensile strength ratio (TSR) that is defined as a ratio of the indirect tensile strength (ITS) of a conditioned specimen to that of an unconditioned specimen. The ITS values of unconditioned and conditioned specimens along with TSR values for both oven dry and surface saturated dry aggregates of NMAS19 and NMAS26.5 mixtures are presented in Table 4.10.

Figs. 4.20 and 4.21 illustrate the ITS values of unconditioned and conditioned specimens, respectively. Results of ITS test clearly indicate that the asphalt mixtures prepared with saturated surface dry aggregates exhibited relatively lower ITS and TSR value compared to that of mixtures made with oven dry aggregates. Similarly results were obtained in studies conducted by Punith et al. (2011) and Xiao et al. (2013) on moist aggregates with foamed WMA mixtures.

In addition, unconditioned and conditioned ITS values of NMAS26.5 mixtures were found significantly higher than NMAS19 mixtures. Further, the reduction of working temperatures to 90 °C and 70 °C resulted in significant reduction in ITS values of control mixtures while it was not significant for WMA mixtures (Table 4.11). The ITS values of W-S mixtures were higher than those of CM, W-R and W-Z mixtures irrespective of NMAS, working temperature and aggregate condition.

The differences between the ITS values of WMA mixtures compacted at 90 ^{0}C and the control mixtures were not statistically significant. However, the reduction of working temperature to 70 °C resulted in significant reduction in ITS values of WMA mixtures compare to that of control mixtures. WMA mixtures compacted at 90 °C and 70 °C had conditioned ITS values around 448 kPa, which is minimum SCDOT requirement (SCDOT, 2011).

However, the interim guidelines for warm mix asphalt published by the IRC do not specify minimum requirement for the conditioned ITS values but recommends a minimum TSR of 80% for the WMA mixtures (IRC:SP:11 2014). Fig. 4.22 illustrates the TSR values of asphalt mixtures. Results indicate that WMA mixtures compacted at 90 °C fulfilled the minimum TSR requirements and WMA mixtures compacted at 70 °C marginally fulfilled the minimum TSR requirements. This was not for the control mixtures compacted at 90 °C and 70 °C. This can be mainly attributed to the significant reduction in the ITS values of conditioned specimen of control mixtures. However, WMA mixtures compacted at 90 °C and 70 °C were more prone to moisture-induced damage than the control mixtures compacted at 130 °C. Similar findings were noticed in studies conducted by Ahmed et al. (2013) and Malladi et al. (2015) for WMA mixtures compacted at 110 °C.

Statistical analysis was conducted to evaluate the effect of the NMAS, aggregate condition, type of mixture and working temperature on moisture-induced damage resistance of WMA mixtures as presented in Table 4.11. It is clear that NMAS, working temperature, and type of mixture had significant effects on moisture-induced damage properties. Working temperature had the most significant effect due to the highest F value, followed by the NMAS and type of mixture. Furthermore, the effect of aggregate condition was also found significant.

Table 4.10. Results of moisture-induced damage properties

Mixing/ Compaction temperature(°C)	Type of mixture	Unconditioned ITS (kPa)		Conditioned ITS (kPa)		TSR (%)	
		OD	SSD	OD	SSD	OD	SSD
NMAS19							
150-165/130	CM	593.5	575.6	538.9	513.6	90.8	89.2
	W-R	605.3	590.5	550.2	535.6	92.1	90.1
	W-S	620.5	600.8	560.5	545.5	92.5	91.5
	W-Z	600.5	585.5	545.7	524.6	91.8	90.0
120-135/90	CM	337.2	317.2	267.6	237.6	79.4	75.0
	W-R	458.5	448.5	370.0	350.0	81.4	77.4
	W-S	463.5	453.5	388.4	368.4	83.8	81.2
	W-Z	360.7	340.7	293.5	263.5	80.7	78.0
110-120/70	CM	298.8	278.8	210.0	173.5	66.8	55.4
	W-R	382.0	372.0	260.3	240.3	70.3	64.6
	W-S	424.6	414.6	337.3	317.3	79.5	76.6
	W-Z	313.1	293.1	209.1	162.5	68.1	62.5
NMAS26.5							
150-165/130	CM	722.1	702.5	667.1	652.5	93.0	92.7
	W-R	730.5	705.5	675.3	660.5	93.5	93.0
	W-S	745.0	720.5	680.5	671.5	94.0	93.5
	W-Z	730.5	705.5	675.3	658.5	93.5	92.8
120-135/90	CM	532.0	512.0	420.8	390.8	79.1	76.4
	W-R	588.7	568.7	487.9	422.6	81.4	80.2
	W-S	636.9	626.9	532.8	517.8	82.9	74.5
	W-Z	578.6	568.6	470.8	455.8	83.7	82.6
110-120/70	CM	434.4	414.4	310.4	285.2	74.3	68.8
	W-R	482.8	462.8	363.7	333.7	75.3	72.1
	W-S	520.4	510.4	409.6	394.6	78.7	77.3
	W-Z	464.3	454.3	351.5	336.5	75.7	71.5

Note: OD-oven dry aggregates, SSD-surface saturated dry aggregates

Table 4.11. Results of one way ANOVA test for moisture-induced properties

Aggregate condition	Response properties	Source of variation					
		NMAS		Type of mixture		Working temperature	
		F	Pr	F	Pr	F	Pr
Oven dry aggregates	Unconditioned ITS	106.52	0.000	5.30	0.009	0.00	0.000
	Conditioned ITS	91.48	0.000	5.55	0.008	99.74	0.000
	TSR	6.38	0.022	4.39	0.018	143.75	0.000
Surface saturated dry aggregates	Unconditioned ITS	91.40	0.000	5.44	0.008	185.95	0.000
	Conditioned ITS	69.66	0.000	4.57	0.016	145.55	0.000
	TSR	4.85	0.042	4.32	0.030	65.90	0.000

Note: F-critical value, Pr-probability value, *Pr-not significant.

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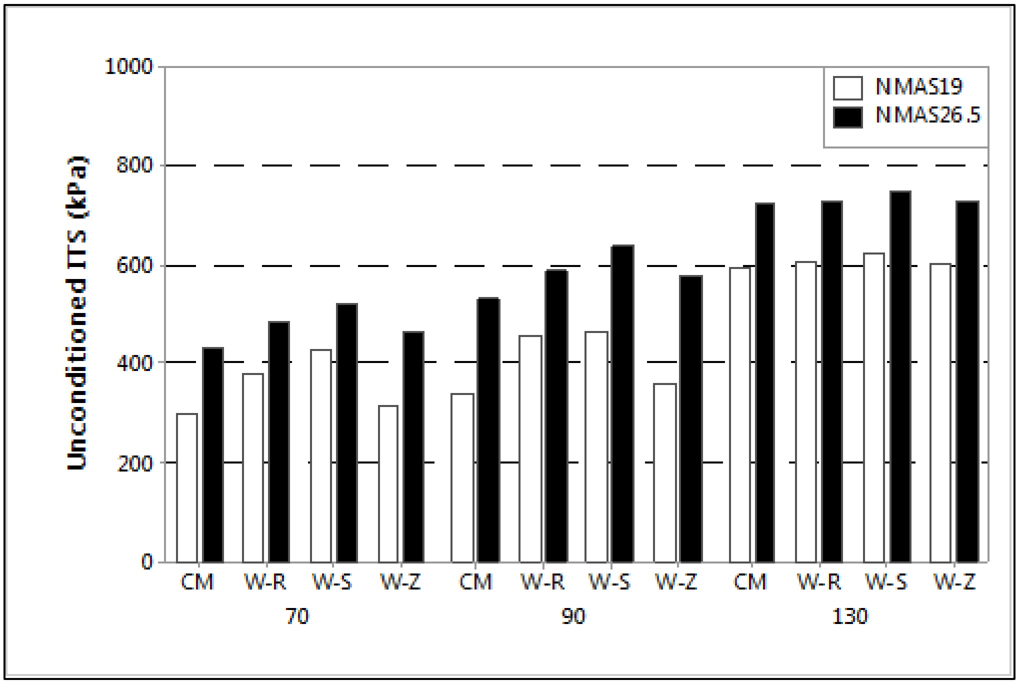

