INFLUENCE OF AGING CONDITION ON PERFORMANCE OF FINE AGGREGATE ASPHALTIC MATRIX

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

NINGAPPA AKHANDAPPAGOL

DEPARTMENT OF CIVIL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA

SURATHKAL-575 025

FEBRUARY 2021

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DECLARATION

By the Ph.D. Scholar

I hereby declare that the Thesis entitled **"INFLUENCE OF AGING CONDITION ON PERFORMANCE OF FINE AGGREGATE ASPHALTIC MATRIX"** which is being submitted to **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of degree of **Doctor of Philosophy** in the **Department of Civil Engineering**, is a bonafide report of the work carried out by me. The material contained in this Thesis has not been submitted to any university or Institution for the award of any degree.

………………………………………..

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Place: NITK, Surathkal

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CERTIFICATE

This is to certify that the Thesis entitled "**INFLUENCE OF AGING CONDITION ON PERFORMANCE OF FINE AGGREGATE ASPHALTIC MATRIX**" submitted by **Mr. NINGAPPA AKHANDAPPAGOL (Register Number: 165052CV16F13),** as the record of the research work carried out by him, is accepted as the Research Thesis submission in partial fulfillment of the requirements for the award of the degree of **Doctor of Philosophy** in the **Department of Civil Engineering.**

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……………………………………

Chairman – DRPC

DEDICATED TO MY TEACHERS, PARENTS AND MY WIFE

৳# ACKNOWLEDGEMENTS

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ABSTRACT

The major distresses in the flexible pavement are fatigue cracking, rutting, and moisture induced damage. There is lack of consideration of ideal test methods to evaluate the distresses present in the asphaltic pavement. By knowing the majority of the distresses appear within the mortar or Fine Aggregate Matrix (FAM) of the asphalt mixture, researchers have started to use this FAM phase in place of full asphalt mixtures to characterise the performance properties. Additionally, one can also attain higher precision in test results from Dynamic Shear Rheometer (DSR) by maintaining the uniformity in the prepared FAM specimens.

The thesis report presents the research study performed on FAM mixtures focusing on its test methodology, rheological investigation results, and conclusions of the study. The main objectives of the present research is (i) to investigate the effect of different long-term oven aging (LTOA) levels on performance properties of FAM mixtures to mitigate the fatigue cracking in asphalt pavement, (ii) to assess and analyse the effect of binder types, different loads, and temperatures on creep and recovery performance of the FAM mixtures, (iii) to assess and analyse the impact of moisture on creep recovery response of FAM mixtures. To achieve this objective, a detailed test plan was prepared based on exhaustive review of research findings related to FAM mixtures and the latest practices for FAM characterisation were adopted by various agencies across the world. Major differences were observed in these practices, particularly with respect to the different aging methods, gradations used/considerations, specimen preparation method, and considerations of air voids, binder content, binder grade, and binder types.

In light of the above, the rheological investigation was carried out on FAM mixtures in three stages, i) Cracking susceptibility of FAM mixtures prepared with three different asphalt binders VG-30, VG-40, and PMB(S) is evaluated through the experimental testing and numerical modeling on FAM mixtures produced at design (laboratory) stage. Various criteria and approaches for the prediction of cracking in FAM mixtures are assessed and their correlation is discussed. Different levels of aging in laboratory are simulated, and the effects of long term oven aging (LTOA) on linear viscoelastic parameters, and fatigue characteristics of FAM mixtures are explored. ii) Creep recovery behavior of FAM mixtures were evaluated by

determining the percent recovery (%R) and non-recoverable creep compliance (J_{nr}) parameters from the Multiple Stress Creep Recovery (MSCR) test at different stress levels and temperatures. Additionally, strain response from the Burgers four element model was also modelled and compared with the observed experimental results, iii) Resistance to moisture-induced damage of FAM mixtures was evaluated by determining the ratios of %R and J_{nr} in dry and wet conditions from the Static Creep Recovery (SCR) test at 40°C for different stress levels.

Results of the study indicated that irrespective of the aging level applied to the FAM specimens, there is a small difference in the LVE limit was found for all FAM mixtures. Viscoelastic properties (|G*| and δ) for FAM specimen aged for 24 hrs at 135°C, and 12 days at 95°C aged FAM specimens showed similar results from the master curve plots. The fatigue life of FAM mixtures decreased as the aging level increases as expected. Despite of the similar viscoelastic properties, the trend observed between FAM mixtures aged 12 days at 95°C and 24 hrs at 135°C were not found to have similar fatigue life. Among FAM mixtures considered, the F2 mixture prepared with asphalt binder (VG-40) showed good resistance against permanent deformation for all the considered temperatures and corresponding stress levels. An important finding of this study also reported that Burgers model can be successfully applied for creep-recovery response of FAM mixtures under different temperatures and stress levels considered in this research. Further, the F3 mixture shows the highest $\%R_{ratio}$ and lowest J_{nr_ratio} values compared to the other two FAM mixtures, indicating a lower sensitivity to moisture damage which could be possibly due to the use of polymer modifier in F3 mixture.