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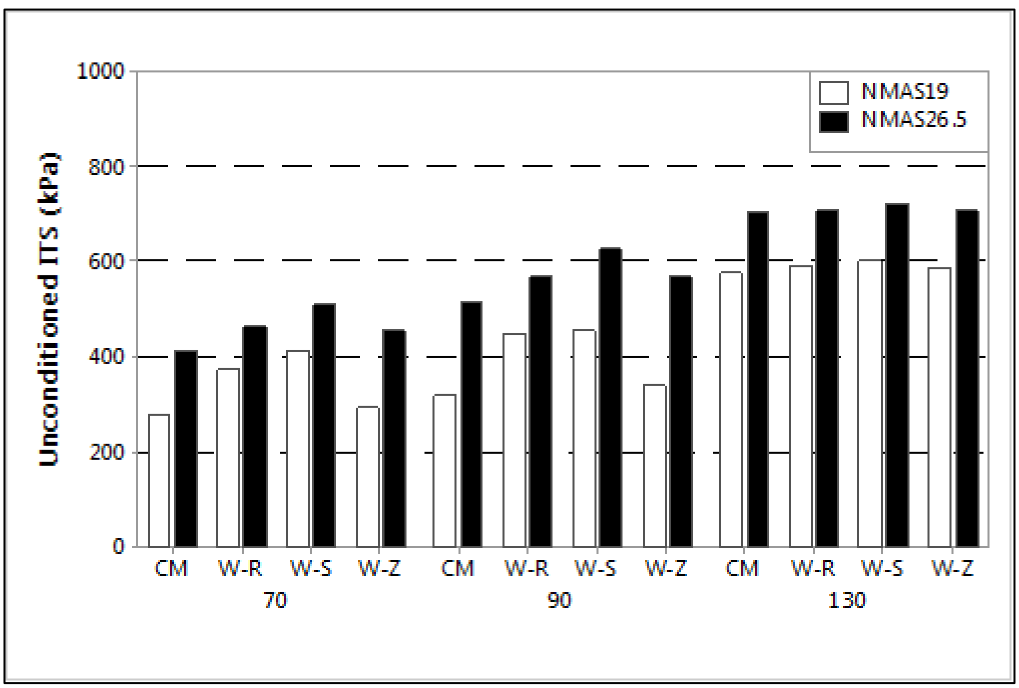
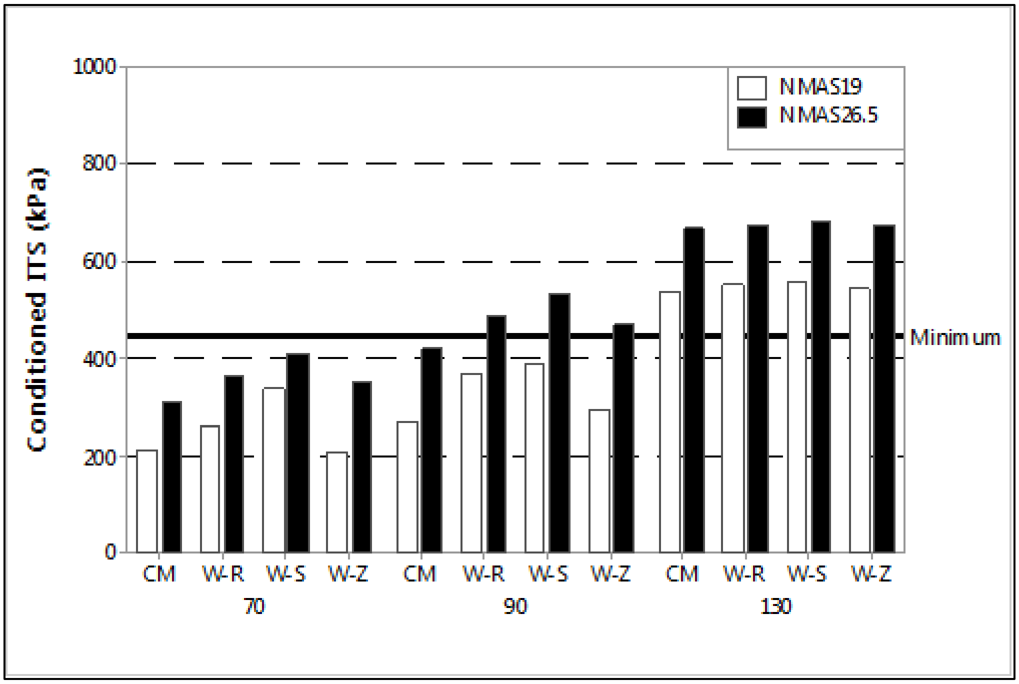


(b)

Fig. 4.20. Unconditioned ITS values

(a) oven dry and (b) surface saturated dry aggregates



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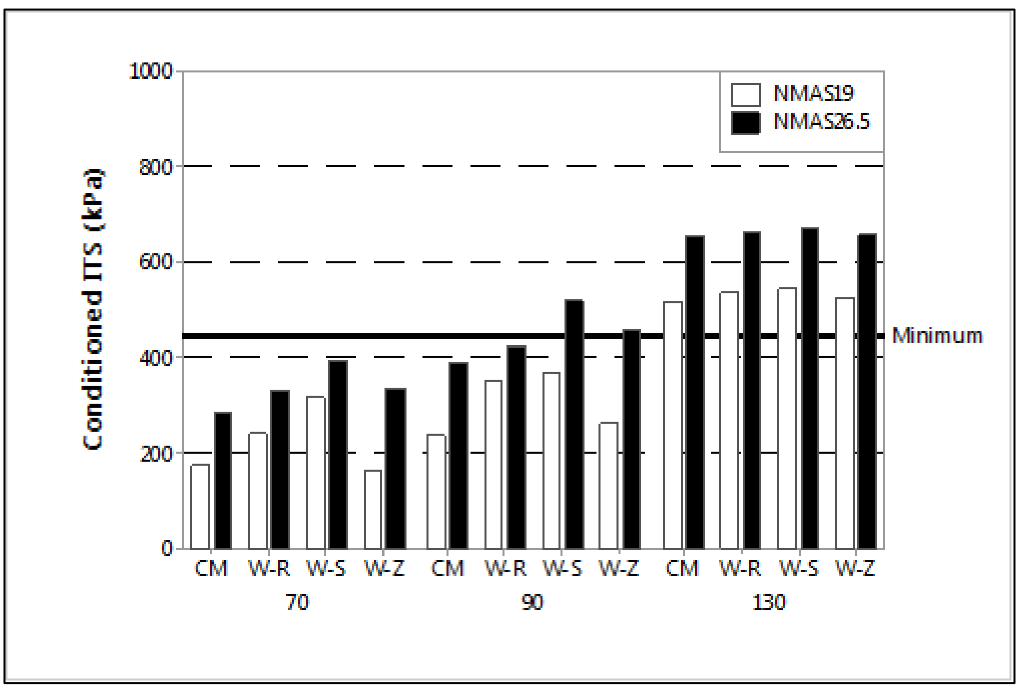
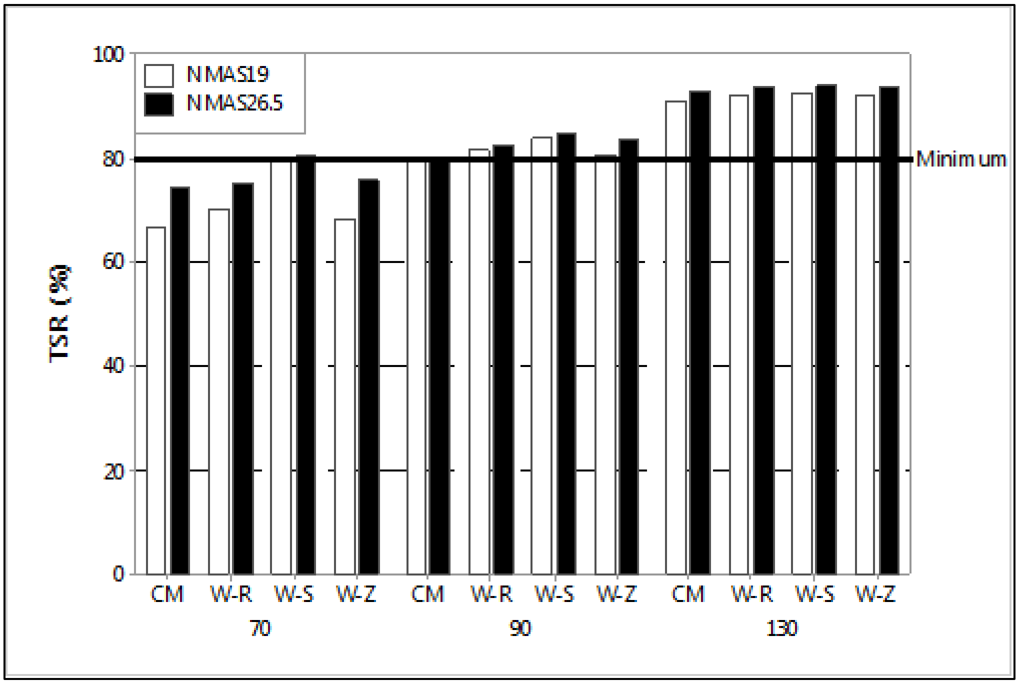


(b)