Overall, based on the findings observed from the above rheological investigations, the FAM phase of full asphalt mixtures can be successfully used to characterise the effect of long-term aging on viscoelastic and fatigue properties of FAM mixtures. Similarly, FAM phase can also be used successfully to describe the permanent deformation, and moisture induced damage characteristics of FAM mixtures.

Keywords: Fine Aggregate Matrix, FAM, Viscoelastic, Fatigue, Rutting, Moisture Damage, Loose Mix Aging, Creep Recovery, Multiple Stress, Static Creep Recovery, MSCR, SCR, Burgers model

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NOMENCLATURE

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BC-1	Bituminous Concrete grading-1
CRMB	Crumb Rubber Modified Bitumen
DSR	Dynamic Shear Rheometer
FAM	Fine Aggregate Matrix Mixture
HMA	Hot Mix Asphalt
IRC	Indian Roads Congress
LTOA	Long Term Oven Aging
LVE	Linear Visco-Elastic
MAS	Maximum Aggregate Size
MCR	Modular Compact Rheometer
MoRTH	Ministry of Road Transport and Highways
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal Maximum Aggregate Size
PAV	Pressure Aging Vessel
PG	Performance Grading
PMB	Polymer Modified Bitumen
RTFOT	Rotary Thin Film Oven Test
SCB	Semi Circular Bend
SGC	Superpave Gyratory Compactor
STOA	Short Term Oven Aging
TS	Time Sweep
TDC	Top Down Cracking
Va	Percent Air Voids
VFA	Percent Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate

VG	Viscosity Grade
WMA	Warm Mix Asphalt
PMB	Polymer Modified Binder
MSCR	Multiple Stress Creep Recovery
SCR	Static Creep Recovery
TTSP	Time-Temperature Superposition
SST	Superpave Shear Tester
IS	Indian Standard

CHAPTER 1

1.0 INTRODUCTION

1.1 BACKGROUND

Fatigue cracking is one of the major distresses in flexible pavements. Cracks can be classified mainly into two groups i) load-related, ii) non-load related, and iii) combination of both. Load-related cracks develop due to the repeated application of traffic loads. Non-load associated cracks develop mainly due to the low pavement temperature. Cracks get further aggravated due to the aging of binders and presence of moisture in the pavement. As a result of aging, the stiffness and brittleness of binders increases, which leads to the high potential for fatigue cracking and decreases the service life of an asphalt concrete. 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. Many researchers have evaluated the fatigue life at 50% loss in initial stiffness (Smith and Hesp 2000; Sadeq et al. 2016). Laboratory tests revealed that the pavement not only experience the fatigue damage during the traffic loading but also have the capacity to recover from this damage during no loads (Kim et al. 2003). Many studies have been carried out to characterise the fatigue damage distress to know the factors that influences the fatigue resistance of Hot Mix Asphalt (HMA). In addition, there are different methods to measure and quantify fatigue cracking resistance of asphalt mixtures (Branco et al. 2008; Caro et al. 2008, 2012, 2014 and Zhu et al. 2017).

Similarly, rutting is also one of the major distresses in asphaltic pavement resulting from heavy traffic loadings during early age of pavement (Brown and Cross 1992). Increase in the traffic loads and climatic temperature over the years has been a major concern for the permanent deformation in the asphalt pavement. In addition, higher temperature sensitivity of asphalt binder intensifies the deterioration of asphalt concrete pavement. Though the rutting phenomenon is related directly to the asphalt binder, permanent deformation of the asphalt mixture is often dependent upon many variables such as stiffness of the asphalt binder, volumetric of asphalt mixture and adhesion between aggregates and the asphalt binder (Zoorob et al. 2012). It has been realized that the conventional asphalt binder from refinery does not meet the required demand from the field in terms of vehicular and climatic loading. As a result, modification using different type of additives, especially polymers has been suggested by various researchers to enrich asphalt binder properties, so that the performance parameters of asphaltic mixture could improve (Aragão et al. 2011; Santagata et al. 2013; Cardone et al. 2014; Daly et al. 2017).