Fig. 4.21. Conditioned ITS values

(a) oven dry and (b) surface saturated dry aggregates



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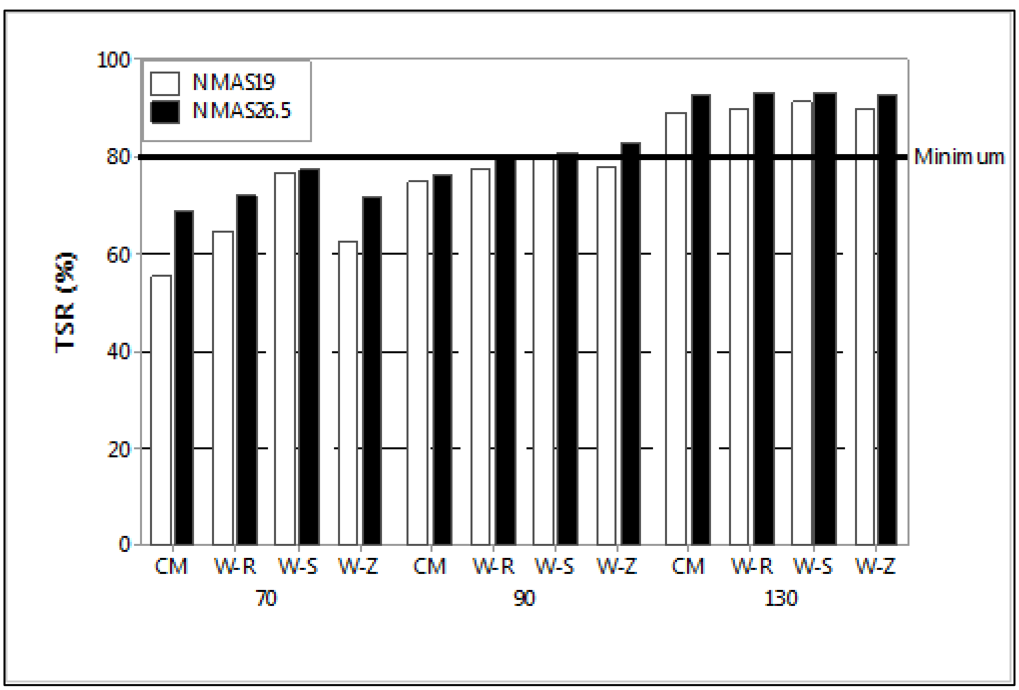


(b)

Fig. 4.22. TSR values (a) oven dry and (b) surface saturated dry aggregates

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

5.1.1 Mix design properties

Mix design properties of asphalt mixtures were evaluated at various working temperature using the Superpave mix design method. The findings are summarized as follows:

- Reduction in working temperature resulted in increase of VTM and VMA, and decrease in VFA values of asphalt mixtures. Furthermore, reduction in working temperature leads to densification problems, resulting in lower G_{mb}.
- Higher N_{des} resulted in lower VTM and VMA, and higher VFA values of asphalt mixtures. WMA and control mixtures compacted at lower working temperature were suitable for higher traffic levels.
- For selected NMAS, working temperature and NMAS, VFA and VMA values of the W-S mixtures were found to be higher than those of CM, W-R, and W-Z mixtures. Subsequently, G_{mb} values of W-R mixtures were higher than those of CM, W-S and W-Z mixtures.
- Design asphalt content of WMA mixtures were found lower than control mixtures and mix design properties were found to be statistically significant for NMAS, N_{des}, working temperature, type of mixture, and binder content.

5.1.2 Workability properties

Workability properties of asphalt mixtures were evaluated for various working temperature using the Locking point and Bahia methods. The findings are summarized as follows:

- NMAS19 mixtures are more workable and less resistance to traffic loading as compared to the NMAS26.5 mixtures. In addition, NMAS19 mixtures undergo aggregate degradation at lower traffic level as compared to the NMAS26.5 mixtures.

- W-S mixtures compacted at 90 °C and 70 °C showed lower CDI values which implies it will take less energy to compact the specimens and higher TDI values indicate that it is more resistance to traffic compared to CM, W-R and W-Z mixtures. However, WMA mixtures compacted at 90 °C and 70 °C showed lower CDI and TDI values than the control mixtures compacted at 130 °C.
- CDI and TDI values calculated using the Bahia and Locking point methods were found to be statistically significant with respect to NMAS, type of mixture, and working temperature.

5.1.3 Rutting properties

Rutting properties of asphalt mixtures were evaluated for various working temperature using WRT. The findings are summarized as follows:

- Rut passes and dynamic stability of asphalt mixtures significantly reduced with the reduction in working temperature. In addition, rut resistance of NMAS26.5 mixtures was found significantly higher than NMAS19 mixtures.
- Rut passes and dynamic stability values were found statistically significant with respect to NMAS, type of mixture, and working temperature.
- W-S mixtures compacted at 90 °C and 70 °C exhibited higher resistance to rutting than those of CM, W-R and W-Z mixtures. However, WMA mixtures compacted at 90 °C and 70 °C showed lower rutting resistance than the control mixtures compacted at 130 °C.

5.1.4 Flexural fatigue properties

Flexural fatigue properties of asphalt mixtures were evaluated for various working temperature using four point bending test. The findings are summarized as follows:

- Flexural strength and fatigue cycles to failure of asphalt mixtures significantly reduced with the reduction in working temperature. In addition, fatigue resistance of NMAS26.5 mixtures were found significantly higher than the NMAS19 mixtures.

- W-S mixtures compacted at 90 °C and 70 °C exhibited higher resistance to fatigue than those of CM, W-R and W-Z mixtures. However, WMA mixtures compacted at 90 °C and 70 °C showed lower fatigue resistance than the control mixtures compacted at 130 °C.
- Flexural strength and fatigue cycles to failure values were found statistically significant with respect to NMAS, type of mixture, and working temperature.

5.1.5 Moisture-induced damage properties

The effect of working temperature moisture-induced damage properties of asphalt mixtures containing oven dry and saturated surface dry aggregates were evaluated using TSR approach. The major conclusions drawn are as follows:

- The reduction in ITS values was significant at lower working temperature regardless of type of mixtures, aggregate condition and NMAS. ITS test results indicate that the asphalt mixtures made with saturated surface dry aggregates exhibited relatively lower ITS value compared to that of mixtures made with oven dry aggregates.
- W-S mixtures compacted at 90 °C and 70 °C exhibited higher resistance to moisture-induced damage, rutting and fatigue than those of CM, W-R and W-Z mixtures. However, WMA mixtures compacted at 90 °C and 70 °C showed lower moisture-induced damage than the control mixtures compacted at 130 °C.
- WMA mixtures prepared with saturated surface dry aggregates were more prone to moisture-induced damage compared to that of WMA mixtures made with oven dry aggregates. In addition, WMA mixtures prepared with surface saturated dry aggregates and compacted at 90 °C and 70 °C marginally fulfilled the minimum TSR requirement.

- Moisture-induced damage properties were found satisfied to be statistically significant with respect to NMAS, type of mixture, working temperature, and aggregate condition.

5.2 RECOMMENDATIONS

This section provides recommendations for the design of WMA mixtures in the light of conclusions of the study performed.

- The variations in the properties of WMA mixtures were found statistically significant in relation to working temperature, and WMA mixtures satisfied the design requirements even at lower compaction temperatures of 90 °C and 70 °C.
- The variations in the mix design properties of WMA mixtures using the Superpave method indicate WMA mixtures compacted at lower working temperature are suitable for higher traffic levels.
- Sasobit is recommended for design of WMA mixtures. These mixtures exhibited higher resistance to moisture-induced damage, rutting and fatigue properties at lower working temperatures. In addition, it is easily workable and more resistant to traffic.
- Among the two aggregate gradations (NMAS26.5 and NMAS19) investigated, mix design, workability and mechanical properties of NMAS26.5 mixtures were significantly higher than the NMAS19 mixtures
- The variations in the moisture-induced damage properties of WMA mixtures were found statistically significant with respect to aggregate condition.

5.3 RECOMMENDATIONS FOR FURTHER RESEARCH

The conclusions drawn and recommendations reported in the above sections are based on the findings of the extensive laboratory studies performed on the WMA mixtures. The following issues need to be addressed in future studies:

- There is a need for performing studies on trial stretches of WMA mixtures on highway, focused on issues pertaining to, the selection of lower working proper mixing and compaction temperature, and design traffic level on long term performance.
- There is a need for evaluating the properties of WMA mixtures at lower working temperature using different binder grades and aggregate sources.
- The properties of WMA mixtures at lower working temperature need to be evaluated using anti stripping agents and recycled aggregates.
- There is a need to validate the properties of WMA mixture properties with respect to rheological and chemical characterisation of WMA modified binders.

APPENDIX A

Example: Calculation of Superpave mix design properties of W-S mixtures (NMAS19) compacted at 90 °C and designed at 75 gyrations.

Consider mixture with 5.5% asphalt content by weight of mixture

- Weight of Aggregate (Including mineral filler) = 1200g
- Weight of the bitumen (Including 3.0% of Sasobit) = 69.63g
- Total weight of the mixture = 1269.63g
- Bulk specific gravity of aggregates, G_{sb} = 2592 kg/m^3
- Maximum theoretical density of loose mixture, G_{mm} = 2428 kg/m^3
- Bulk Density of Specimen, G_{mb} = 2318 kg/m^3
- Air Voids, VTM (%) $= \frac{\text{Gmm}-\text{Gmb}}{\text{Gmm}} \times 100$

  = 4.56
- Aggregate content (% by total weight of mix), P_s = 100 × [1200 / (1200 + 69.63)]

  = 94.51
- Voids in Mineral Aggregate, VMA (%) $= 100 - \frac{\text{Gmb}*\text{Ps}}{\text{Gsb}}$

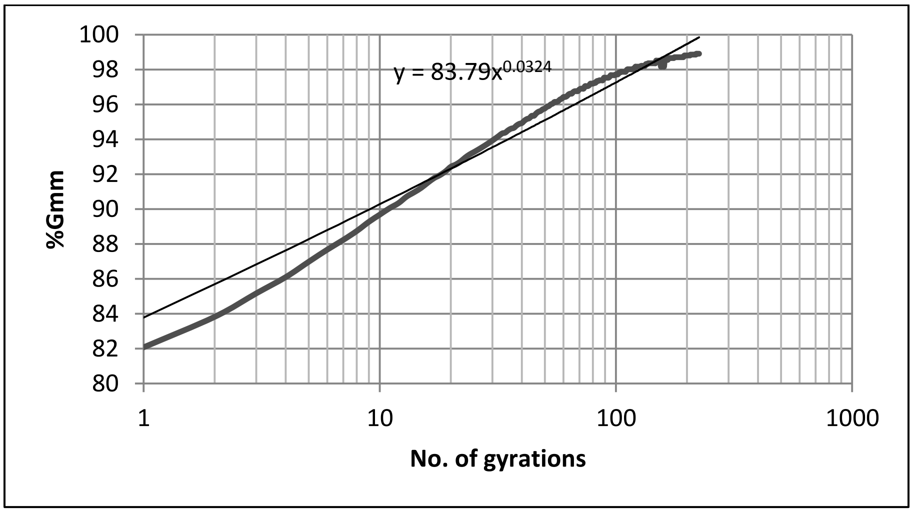
  = 15.49
- Voids Filled with Asphalt, VFA (%) $= \frac{\text{VMA}-\text{VTM}}{\text{VMA}} \times 100$

  = 70.56

APPENDIX B

<u>Example:</u> Calculation of CDI and TDI of CM mixtures (NMAS19) compacted at 130 °C using Locking point and Bahia method.

Consider CM mixture with 6.0% asphalt content by weight of mixture.



A.1. Densification curve showing number of gyrations versus $\%G_{mm}$

<u>Locking Point Method</u>

- Gyrations at aggregate Locking Point (LP) = 49
- $\%G_{mm}$ at 1st Gyration = 82.08%
- $\%G_{mm}$ at 49th Gyration = 95.72%
- $\%G_{mm}$ at 49th Gyration = 95.72%
- $\%G_{mm}$ at 225th Gyration = 98.90%

Using the equation from Fig. A1, calculate area under densification curve from 1st gyration to 49th gyration.

CDI = 450.70

Using the equation from Fig. A1, calculate area under densification curve from 49th gyration to 98% G_{mm} gyration.

TDI = 228.80

<u>Bahia Method</u>

- Gyrations at 92% of G_{mm} = 23
- $\%G_{mm}$ at 8th Gyration = 82.08%
- $\%G_{mm}$ at 92% of G_{mm} Gyration = 92.95%
- $\%G_{mm}$ at 225th Gyration = 98.90%

Using the equation from Fig. A1, calculate area under densification curve from 8th gyration to 92% of G_{mm} gyration.

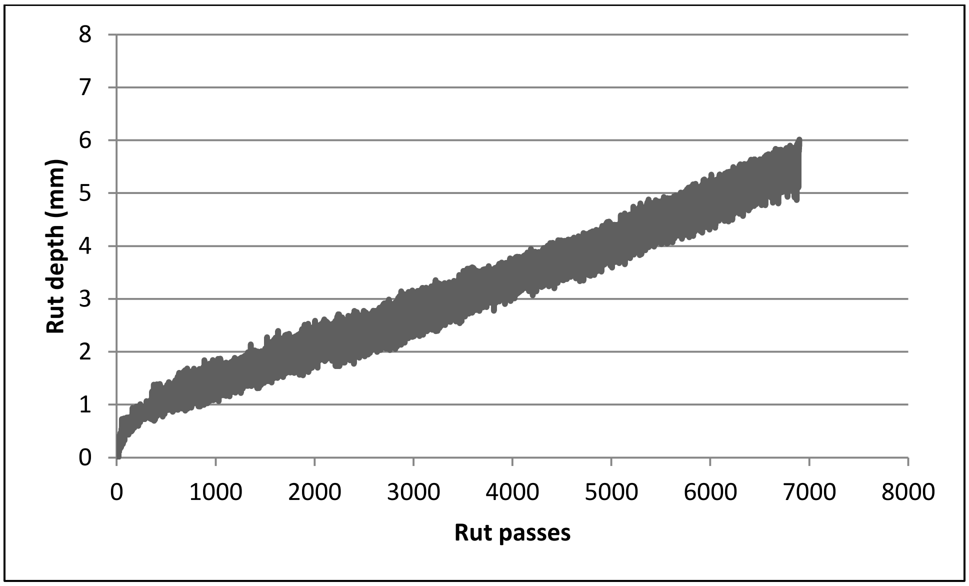
CDI = 39.6

Using the equation from Fig. A1, calculate area under densification curve from 92% of G_{mm} gyration to 225th Gyration.

TDI = 637.8

APPENDIX C

<u>Example:</u> Calculation of rutting properties in terms of rut depth and dynamic stability of CM mixtures (NMAS19) compacted at 90 °C. Consider CM mixture with 6.0% asphalt content by weight of mixture.



A.2. Typical curve showing rut depth versus rut passes of WRT

- Rut passes to 6mm rut depth = 7000
- N_{15} = loading cycles in 15 minutes = 630
- d_{60} = rut depth at the 60 minute = 2.632 mm
- d_{45} = rut depth at the 45 minute = 2.305 mm
- Dynamic stability = $\frac{N_{15}}{d_{60}-d_{45}}$ = 1932 (mm/min)

APPENDIX D

Example: Calculation of flexural fatigue properties in terms of fatigue cycles and flexural strength of W-S mixtures (NMAS19) compacted at 90 °C. Consider W-S mixture with 5.5% asphalt content by weight of mixture.

- Number of fatigue cycles to failure (initial 5mm cracking) = 7558
- ρ = failure load = 1.96 kN
- l = length of the fatigue beam = 280 mm
- b = breadth of the fatigue beam = 75 mm
- d = depth of the fatigue beam = 75 mm.
- Flexural strength = $\frac{\boldsymbol{\rho l}}{\boldsymbol{bd^2}}$ = 2.4 kPa

APPENDIX E

<u>Example:</u> Calculation of Unconditioned and Conditioned ITS values and TSR values of W-S mixtures (NMAS19) prepared with oven dry aggregates compacted at 90 °C. Consider W-S mixture with 5.5% asphalt content by weight of mixture.

Indirect tensile strength, ITS= $\frac{\mathbf{2000}\boldsymbol{P}}{\boldsymbol{\pi D t}}$

<u>Unconditioned ITS specimen</u>

- P= Failure load = 5.17 kN
- D= diameter of specimen = 100 mm
- T= thickness of specimen = 71.5 mm
- ITS = 463.528 kPa

<u>Conditioned ITS specimen</u>

- P= Failure load = 4.35 kN
- D= diameter of specimen = 100 mm
- T= thickness of specimen = 71.5 mm
- ITS = 388.401 kPa

<u>Tensile strength ratio</u>

TSR = $\frac{\boldsymbol{Conditioned\ ITS}}{\boldsymbol{Unconditioned\ ITS}}$

= 83.8%

REFERENCES

AASHTO T 283. (2007). *Standard method of test for resistance of compacted hot-mix asphalt (HMA) to moisture-induced damage*, American Association of State Highway and Transportation Officials, Washington, D.C.

Adriana, V., and David, H. T. (2012). “Rutting characterization of warm mix asphalt and high RAP mixtures.” *Road Materials and Pavement Design*, 13(1), 1-20.

Ahmed, T. A., Elie Y. H., Sebaaly, P. E., and Nate, M. (2013). “Influence of aggregate source and warm mix technologies on the mechanical properties of asphalt mixtures.” *Advances in Civil Engineering Materials*, 2(1), 400–417.

Ajay, S., Animesh, D., and Pandey, B. B. (2000). "Flexural fatigue characteristics of asphalt concrete with crumb rubber." *International Journal of Pavement Engineering*, 1(2), 119-132.

Akisetty, C. K. (2008). “Evaluation of warm asphalt additives on performance properties of CRM binders and mixtures containing warm mix asphalt additive.” Ph.D. Dissertation, Clemson University, Clemson, South Carolina.

Akisetty, C. K., Lee, S. J., and Amirkhanian, S. N. (2009). “Effects of compaction temperature on volumetric properties of rubberized mixtures containing warm-mix additives.” *Journal of Materials in Civil Engineering*, 21(8), 409-415.

Akisetty, C. K., Soon-Jae, L., and Amirkhanian, S. N. (2010). “Laboratory investigation of the influence of warm asphalt additives on long-term performance properties of CRM binders.” *International Journal of Pavement Engin*eering, 11(2), 153-160.