There is still a major concern regarding the resistance of unmodified and modified HMA mixtures to moisture damage. In general, the presence of water in asphalt mixtures weakens its structural ability as the bond between the aggregates and the mastic is weakened (adhesive deterioration), and also adversely affects the resistance properties of the mastic (cohesive deterioration). Details about mechanisms of moisture damage and characterisation in asphalt mixtures can be found elsewhere in HMA (Caro et al. 2008; Xiao and Amirkhanian 2009; Caro et al. 2010; Apeagyei et al. 2015; Karmakar et al. 2018). In recent years, the many authors have followed the traditional test procedures (e.g., Humburg Wheel Tracking test, Tensile Strength Ratio (TSR), Indirect Tensile Strength (ITS) in dry and wet condition, and dynamic modulus etc. to evaluate the moisture damage potential of asphalt mixtures (Powell et al. 2007; Punith et al. 2011; Xiao et al. 2013; Martin 2014; Shiva Kumar and Suresha 2018). Further, bond loss caused by the presence of moisture at or within the binder-aggregate interface results in the deterioration of the asphalt mixtures mechanical properties, i.e., loss of stiffness and mechanical strength, which ultimately results in a rutting of road structure (Grenfell et al. 2015). In addition to moisture induced damage in asphalt pavements, the presence of moisture can also intensifies typical pavement distresses such as fatigue and permanent deformation (Epps et al. 2003). There is lack of consideration of ideal test method to evaluate the distresses present in the asphaltic pavement. So, researchers have found that FAM is important because it is a single characteristic length scale smaller than the asphalt mixture and is therefore closer in characteristic size of the damage that occurs within the full asphalt mixture

(Kim 2003). Experiments with FAM have been used to study fatigue damage, moisture damage, and rutting behavior in asphalt mixtures, with the argument that the phenomena occur largely between the coarsest aggregate particles and so tests with FAM should provide direct indications of how they will affect asphalt mixture (Zollinger 2005; Branco and Franco 2009; Palvadi et al. 2011; Underwood and Kim 2013; Im et al. 2015; Karki et al. 2015; Nabizadeh 2015; Sanchez 2018). The Fine Aggregate Matrix (FAM) phase is shown in Figure 1.1.

FAM is defined as the combination of fine aggregates, mineral fillers and asphalt binder which is relatively more uniform (Caro et al. 2008; Masad et al. 2008). It is important to note that, unlike the need for vast laboratory infrastructure for evaluation of asphaltic mixture, the performance evaluation on FAM mixtures in the laboratory needs only Dynamic Shear Rheometer (DSR).

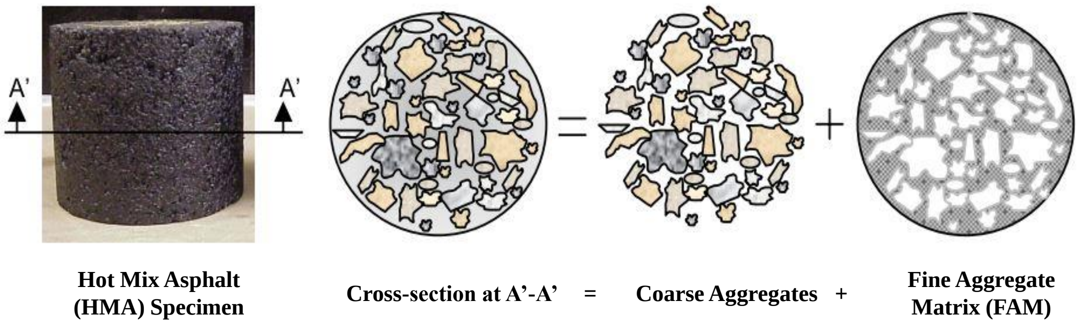


Figure 1.1 Representation of Fine Aggregate Matrix (FAM) (Caro et al. 2008)

Therefore, it not only saves the maximum space in the laboratory but also requires lesser time and consumes small amount of materials for the preparation of FAM specimens in the laboratory. Additionally, one can attain higher precision in test results from DSR by maintaining the uniformity in the prepared FAM specimens. Overall, characterization of FAM phase in place of full asphalt mixtures in the laboratory is faster which saves testing time, and reduces labour work to prepare FAM specimens. Kim et al. (2001) made the first attempt in this direction by investigating the viscoelastic properties of FAM mixtures which has been shown to be cheaper, simpler, less time consuming and repeatable. Overall, it can be concluded that the FAM mixture can effectively be used for the qualitative characterisation of all asphaltic mixtures (Suresha and Ningappa 2018). It is important to note that the FAM is the primary phase tending to deform when full asphalt mixtures are subjected to different type of loading behaviour. Therefore, FAM is the phase where performance characteristics need to be properly examined and must be closely related to overall asphalt concrete mixture performance (Im et al. 2017).