Ala, R. A., Munir, N., Shad, S., Ayman, A., Arjun, R., and Ahmad, A. (2013). “Determining the limitations of warm mix asphalt by water injection in mix design, quality control and placement.” *Report No.FHWA/OH-2013/9*, Ohio Department of Transportation and University of Akron.

Ali, J., Meor, O., Zhanping, Y. (2013). “Performance of warm mix asphalt containing Sasobit: State-of-the-art.” *Construction and Building Materials*, 38, 530–553.

Al-Qadi., Jeff, K., and Jim, M. (2011). “A study on warm-mix asphalt.” *Report No. FHWA ICT-11-085*, Illinois Center for Transportation, University of Illinois, Illinois.

Al-Qadi., Jeff, K., and Jim, M. (2012). “Short-term performance of modified stone matrix asphalt (SMA) produced with warm mix additives.” *Report No.FHWA-ICT-21-001*, Illinois Center for Transportation, University of Illinois, Illinois.

Ambika, B., Gajendra, K., Girish, S., and Jain, P. K. (2013). “Evaluation of field performance of warm-mix asphalt pavements in India.” *Proceedings in 2nd Conference of Transportation Research Group of India (2nd CTRG)*, Agra, India, 104, 158-167.

Amir, K., and Leila, H. (2012). “Laboratory evaluation of moisture damage and rutting potential of WMA foam mixtures.” *International Journal of Pavement Engineering*, 13(5), 415-423.

Arun, G., and Sunil, B. (2013). “Performance of warm mix asphalt for Indian conditions.” *Indian Highways*, 41(9), 29-39.

Ashley, B., Mohamed, R., and Christopher, W. (2011). “Investigation of warm-mix asphalt using IOWA aggregates.” *Report No. IHRB Project TR-599*, Institute for Transportation, Iowa State University, Iowa, USA.

ASTM D 4867/D4867 M. (2004). *Standard test method for effect of moisture on asphalt concrete paving mixtures*, West Conshohocken, Pennsylvania.

Ayman, Ali., Ala, A., Munir, N., Ahmad, A., Arjun, R., and David, P. (2013). “Effect of temperature reduction, foaming water content and aggregate moisture content on performance of foamed warm mix asphalt.” *Construction and Building Materials*, 48, 1058–1066.

Barthel, W., Marchand, J., and Von Devivere, M. (2004). “Warm mix asphalt by adding a synthetic zeolite.” *Proceedings of the Third Eurasphalt and Eurobitumen Conference*, 1, 1241-1249.

Bahia H. U., Friemel, T., Peterson, P., and Russell, J. (1998). "Optimization of constructability and resistance to traffic: a new design approach for HMA using the Superpave gyratory compactor." *Journal of the Association of Asphalt Paving Technologists*, 67, 189–232.

Behnam, K., Ratnasamy, M., Law, T. H., Robiah, Bt., and Abbas S. (2013). "An overview of the emerging warm mix asphalt technology*." International Journal of Pavement Engineering*, 10, 1080/10298436.

Bennert, T. (2012). "Early age rutting potential of warm mix asphalt (WMA)." *Report No. C-10-08*, Center for Advanced Infrastructure and Transportation (CAIT), Rutgers University, New Jersey.

Blades, C., and Kearney, E. (2004). "Asphalt paving principles", *CLRP #04–3*, Cornell Local Roads Program

Bonaquist, R. F. (2011). "Mix design practices for warm mix asphalt," *NCHRP 691*, Transportation Research Board, USA.

Bower, N., Wen, H., Wu, S., Willoughby, K., Weston, J., and DeVol, J. (2012). "Evaluation of the performance of warm mix asphalt in Washington State." *International Journal of Pavement Engineering*, 17(5), 423-434.

Burak, S., Ali, T., and Cagri, G. (2013a). "Evaluation of moisture characteristics of warm mix asphalt involving natural zeolite." *Road Materials and Pavement Design*, 14(4), 933-945.

Burak, S., Ali, T., and Cagri, G. (2013b). "Evaluation of natural zeolite as warm mix asphalt additive and its comparison with other warm mix additives." *Construction and Building Materials*, 43, 242–252.

Burak, S., and Julide, O. (2013c). "Utilization of recycled asphalt concrete with different warm mix asphalt additives prepared with different penetration grades bitumen." *Construction and Building Materials*, 45, 173–183.

Button, J. W., Cindy, E., and Andrew, W. (2007). "A synthesis of warm-mix asphalt." *Report No. SWUTC/07/0-5597-1*, Texas Transportation Institute, Texas, USA.

Button, J. W., Cindy, E., and Andrew, W. (2010). "Field and laboratory investigation of warm mix asphalt in Texas." *Report No. FHWA/TX-10/0-5597-2*, Texas Transportation Institute, Texas, USA.

Capitao, S. D., Picado-Santos, L. G., and Martinho, F. (2012). "Pavement engineering materials: Review on the use of warm-mix asphalt." *Construction and Building Materials*, 36, 1016–1024.

Carmen, R., German, M., Luis, B., and Fernando, M. (2012). "Warm mix asphalt: an overview." *Journal of Cleaner Production*, 24, 76-84.

Chowdhury, A. and Button, J. W. (2008). "A review of warm mix asphalt." *Report No.SWUTC/08/473700-00080-1*, Texas Transportation Institute, Texas, USA.

Cooper III, S. B., Mohammad, L. N., & Elseifi, M. A. (2011). "Laboratory performance characteristics of Sulfur-modified warm-mix asphalt." *Journal of Materials in Civil Engineering*, 23(9), 1338-1345.

D'Angelo., Eric, H., John, B., Gaylon, B., Matthew, C., Jack, C., Thomas, H., Mostafa, J., Wayne, J., Dave, N., Brian, P., Ron, S., and Bruce, Y. (2008). "Warm mix asphalt: European practice." *Report No. FHWA-PL-08-007*, Federal Highway Administration, U.S. Dept. of Transportation, Washington, DC.

Diefenderfer, S., & Hearon, A. (2008). "Laboratory evaluation of warm asphalt technology for use in Virginia." *Report No. VTRC 09-R11*, Virginia Transportation Research Council, U.S Department of Transportation, USA.

Dinis-Almeida, M., Castro-Gomes, J., and Lurdes, A. (2012). "Mix design considerations for warm mix recycled asphalt with bitumen emulsion." *Construction and Building Materials*, 28, 687–693.

Elsa, S. A., Angel, V. Z., Daniel, C. F., and Maria, D. P. (2011). "Evaluation of compactability and mechanical properties of bituminous mixtures with warm additives." *Construction and Building Materials*, 25(5), 2304–11.

Elsa, S. A., Angel, V. Z., and Daniel, C. F. (2012). "Effect of type of compaction on mechanical properties in warm-mix asphalts." *Journal of Materials in Civil Engineering*, 24(8), 1043-1049.

Ebrahim, S., Hassan, Z., and Ali, M. (2012). "The effect of aggregate gradation on creep and moisture susceptibility performance of warm mix asphalt." *International Journal of Pavement Engineering*, 10, 1080/10298436.

Elie, Y. H. and Edward, M. C. (2011). “Evaluation of the Cecabase warm-mix additive.” *University Of Nevada Reno in association with CECA Arkema Group,* Nevada, USA.

EN, B. (2002). 12697-22. *Test Methods for Hot Mix Asphalt, Part-22, Wheel Tracking.* European Standard, UK.

Emanuele, T., Claudio, B., and Edoardo, M. (2013) “Laboratory investigation into the effects of working temperatures on wax-based warm mix asphalt.” *Construction and Building Materials*, 44, 774–780.

EPA. (2000). “Hot mix asphalt plants emission assessment report.” *EPA-454/R-00-019* United States Environmental Protection Agency, USA.

European Asphalt Pavement Association. (2010). “The use of warm mix asphalt.” EAPA position paper. <www.eapa.org.>

Estakhri, C., Button, J., and Alvarez, A. E. (2010). “Field and laboratory investigation of warm mix asphalt in Texas.” *Report No.FHWA/TX-10/0-5597-2,* Texas A&M University, Texas, USA.

Fakhri, M., Ghanizadeh, A. R., and Omrani, H. (2013). “Comparison of fatigue resistance of HMA and WMA mixtures modified by SBS.” *Proceedings in 2nd Conference of Transportation Research Group of India (2nd CTRG)*, Agra, India, 104, 168 – 177.

Feipeng, X., Wenbin, Z., and S. N. Amirkhanian. (2009). “Fatigue behavior of rubberized asphalt concrete mixtures containing warm asphalt additives." *Construction and Building Materials*, 23, 3144–3151.

Feipeng, X., Wenbin, Z., Tejash, G., and S. N. Amirkhanian. (2010a). “Influence of antistripping additives on moisture susceptibility of warm mix asphalt mixtures.” *Journal of Materials in Civil Engineering*, 22(10), 1047-1055.