Fatigue, permanent deformation, and moisture induced damage performance of asphalt mixtures are being evaluated in the laboratory using, triaxial test, Semi-Circular Bend (SCB) tests etc (Underwood and Kim 2011; Haghshenas et al. 2016; Singh et al. 2017; Rastegar etal. 2018; Nemati 2019). Although the linear viscoelastic stiffness, fatigue characteristics, permanent deformation, and moisture damage behavior of full asphalt mixtures can be determined through experiments, it is generally time consuming and expensive to reach repeatable results. Thus, it is attractive to pursue alternative methods that are cheaper, faster, simpler, and repeatable in order to efficiently evaluate and predict asphalt mixtures' core mechanical characteristics (Nabizadeh et al. 2017). However, tests were carried out on FAM mixtures due to its several benefits such as consistency, repeatability, reproducibility and simplicity in terms of specimen preparation, testing, and experimental results. Therefore, FAM specimen test is gaining more attention by researchers worldwide to characterise the fatigue, rutting, and moisture induced damage properties of asphalt mixtures. Thus, a summary on the various test specifications used in conducting FAM test and its application is needed. This will help researchers and practitioners in road construction industry to understand the importance of the test technique to assess both rutting and fatigue cracking behaviour of FAM mixtures. Although, limited research are available regarding the FAM test and findings on FAM mixtures fatigue, rutting, and moisture induced damage properties and it is visualised that FAM specimens testing carried out using the DSR methodology turn out to be promising test method to determine the fatigue, rutting, and moisture induced damage performance of FAM mixtures (Kim et al. 2007; Masad et al. 2008; Caro et al. 2008; Branco et al. 2008; Vasconcelos et al. 2010; Montenaz et al. 2020).

Till date, a number of studies have been conducted to check the role of fine aggregate matrix (FAM) in characterising linear viscoelastic properties, time dependent behaviour and fatigue properties of asphalt concrete mixture to predict the entire mixtures behaviour (Aragao et al. 2013; Kim and Aragao. 2013; Ban et al. 2013; Karki et al. 2015; Im et al. 2015;). Karki et al. (2015) used the micromechanical modelling approach to predict the dynamic modulus of asphalt concrete mixtures and concluded that the FAM phase can anticipate viscoelastic properties of asphalt concrete mixtures. Underwood and Kim (2011) studied the dynamic modulus and phase angle of FAM and full asphalt concrete mixture and concluded that, the FAM mixtures found to have the sensitivity which is more in line with that observed for full asphaltic mixtures under all of the tested conditions. The fatigue cracking property of asphaltic concrete mixtures and FAM mixtures was further compared, and similar ranking for fatigue life was observed for both the cases (Bemis and Bennett 2009; Motemad 2012). Overall, the FAM mixture is able to characterise the full asphalt concrete mixtures in a qualitative way (Suresha and Ningappa 2018).

Many researches have been carried out to study the effect of aging on the rheological properties of asphalt binders (Mirza and Witczak 1995; Ruan et al. 2003; Glover et al. 2005; Ling et al. 2017, Prabin et al. 2017). Further, numbers of studies have been reported recently for the corresponding phenomena at asphaltic mixture level too (Elwardany et al. 2016; Elwardany et al. 2018; Rastegar et al. 2019; Zhang et al. 2019; Zhou et al. 2019; Chen and Solamainian 2020;). All these studies have given more concentration to quantify the effect of aging on fundamental properties of asphalt binders. Hence, there is a need for researchers to study the changes in physical properties of asphalt concrete mixtures due to the aging effect. However, it is important to consider changes in physical properties of asphalt concrete mixtures during field aging while preparing laboratory specimens for long-term performance testing. Recently, researchers studied the aging effect on physical properties of full length asphalt concrete mixtures. Further, researchers have used the current laboratory aging protocol for short term oven aging (STOA) at 135°C for 4h before compaction and long-term oven aging (LTOA) at 85°C for 5days (AASHTO R30) on compacted specimens. Also, recently recommended loose mixture aging protocols at 95°C and 135°C for different aging duration level (NCHRP 09-54) are used to study the aging effect on viscoelastic and fatigue properties of asphalt concrete mixtures (Elwardany et al. 2016; Hanz et al. 2017; Yin et al. 2017; Chen et al. 2018; Nobakht et al. 2018; Sahebzamani et al. 2018; Rastegar et al. 2018; Ogbo et al. 2019).

As mentioned earlier, aging changes the physical property of asphalt mixtures by increasing stiffness, brittleness, and decreasing relaxation capability. Therefore, it is important to give due consideration to aging phenomena at the mixture design stage to provide a durable pavement structure. To achieve this problem, aging of asphaltic mixtures needs to be simulated in the laboratory. Based on the extensive review of literature, to the best of the knowledge, limited research work till date has been reported which aimed at understanding the effect of LTA on FAM mixture (Zhu et al. 2017; Li et al. 20148; Sanchez et al. 2019). Laboratory compacted FAM was conditioned at 85°C for 5 days to simulate long term aging as per AASHTO R30 before evaluating fatigue property in their study. It is important to note that the aging process can be accelerated with the help of increased conditioning temperature to reduce the conditioning time in order to achieve the same degree of aging (Elwardani et al. 2016; Hanz and Reinke 2016; Chen et al. 2018). Since the standard protocol recommends conditioning the specimen for 5 days which is a significantly longer time period, however, it can be reduced by increasing the conditioning temperature. Such changes may significantly save the conditioning time. Though the increase in conditioning temperature can decrease the conditioning time, it is important to quantify the decrease in conditioning time with a corresponding increase in conditioning temperature considering its influence on long term performance parameter. This motivated the authors to investigate the impact of different aging and conditioning time for different FAM to simulate the aging (long term aging) of asphaltic mixture and the corresponding effect on different viscoelastic properties and long term performance.

Further, development of different methods for predicting asphalt binders rutting properties led to the implementation of Multiple Stress Creep and Recovery (MSCR) test (D'Angelo 2009). This method has been shown to apply for unmodified or modified binders in several laboratory and field investigations. Considering the success of MSCR protocol for evaluating the high temperature performance of asphalt binder, many attempts have been made by researchers in the recent years to investigate the creep recovery behaviour at asphaltic mixture level by implementing the similar approach which was used for the asphalt binder level (Huang et al. 2011; Celauro et al. 2012; Arabani and Kamboozia 2013; You et al. 2014; Gao et al. 2015; Darabi et al. 2019; Domingos et al. 2019; Vajipeyajula et al. 2019). Additionally, recommendations given by Elnasri et al. (2016) and Montañez et al. (2020) to the MSCR test protocol were extended to study the rutting performance of FAM mixtures. The MSCR test stands out because its results are more reliable than the traditional parameters based on linear viscoelastic property to measure its susceptibility to rut resistance, as well as being a simple procedure which enables quick characterization of the viscoelastic materials (D'Angelo 2009; Saboo and Kumar 2015).

To date, a number of studies were carried out to investigate the role of FAM in characterizing the permanent deformation properties in overall asphaltic mixtures (Nabizadeh et al. 2017; Im et al. 2017; Li et al. 2020; Montañez et al. 2020; Sadeq et al. 2020). The static creep recovery test was carried out by Nabizadeh et al. (2017) to assess the permanent deformation characteristics of FAM and full asphalt mixtures under different stress levels and temperatures. Comparison of creep recovery behaviour of FAM and asphaltic mixtures in their study indicated was done and found to have produced similar ranking for both the cases. It was also recommended that the asphaltic mixture characteristics can be hypothetically predicted using FAM testing. There are also few other studies in this area where FAM mixture has been examined using standard MSCR test protocol under different stress levels and temperature (s) (Montañez et al. 2020; Sadeq et al. 2020). Therefore, considering the capability of MSCR test in predicting rutting performance of asphalt binder and mixes, and limited number of reported studies on FAM in this direction, there is a need for further study so that a better understanding could be developed in this regard. This research work is an attempt in this direction by evaluating FAM mixtures under different stress levels and temperature (s) using MSCR test.

It is an established fact that asphalt mixtures act as viscoelastic material, i.e, its shows both viscous and elastic properties and the relation between stress and strain depends on the time (Aragão et al. 2016; Moreno-Navarro et al. 2018). Modeling the response of viscoelastic material has been shown as a novel approach to quantify the physical and mechanical properties. Many researchers have tried various mathematical and theoretical models to model the creep and recovery response from MSCR test on binders and asphaltic mixtures (Delgadillo and Bahia 2010; Celauro et al. 2012; Arabani and Kamboozia 2013; Gao et al. 2015; Domingos et al. 2019). Among different existing models, the Burgers model was used by many researchers to simulate the creep and recovery response of asphalt binders and mixtures and found to be highly promising (Szydlo and Mackiewicz 2005; Giuliani et al. 2006; Celauro et al. 2012; Saboo and Mudgal 2018; Ashish and Singh 2019; Goli et al. 2019). The main benefit of Burgers four element parameters is that it can make a strong distinction between elastic, delayed elastic and viscous responses. Although many studies are available on the viscoelastic modelling of creep-recovery response for asphalt binder as well as asphaltic mixture, the corresponding analysis on FAM mixture is very limited. Therefore, one of the aim of this study is to model the creep-recovery response of various FAM mixtures under different stress levels and temperatures using Burgers model. Also, not much test methods were used for characterizing the rutting behaviour of FAM mixtures. Furthermore, limited studies have been carried out to study the impact of moisture on FAM mixtures (Caro et al. 2012; Caro et al. 2015; Montenaz et al. 2020). Therefore, research was also carried out to study the impact of moisture on unmodified and modified FAM mixtures.

Therefore, the main objective of this research is to evaluate the various viscoelastic properties of FAM mixtures aged using varied level of conditioning (by changing the temperature and duration), including AASHTO R30 and newly recommended NCHRP 09-54 protocols for the same. It is important to note that the amplitude strain level needs to be beyond the linear viscoelastic range for inducing fatigue damage to the material. Therefore, strain sweep test was initially conducted on various specimens conditioned at different aging levels to demarcate the boundary line between linear and non-linear viscoelastic zone. Subsequently, temperature and frequency sweep test was carried out on different specimens by applying amplitude strain level within linear viscoelastic range which helped to examine the effect of different aging level over a wide range of frequency by drawing the master curve for complex shear modulus (|G*|) and phase angle (δ) based on the Time-Temperature Superposition (TTSP) principle. Finally, the fatigue property of FAM mixtures conditioned at different aging level was evaluated using a time sweep test to reach an appropriate conclusive remark.