Feipeng, X., and S. N. Amirkhanian. (2010b). “Effects of liquid antistrip additives on rheology and moisture susceptibility of water bearing warm mixtures.” *Construction and Building Materials*, 24, 1649–1655.

Feipeng, X., Bradley, P., V. S. Punith., and S. N. Amirkhanian. (2011). "Utilization of foaming technology in warm-mix-asphalt mixtures containing moist aggregates." *Construction and Building Materials*, 23, 1328-1337.

Feipeng, X., V. S. Punith., and S. N. Amirkhanian. (2012a). "Low-volume road WMA mixtures: Moisture susceptibility of mixtures containing coal ash and roofing shingle with moist aggregate." *Construction and Building Materials*, 24, 48-56.

Feipeng, X., Punith, V. S., and S. N. Amirkhanian. (2012b). "Effects of non-foaming WMA additives on asphalt binders at high performance temperatures." *Fuel*, 94, 144–155.

Feipeng, X., V. S. Punith, and Bradley, J. P. (2013a). "Effect of compaction temperature on rutting and moisture resistance of foamed warm-mix-asphalt mixtures." *Journal of Materials in Civil Engineering*, 25(9), 1344-1352.

Feipeng, X., V. S. Punith., S. N. Amirkhanian., and Carl, T. (2013b). "Improved resistance of long-term aged warm-mix asphalt to moisture damage containing moist aggregates." *Journal of Materials in Civil Engineering*, 25(7), 913-922.

Fereidoon, M. N., and Alireza, A., Gholam, H. H., and Hossein, R. (2014). "Rutting performance prediction of warm mix asphalt containing reclaimed asphalt pavements." *Road Materials and Pavement Design*, 15(1), 207-219.

Francisco, M., Rosana, M., and Gonzalo, C. (2012). "Rheological properties of asphalt binders with chemical tensoactive additives used in Warm Mix Asphalts (WMAs)." *Construction and Building Materials*, 29, 135–141.

Gandhi, T. (2008). "Effects of warm asphalt additives on asphalt binder and mixtures properties." Ph.D. Dissertation, Clemson University, Clemson, South Carolina, USA.

Gandhi, T., William, R., and Amirkhanian, S. N. (2010). "Laboratory evaluation of warm mix asphalt ageing characteristics." *International Journal of Pavement Engineering*, 11(2), 133-142.

Gautam, B. N. (2013). "Warm mix design of bituminous concrete using Rediset WMX." *GRA - Global Research Analysis*, 2(6), 70-73.

Gui-juan, Z., and Ping, G. (2012). “Workability of Sasobit warm mixture asphalt.” *Proceedings in International Conference on Future Energy, Environment, and Materials,* Hong Kong, 16, 1230 – 1236.

Gaudefroy, V., Olard, F., Cazacliu, B., de La Roche, C., Beduneau, E., and Antoine, J. P. (2007). “Laboratory investigations of mechanical performance of foamed bitumen mixtures that use half-warm aggregates.” *Journal of the Transportation Research Board-1998,* 89-95.

Hanz, A., Faheem, A., Mahmoud, E., and Bahia, H. (2010). "Measuring effects of warm-mix additives: Use of newly developed asphalt binder lubricity test for the dynamic shear rheometer." *Journal of the Transportation Research Board-2180,* 85-92.

Hill, B. (2011). “Performance evaluation of warm mix asphalt mixtures incorporating reclaimed asphalt pavement.” Master of Science in Civil Engineering thesis, University of Illinois, Illinois.

Hurley, G., and Prowell, B. (2005a). “Evaluation of Aspha-Min zeolite for use in warm mix asphalt.” *National Center for Asphalt Technology (NCAT) Report No. 05-04*, Auburn, Alabama.

Hurley, G., and Prowell, B. (2005b). “Evaluation of Sasobit for use in warm mix asphalt.” *National Center for Asphalt Technology (NCAT) Report No. 05-06,* Auburn, Alabama.

Hurley, G., and Prowell, B. (2006a). “Evaluation of Evotherm for use in warm mix asphalt.” *National Center for Asphalt Technology (NCAT) Report No. 06-02,* Auburn, Alabama.

Hurley, G., and Prowell, B. (2006b). “Evaluation of potential processes for use in warm mix asphalt.” *National Center for Asphalt Technology (NCAT) Report No. 06-04*, Auburn, Alabama.

Hajj, E., and Cortez, E. (2011). “Evaluation of the Cecabase™ Rt warm-mix additive.” M-Tech report, Department of Civil and Environmental Engineering, University of Nevada, USA.

Hamzah, M. O., Jamshidi, A., Shahadan, M. R., and Yahaya, A. S. (2010). “Evaluation of engineering properties and economic analysis.” *Journal of Applied Sciences*, 10(20), 2433-2439.

Hamzah, M. O., Golchin, B., Jamshidi, A., and Chailleux, E. (2015). "Evaluation of Rediset for use in warm-mix asphalt: A review of literatures." *International Journal of Pavement Engineering*, 16 (9), 809-831.

Hossain, Z., Bhudhala, A., Zaman, M., O’Rear, E., Cross, C., and Lewis, S. (2009). “Evaluation of the use of warm mix asphalt as a viable paving material in the United States.” *Cooperative Agreement: DTFH61-06-H-00044: Task 3*, College of Engineering, University of Oklahoma, Norman, Oklahoma.

Hossain, Z., Zaman, M., O’Rear, E., and Dar-Hao, C. (2012). “Effectiveness of water-bearing and anti-stripping additives in warm mix asphalt technology.” *International Journal of Pavement Engineering*, 13(5), 424-432.

Hugo, M. R., Joel, R. M., Joana, P., and Salah, E. Z. (2010a). “Optimization of warm mix asphalts using different blends of binders and synthetic paraffin wax contents.” *Construction and Building Materials*, 24, 1621–1631.

Hugo, M. R., Joel, R. M., Claudia, I., and Paulo, A. A. (2010b). “Assessment of the performance of warm mix asphalts in road pavements.” *International Journal of Pavement Research and Technology*, 3(3), 119-127.

IRCSP 11. (2014). *The interim guidelines for warm mix asphalt*. Indian Road Congress, New Delhi, India.

James, C. N. and Donna, J. (2011). “Literature review of lower temperature asphalt systems.” *Proceedings of the Institution of Civil Engineers*, 1100051.

James, E. W., and Bradley, J. P. (2013). “Laboratory evaluation of warm-mix open graded friction course mixtures.” *Journal of Materials in Civil Engineering*, 25(3), 403-410.

Jamshidi, A., Hamzah, M. O., and You, Z. (2013). “Performance of warm mix asphalt containing Sasobit: State-of-the-art.” *Construction and Building Materials*, 38, 530–553.

Jean, M. C. and Bernard, T. (2008). “Warm mix asphalt paving technologies: A road builder’s perspective.” *Paper presentation of annual conference,* Transportation Association of Canada.

Jenkins, K. (2000). “Mix design considerations for cold and half-warm bituminous mixtures with emphasis on foamed bitumen.” Doctoral Dissertation, Stellenbosch University, Stellenbosch, South Africa.

Jesse, D. D., and Isaac, L. H. (2013). “Rutting and moisture damage resistance of high reclaimed asphalt pavement warm mixed asphalt: loaded wheel tracking vs. conventional methods.” *Road Materials and Pavement Design*, 14(2), 148-172.

Jianchuan, C., Junan, S., and Feipeng, X. (2011). “Moisture susceptibility of warm-mix asphalt mixtures containing Nano sized hydrated lime.” *Construction and Building Materials*, 23, 1552-1559.

Joel, R. M. O., Hugo, M .R. D., Liliana, P.F. A., Juan, A. G. (2012). “The role of a surfactant based additive on the production of recycled warm mix asphalts – Less is more.” *Construction and Building Materials*, 35, 693–700.

Joel, R. M. O., Hugo, M .R. D., Liliana, P.F. A., Sara, R. M. F. (2013). “Use of a warm mix asphalt additive to reduce the production temperatures and to improve the performance of asphalt rubber mixtures.” *Journal of Cleaner Production*, 41, 15-22.

John, F. R., and Mareily, M. S. (2013). “Assessment of warm mix asphalt (WMA) for heavy traffic airfields.” *92nd Annual Meeting (CD-ROM),* Transportation Research Board, Washington, D.C.

Jun, Z. (2010). “Effects of warm-mix asphalt additives on asphalt mixture characteristics and pavement performance.” Master's thesis, University of Nebraska, Lincoln.

Kandhal, S. P. (2010). “Warm mix asphalt technologies: an overview.” *Indian Roads Congress*, 144(561).

Kandhal, S. P., and Allen C. L. (2003). "Accelerated laboratory rutting tests: Evaluation of the asphalt pavement analyzer." *NCHRP 508,* Transportation Research Board, Washington, D.C.

Kai, S., Ryota, M., and Yoshitaka, H. (2009). “Laboratory evaluation of WMA mixture for use in airport pavement rehabilitation.” *Construction and Building Materials*, 23, 2709–2714.

Kanitpong, K., Sonthong, S., Nam, K., Martono, W., and Bahia, H. U. (2007). "Laboratory study on warm-mix asphalt additives." *86th Annual Meeting (CD-ROM),* Transportation Research Board, Washington, D.C.

Kanitpong, K., Charoentham, N., and Likitlersuang, S. (2012). “Investigation on the effects of gradation and aggregate type to moisture damage of warm mix asphalt modified with Sasobit.” *International Journal of Pavement Engineering*, 13(5), 451-458.

Kavussi, A., Qorbani, M., Khodaii, A., and Haghshenas, H. F. (2014). “Moisture susceptibility of warm mix asphalt: A statistical analysis of the laboratory testing results.” *Construction and Building Materials*, 52, 511–517.

Koenders, B. G., Stoker, D. A., Bowen, C., De Groot, P., Larsen, O., Hardy, D., & Wilms, K. P. (2000). "Innovative processes in asphalt production and application to obtain lower operating temperatures.” *2nd Eurasphalt & Eurobitume Congress*, Barcelona, Spain.

Ke-zhen, Y., Hong-bin, X., and Heng-long, Z. (2013). “Effect of mineral filler on properties of warm asphalt mastic containing Sasobit.” *Construction and Building Materials*, 48, 622–627.

Khodaii, A., Kazemi, T., Haghshenas, H. (2012). “Hydrated lime effect on moisture susceptibility of warm mix asphalt.” *Construction and Building Materials*, 36, 65–170.

Kim, H., Soon-Jae, L., Amirkhanian, S. N. (2012a). “Influence of warm mix additives on PMA mixture properties.” *Journal of Transportation Engineering*, 138(8), 991-997.

Kim, Y., Zhang, J., and Ban, H. (2012b). “Moisture damage characterization of warm-mix asphalt mixtures based on laboratory-field evaluation.” *Construction and Building Materials*, 31, 204–11.

Kim, H., Soon-Jae, L., S. N. Amirkhanian., and Kyu-Dong, J. (2013). "Quantification of oxidative aging of polymer-modified asphalt mixtures made with warm mix technologies." *Journal of Materials in Civil Engineering*, 25(1), 1-8.

Kristjansdottir, O., Michael, L., Muench, S.T., and Burke, G. (2006). "Assessing the potential for warm mix technology adoption." *86th Annual Meeting*, *(CD-ROM),* Transportation Research Board, Washington, D.C.

Kristjansdottir, O. (2007). "Warm mix asphalt technology adoption." *NVF 33 Annual meeting*, Norway.

Kunnawee, K., Nuttaporn, C., and Suched, L. (2012). "Investigation on the effects of gradation and aggregate type to moisture damage of warm mix asphalt modified with Sasobit." *International Journal of Pavement Engineering*, 13(5), 451-458.

Kvasnak, A., Prowell, B and Hurley, G. (2009). "Engineering properties, emissions, and field performance of warm mix asphalt technologies." *National Center for Asphalt Technology, NCHRP 9-47A Interim Report (1)*, Auburn, Alabama.

Lee, S. J., Amirkhanian, S. N., Thodesen, C., and Shatanawi, K. (2006). "Effect of compaction temperature on rubberized asphalt mixes." *Proceedings of the asphalt rubber*, 3, 583-97.

Lee, M. S., Kim, S., & Kim, K. W. (2012). "Estimation of optimum compaction temperature for PMA and WMA mixtures by volumetric property evaluation." *Journal of Testing and Evaluation*, 40(3), 463-475.

Leiva, F. and West, R. (2008). "Analysis of hot–mix asphalt lab compactability using lab compaction parameters and mix characteristics." *Journal of the Transportation Research Board-2057*, 89–98.

Liu, J. (2010). "Evaluation of warm mix asphalt for Alaska conditions." *Report No. FHWA-AK-RD-12-12*, Alaska University Transportation Center, Alaska.

Liu, J., Saboundjian, S., Li, P., Connor, B., and Brunette, B. (2011). "Laboratory evaluation of Sasobit-modified warm-mix asphalt for Alaskan conditions." *Journal of Materials in Civil Engineering*, 23(11), 1498-1505.

Louay, N. M. and Khalid, A. S. (2007). "A look at the bailey method and locking point concept in super pave mixture design." *Transportation Research Circular No E-C124.,* Transportation Research Board, 17-37.

Liantong, M., Xun, L., Xing, F., M. Huurman., and Shaopeng, W. (2012). "Laboratory investigation of compaction characteristics and performance of warm mix asphalt containing chemical additives." *Construction and Building Materials*, 37, 239–247.

Mansour, F., Ali, R. G., and Hamed, O. (2013). "Comparison of fatigue resistance of HMA and WMA mixtures modified by SBS". *Proceedings in 2nd Conference of Transportation Research Group of India (2nd CTRG),* Agra, India, 104, 168 – 177

Marcelo, S. M., Jo Sias, D., Heather, L. B., and William, C. M. (2012). "Evaluation of moisture and low-temperature cracking susceptibility of warm-mixture asphalt." *International Journal of Pavement Engineering*, 13(5), 395-400.

Martinsh, Z., and Viktors, H. (2010). "Research on properties of warm mix asphalt." *Scientific Journal of Riga Technical University,* 11, 77-84.

MeadWestvaco. (2009). "Evotherm warm mix asphalt in crow wing county, Minnesota: Eliminating thermal cracking at reduced cost." MWV Asphalt Innovations, North Charleston.<www.meadwestvaco.com>

Meor, O. H., Mohamad, Y. A., and Zulkurnain, S. (2011). "Resistance to disintegration of warm porous asphalt incorporating Sasobit." *Australian Journal of Basic and Applied Sciences*, 5(9), 113-121.

Middleton, B., and Forfylow, B. (2008). "An evaluation of warm mix asphalt produced with the Double barrel green process." *7th International Conference on Managing Pavement Assets*, Calgary, AB.

Ministry of Road Transport and Highway. (2013). *Specifications for road and bridge works.* 5th Revision, Indian Road Congress, New Delhi, India.

Mohd, R. M. H., Shu, W.G., and Zhanping, Y. (2013). "Comparative study on the properties of WMA mixture using foamed admixture and free water system." *Construction and Building Materials*, 4, 45–50.

Malladi, H., Ayyala, D., Tayebali, A. A. and Khosla, N. P. (2015). "Laboratory evaluation of warm-mix asphalt mixtures for moisture and rutting susceptibility." *Journal of Materials in Civil Engineerin*g, 27(5), 401-416.

Martin, A. E. (2014). "Evaluation of the moisture susceptibility of WMA technologies," *NCHRP 763*, Transportation Research Board, Washington, D.C.

Mo, L., Li, X., Fang, X., Huurman, M., and Wu, S. (2012). "Laboratory investigation of compaction characteristics and performance of warm mix asphalt containing chemical additives." *Construction and Building Materials*, 37, 239–247.

Moghadas Nejad, F., Azarhoosh, A., Hamedi, G. H. and Roshani, H. (2014). "Rutting performance prediction of warm mix asphalt containing reclaimed asphalt pavements." *Road Materials and Pavement Design*, 15(1), 207-219.

Ministry of Road Transport and Highway. (2013). "Specifications for road and bridge works." *5th Revision*, Indian Road Congress.

Mirzababaei, P. (2016). "Effect of Zycotherm on moisture susceptibility of Warm Mix Asphalt mixtures prepared with different aggregate types and gradations," *Construction and Building Materials*, 116, 403-412.

Nishant, M. S. (2010). “Evaluation of selected warm mix asphalt additives.” Master's thesis, University of Iowa, University of Iowa, Iowa.

Newcomb, D. (2007). “An introduction to warm-mix asphalt.” *National Asphalt Pavement Association*, Lanham, Maryland.

Nathan, B., Haifang, W., Kim, W., Jim, W., and Joe, D. (2012). “Evaluation of the performance of warm mix asphalt in Washington State.” *REPORT NO. WA-RD 789.1*, Washington State University, Dept. of Civil and environmental Engineering, Pullman.

Nazimuddin, M. W., Rajan, S., William, K., and Louay, M. (2012). “Effects of temperature and shear rate on viscosity of Sasobit® modified asphalt binders.” *International Journal of Pavement Research and Technology*, 5(6), 369-378.

Prabir, K. D., Yuksel, T., and Bjorn, B. (2012a). “Evaluation of fracture and moisture damage performance of wax modified asphalt mixtures.” *Road Materials and Pavement Design*, 13(1), 142-155.

Prabir, K. D., Yuksel, T., and Bjorn, B. (2012b). “Low temperature cracking performance of WMA with the use of the Superpave indirect tensile test.” *Construction and Building Materials*, 30, 643–649.

Prowell, B. and Hurley, G. (2007). “Warm-mix asphalt: Best Practices” *Quality improvement series, National Asphalt Pavement Association,* Lanham, Maryland.

Petit, C., Millien, A., Canestrari, F., Pannunzio, V., and Virgili, A. (2012). “Experimental study on shear fatigue behavior and stiffness performance of Warm Mix Asphalt by adding synthetic wax.” *Construction and Building Materials*, 34, 537–544.