Similarly, to analyse the creep recovery response of three different types of FAM mixtures, two different stress levels and three temperatures were considered. Further, Burgers model was used to analyse the measured response of FAM mixtures. The importance of model parameters which indicates the elastic and viscous behaviour of different FAM mixtures and impacts on the characteristics of the permanent deformation was determined. Furthermore, it is important to note that the FAM is the primary phase tending to deform when full asphalt mixtures are subjected to change in environmental conditions and different type of loading behaviours. Therefore, FAM is the phase where deformation characteristics need to be properly examined in dry and wet condition and must be closely related to overall asphalt concrete mixture performance (Caro et al. 2012; Caro et al. 2015; Im et al. 2017). In this research, to analyse the impact of moisture on creep recovery response of three different types of FAM mixtures under dry and wet condition, four different stress levels at temperature of 40°C was considered.

1.2 STATEMENT OF RESEARCH PROBLEM

In India, majority of the roads are flexible pavements constructed using HMA technology which includes aggregates, fillers and binders. The source of binders is typical and referred as “Bitumen” (Asphalt). Straight-run (plain) bitumen of Viscosity Grading (VG-10; VG-20; VG-30; VG-40) and modified binders (PMB; CRMB) is currently in practice. The flexible pavement is constructed with different layers such as base layer and surface layer. In this study, main concentrations will be given to characterise the bituminous/surface layer in the flexible pavement.

The characterization of full HMA mixtures in laboratory is complex, as it consumes more materials, needs more number of instruments which are costlier and consumes more time. So, in recent years researchers have started to characterize the FAM mixtures in palace of HMA mixtures to understand the mixtures properties in better way and it needs only one instrument Dynamic Shear Rheometer (DSR) ASTM D-7552.

Aging may cause changes in physical property of asphalt concrete mixtures by increasing stiffness, brittleness and decreasing relaxation capability. By considering this, fatigue cracking properties of aged asphalt mixtures are desirable at the mix design stage. To achieve this problem, aging of asphalt mixtures should be simulated in the laboratory. There are only two studies on LTOA aged FAM mixtures that has been conducted till date (Zhu et al. 2017; Zhou et al. 2019). In this study, strain sweep test and time sweep test have been carried out to characterise the fatigue property of FAM mixtures inclusive of recycled asphalt shingles (RAS). Researcher used long-term oven aging (LTOA) protocol 85°C for 5days (AASHTO R30) on compacted FAM samples before conducting the fatigue test. Further, concluded that incorporation of RAS causes decrease in fatigue life of FAM mixtures. Thus, there is need for carrying out studies on different FAM mixtures to simulate the laboratory aging (LTOA). It is useful to obtain novel information about the effect of different aging protocols (AASHTO R30 and NCHRP 9-54) on viscoelastic and fatigue cracking potential of FAM mixtures.

Permanent deformation is also one of the major distresses in asphaltic pavement, resulting from heavy traffic loadings during pavement life. Increase in the traffic loads and climatic temperature over the years has been a major concern for the permanent deformation in the asphalt pavement. In addition, higher temperature sensitivity of asphalt binder intensifies the deterioration of asphalt concrete pavement. It has been realized that the conventional asphalt binder from refinery does not meet the required demand from the field in terms of vehicular and climatic loading. As a result, modification using different type of additives, especially polymers has been suggested by various researchers to enrich asphalt binder properties, so that the performance parameters of asphaltic mixture could improve. This motivated authors to consider polymer modified asphalt binders along with virgin asphalt binder(s) for the laboratory investigation on FAM mixtures in this research work. To analyse the creep recovery response of three different types of FAM mixtures, two different stress levels and three temperatures were considered.

Modeling the response of viscoelastic material has been shown as a novel approach to quantify the physical and mechanical properties. Many researchers have tried various mathematical and theoretical models to model the creep and recovery response from MSCR test on binders and asphaltic mixtures (Delgadillo and Bahia 2010; Celauro et al. 2012; Arabani and Kamboozia 2013; Gao et al. 2015; Domingos et al. 2019). Among different existing models, the Burgers model was used by many researchers to simulate the creep and recovery response of asphalt binders and mixtures and found to be highly promising (Szydlo and Mackiewicz 2005; Giuliani et al. 2006; Celauro et al. 2012; Saboo and Mudgal 2018; Ashish and Singh 2019; Goli et al. 2019). The main benefit of Burgers four element parameters is that it can make a strong distinction between elastic, delayed elastic and viscous responses. Although many studies are available on the viscoelastic modelling of creep-recovery response for asphalt binder as well as asphaltic mixture, the corresponding analysis on FAM mixture is very limited. Therefore, one of the aim of this study is to model the creep-recovery response of various FAM mixtures under different stress levels and temperatures using Burgers model.

In addition to the above distresses, there is still a major concern regarding the resistance of unmodified and modified HMA mixtures to moisture damage. In general, the presence of water in asphalt mixtures weakens its structural ability as the bond between the aggregates and the mastic is weakened (adhesive deterioration), and also adversely affects the resistance properties of the mastic (cohesive deterioration). It is important to note that the FAM is the primary phase tending to deform when full asphalt mixtures are subjected to change in environmental conditions and different type of loading behaviours. Therefore, FAM is the phase where deformation characteristics need to be properly examined in dry and wet condition and must be closely related to overall asphalt concrete mixture performance. This motivates to assess and analyse the impact of moisture on creep recovery response of FAM mixtures prepared with three different types of binders at four different stress levels and testing temperature of 40°C was considered in this research.

Although limited research available regarding the FAM test and findings on FAM mixtures fatigue, rutting and moisture induced damage properties, it is visualised that FAM specimens testing carried out using the DSR methodology turn out to be promising test method to determine the viscoelastic properties, fatigue, rutting and moisture induced damage performance of FAM mixtures.

1.3 RESEARCH OBJECTIVES AND SCOPE

The main aim of the present research is (i) to investigate the effect of different long-term oven aging (LTOA) levels on performance properties of FAM mixtures to mitigate the fatigue cracking in asphalt pavement, (ii) to assess and analyse the effect of binder types, different loads, and temperatures on creep and recovery performance of the FAM mixtures, (iii) to assess and analyse the impact of moisture on creep recovery response of FAM mixtures. The specific objectives of present research are as follows:

1. To study the effect of different aging levels on viscoelastic properties of FAM mixtures
2. To study the effect of different aging levels on fatigue properties of FAM mixtures
3. To study the rutting properties of FAM mixtures
4. To study the moisture induced damage properties of FAM mixtures.

The Dynamic Shear Rheometer (DSR) was used to characterise the viscoelastic properties, fatigue failure, rutting, and moisture induced damage of FAM mixtures under strain/stress controlled modes by finding the rheological parameters such as complex shear modulus (|G*|) and Phase angle (δ).

In this study, the linear viscoelastic properties of aged FAM mixtures are evaluated (Using AASHTO R30 and newly recommended NCHRP 09-54 protocols). To study these properties, strain sweep test was conducted at different aging levels to determine LVE limit and also this test will help in determining larger strain levels outside the LVE region that are used for time sweep test. Temperature and frequency sweep test was conducted on FAM mixtures under different aging levels. The master curve of complex shear modulus |G*| and phase angle δ were constructed based on the time-temperature superposition principle (TTSP). The sigmoidal predictive model is used to validate the measured viscoelastic parameters. The fatigue property of FAM mixtures aged at different aging level was then evaluated using time sweep test and rutting properties of FAM mixtures using MSCR test with considering the rest periods. In addition, to know the effect of moisture on FAM mixtures, static creep and recovery test was conducted on both dry and wet conditioned FAM specimens prepared with different binder types. Finally concluding remarks of the study are summarized.

1.4 ORGANIZATION OF THE THESIS

This thesis is organized into seven chapters followed by the list of references. The background on utilization of Fine Aggregate Matrix phase (FAM) in place of full asphalt mixture for characterization of viscoelastic, fatigue, rutting and moisture induced damage properties, benefits of FAM mixture characterization in the laboratory, and its importance in the asphaltic industry, statement of research problem, research objectives and scope, and thesis organization of this research are presented in the Chapter 1.

Chapter 2 is in the form of review paper published by Journal of Construction and Building Materials (JCBM), entitled **"Recent trends and laboratory performance studies on FAM mixtures: A state-of-the-art review".** This study presents the comprehensive review of the research findings, and standard practices considered for selection of materials, different aggregate gradations, selection of asphalt content, air voids for FAM mixtures in order to evaluate the viscoelastic, fatigue, rutting, and moisture induced damage characteristics. Also, a discussion on advantages and drawbacks of different methods adopted for preparation of FAM specimens, the details of the different laboratory tests conducted on FAM specimens using dynamic shear rheometer.