Punith, V. S., Feipeng, X., and Amirkhanian, S. N. (2011a). “Effects of moist aggregates on the performance of warm mix asphalt mixtures containing non-foaming additives.” *Construction and Building Materials*, 39(5), 847–857.

Punith, V. S., Xiao, F., and Amirkhanian, S. N. (2011b). “Performance of warm mix asphalt mixtures containing recycled coal ash and roofing shingles with moist aggregates for low volume roads.” *Journal of Transportation Research Record-2205*, 48–57.

Punith V. S., Feipeng, X., and Amirkhanian, S. N. (2012). “Evaluation of moisture sensitivity of stone matrix asphalt mixtures using polymerized warm mix asphalt technologies.” *International Journal of Pavement Engineering*, 13(2), 152-165.

Punith, V. S., Feipeng, X., and David, W. (2013). “Performance characterization of half warm mix asphalt using foaming technology.” *Journal of Materials in Civil Engineering*, 25(3), 382-392.

Punith, V. S., Xiao, X., and Amirkhanian, S. N. (2011). “Effects of moist aggregates on the performance of warm mix asphalt mixtures containing non-foaming additives.” *Construction and Building Materials*, 39(5), 847–857.

Rubio, M. C., Martínez, G., Baena, L., & Moreno, F. (2012). “Warm mix asphalt: an overview.” *Journal of Cleaner Production*, 24, 76-84.

Sanchez-Alonso, E., Vega-Zamanillo, A., Castro-Fresno, D. and DelRio-Prat, M. (2011). "Evaluation of compactability and mechanical properties of bituminous mixes with warm additives." *Construction and Building Materials,* 25, 2304–2311.

Schmitt, R., Johnson, C., Bahia, H., and Hanz, A. (2009). “Effects of temperature and compaction effort on field and lab densification of HMA.” *Journal of Association of Asphalt Paving Technology*, 78, 171–208.

South Carolina DOT. (2011). "*Supplemental technical specifications for hot-mix asphalt material properties SCDOT designation*." *SC-M-402 (2/13),* South Carolina.

Stakston, A., Bahia, H., and Bushek, J. (2002). “Effect of fine aggregate angularity on compaction and shearing resistance of asphalt mixtures.” *Journal of the Transportation Research Board*, 1789, 14–24.

Sheng, Z., Baoshan, H., Xiang, S., and Mark, W. (2013). “Comparative evaluation of warm mix asphalt containing high percentages of reclaimed asphalt pavement.” *Construction and Building Materials,* 44, 92–100.

Shu, W. G., and Zhanping, Y. (2012). “Mechanical properties of porous asphalt pavement materials with warm mix asphalt and RAP.” *Journal of Materials in Civil Engineering*, 138(1), 90-97.

Shu, W. G., Mohd, R. M. H., and Zhanping, Y. (2013). “Performances evaluation of Cecabase® RT in warm mix asphalt technology.” *Proceedings in 13th COTA International Conference of Transportation Professionals (CICTP 2013),* China, 96, 2782 – 2790

Stacey, P. E., and Amy, H. (2008). “Laboratory evaluation of warm asphalt technology for use in Virginia*.” Report No. VTRC 09-R11*, Virginia Transportation Research Council, U.S Department of Transportation, USA.

Shad, S., Munir, D. N., Abdalla, A., and David, P. (2012). “Field evaluation of warm-mix asphalt technologies.” *Journal of Materials in Civil Engineering*, 24(11), 1343-1349.

Sundaram, L., and Angelo, A. (2008). “Surface active bitumen additive for warm mix asphalt with adhesion promoting properties.” Akzo Nobel Surface Chemistry LLC.

Szabolcs, B., Gandhi, T., and Amirkhanian, A. N (2009). “Determination of zero shears viscosity of warm asphalt binders.” *Construction and Building Materials*, 23, 2080–2086

The Asphalt Rubber Technology Service (ARTS) (2010). “Crumb rubber-modified warm-mix asphalt study.” South Carolina’s Department of Health and Environmental Control (DHEC) and Clemson University. <www.ces.clemson.edu/arts/.>

The Asphalt Institute. (2001). *"Superpave Mix Design*." *Superpave Series No. 2 (SP-02)*, Asphalt Institute. Lexington, Kentucky.

Vargas-Nordcbeck, A., and Timm, D. H. (2012). “Rutting characterization of warm mix asphalt and high RAP mixtures.” *Road Materials and Pavement Design*, 13(1), 1-20.

Vavrik, W., Fries, R., and Carpenter, S. (1999). “Effect of flat and elongated coarse aggregate on characteristics of gyratory compacted samples.” *Journal of the Transportation Research Board*, 1338, 28–36.

Vaitkus, A., Cygas, D., Laurinavicius, A., and Perveneckas, Z. (2008). “The research on the use of warm mix asphalt for asphalt pavement structures.” *Report No. 10223*, Vilnius Gediminas Technical University, Vilnius.

Vavrik, W. R., and Carpenter, S. H. (1998). "Calculating air voids at specified number of gyrations in superpave gyratory compactor.' *Journal of the Transportation Research Board*, 1630, 117–125.

Walaa, M., Alexander, A., Louay, M., and Emin, K. (2013). “Evaluation of high RAP-WMA asphalt rubber mixtures.” *Road Materials and Pavement Design*, 14(2), 129-147.

Wang, Y., Jingwen, Z., Liping, L., and Lijun, S (2013). “Gradation evaluation of asphalt rubber mixture with warm-mix additive.” *Proceedings in 13th COTA International Conference of Transportation Professionals (CICTP 2013)*, China, 96, 31 – 38.

Wenbin, Z., Feipeng, X., Amirkhanian, A. N., and Bradley, J. P. (2012). “Characterization of rutting performance of warm additive modified asphalt mixtures.” *Construction and Building Materials*, 31, 265–272.

Xiang, S., Baoshan, H., Emily, D. S., and Xiaoyang, J. (2012) “Laboratory evaluation of moisture susceptibility of foamed warm mix asphalt containing high percentages of RAP.” *Construction and Building Materials,* 35, 125–130.

Xin, Y., Yuhong, W., and Yilin, L. (2013a). “Impacts of water content on rheological properties and performance-related behaviors of foamed warm-mix asphalt.” *Construction and Building Materials*, 48, 203–209.

Xin, Y., Yuhong, W., and Yilin, L. (2013b). “Effects of types and content of warm-mix additives on CRMA.” *Journal of Materials in Civil Engineering*, 25(7), 939-945.

Xiao, F., Punith, V. S. and Putman, B. J. (2013). “Effect of compaction temperature on rutting and moisture resistance of foamed warm-mix-asphalt mixtures.” *Journal of Materials in Civil Engineering,* 25(9), 1344-1352.

Yiqiu, T., Meng, G., Huining, X., and Rui, Z. (2012). “Comparative study on laboratory performance of hot and warm-mix asphalt mixtures.” *Journal of Testing and Evaluation*, 40(5), 1-9.

Zaumanis, M. (2010). “Warm mix asphalt investigation.” Master of Science thesis, Department of Civil Engineering, Technical University of Denmark, Denmark.

Zelalem, A., and Amit, B. (2012). “Binder rheology and performance in warm mix asphalt.” *Report No. FHWA/TX-12/0-6591-1*, Center for Transportation Research, University of Texas, Austin.

Ziari, H., Behbahani, H., Izadi, A., and Nasr, D. (2013). “Long term performance of warm mix asphalt versus hot mix asphalt.” *Journal of Central South University*, 20, 256−266.

Zhao, W., Xiao, F., Amirkhanian, S. N., & Putman, B. J. (2012). "Characterization of rutting performance of warm additive modified asphalt mixtures," *Construction and Building Materials*, 31, 265–272.

Ziari, H., Mirzababaei, P. and Babagoli, R. (2016). "Properties of bituminous mixtures modified with a nano-organosilane additive," *Petroleum Science and Technology*, 34(4), 386-393.

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LIST OF PUBLICATIONS

Publications based on Ph.D Research Work

<u>*Articles in SCI journals*</u>

1. Shivakumar, G., and Suresha, S. N. (2017). "Evaluation of properties of nonfoaming warm mix asphalt mixtures at lower working temperatures." ***Journal of Materials in Civil Engineering***, ASCE, DOI: 10.1061/(ASCE)MT.1943-5533.0002071
2. Shivakumar, G., and Suresha, S. N. (2018). "Evaluation of workability and mechanical properties of non-foaming warm mix asphalt mixtures." ***Advances in Civil Engineering Materials***, ASTM (Accepted).
3. Shivakumar, G., and Suresha, S. N. (2018). "State of the art review on mix design and mechanical properties of warm mix asphalt." ***Road Materials and Pavement Design***, Taylor & Francis (Acceptance with revision).

<u>*Conference*</u>

4. Shivakumar, G., and Suresha, S. N. (2016). "Evaluation of Volumetric Properties of WMA Mixtures Made using SGC & Marshall Compaction." Technical paper and poster presented in ***conference on sustainable asphalt pavements for developing countries (CONSAP)***, New Delhi.