The details of various materials used during laboratory investigation of FAM mixtures, details of physical properties of unmodified and modified asphalt binders, aggregate gradations for FAM mixtures, the method used for FAM specimen preparation, the details of different laboratory tests are provided in Chapter 3. The specially fabricated mould was used in this study for the preparation of rectangular FAM specimens by direct compaction method is now filed for an Indian patent, entitled **"Direct Compaction Mould for Preparation of Bitumen Bounded Fine Aggregate Matrix Specimens".**

Chapter 4 presents a technical paper accepted for Journal of Construction and Building Materials (JCBM), the title of this paper is **"Laboratory evaluation of long-term aging effect on linear viscoelastic and fatigue properties of FAM mixtures".** The main objective of this study is to evaluate the various viscoelastic properties of FAM mixtures aged using varied level of conditioning (by changing the temperature and duration), including AASHTO R30 and newly recommended NCHRP 09-54 protocols for the same. Linear Visco-Elastic (LVE) limit of each FAM mixtures was initially determined by conducting strain sweep test. Viscoelastic properties ($|G^*|$ and δ) and master curve shape parameters of FAM mixtures were further determined from temperature and frequency sweep test. Fatigue properties of FAM mixtures at different aging levels were evaluated using strain controlled time sweep test. Findings of this study on FAM phase can be successfully used to characterize the effect of long-term aging on performance studies of FAM mixtures.

Chapter 5 of this dissertation is in the form of a technical paper submitted for Advances in Civil Engineering Materials (ACEM), entitled **"Laboratory Evaluation and Rheological Modeling of Creep-Recovery Behavior of FAM Mixtures".** The main aim of this study is to assess and analyse the creep and recovery performance of FAM mixtures. The creep recovery behavior of FAM mixtures is determined by conducting the Multiple Stress Creep Recovery (MSCR) test on FAM mixtures. In addition, strain response from the Burgers four element model was also modelled and compared with the observed experimental results under different temperature and stress levels considered for this study. The findings observed from rheological investigation of FAM phase in this study can be successfully used to describe the permanent deformation characteristics of FAM mixture.

In Chapter 6 of this dissertation, resistances to moisture-induced damage of the FAM mixtures were evaluated as per methodology adopted by Caro and Montanez. The creep recovery behavior of FAM mixtures in dry and wet condition is determined by conducting the Static Creep and Recovery (SCR) test on FAM mixtures. In addition, the effects of binder types used in FAM mixtures on moisture-induced damage of the same mixtures were evaluated in terms of percentage recovery and non-recoverable creep compliance ratios. Conclusions and recommendations drawn based on the present investigation are given in Chapter 7.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 GENERAL

The main purpose of comprehensive review was to present the current knowledge about the various test procedures adopted by different researchers to evaluate the viscoelastic, fatigue, rutting, and moisture induced damage properties of FAM mixtures. Although there are less research available regarding the FAM test and findings on FAM mixture properties, it is found that FAM specimen testing using DSR methodology turn out to be promising test method. This review is divided into three major heads which includes, i) FAM material characterisation, ii) Fabrication of FAM specimens, and iii) Performance evaluation of FAM mixtures. A summary regarding the current review is provided at the end of the review discussion on FAM mixtures.

2.2 MIX DESIGN OF F.A.M MIXTURES

Materials: The materials used in FAM mixtures are, asphalt binder, aggregates, and fillers. Many studies have been carried out using different type of asphalt binders and aggregates. Even, studies with RAP/RAS in FAM mixtures have been evaluated (He et al. 2016; Zhu et al. 2017; Sanchez et al. 2017). In addition, different WMA additives such as Aspha-Min, Evotherm, Sasobit, Advera and Rediset have been incorporated in FAM mixtures to improve the healing and fatigue properties (Caro et al. 2008; Sadeq et al. 2016). In order to select and finalise the quantity of materials for the preparation of FAM mixtures, different methods have been incorporated. The details of materials (aggregates and asphalt binders), aggregate gradation and varying air voids studies are explained in detail.

Different Aggregate Gradations*:* The maximum aggregate sizes used for the studies of FAM mixtures are 0.6 mm, 1.18 mm, 2.00 mm, 2.36 mm, 4.00 mm and 4.75 mm have been studied. In addition, Nominal Maximum Aggregate Size (NMAS) of 0.3mm, 0.6mm, 1.18mm, 2.36mm and 2.36mm are also been studied (Martono et al. 2007; Bhasin et al. 2008; Aragao et al. 2009, 2012; Karki et al. 2015). Freire et al.

(2017) studied the FAM mixture with three different NMAS (4.00, 2.00, and 1.18 mm). Aggregate size less than 0.075 mm acts as fillers (Hydrated lime and Limestone) (Kim et al. 2003). There are different gradations in preparation of FAM mixtures and Asphalt mastics. However, there are inconsistencies in the review of literature with respect to the FAM being used as a technique for HMA characterization. One of these inconsistencies is related to the choice of the sieve that limits the NMAS used in these mixtures. Some authors defined the sieve (1.18 mm) as the upper limit for designing FAM samples (Kim et al. 2003; Zollinger 2005; Arambula 2007; Masad et al. 2008; Caro et al. 2008; Branco et al. 2008; Vasconcelos et al. 2010; Palvadi et al. 2012; Tong 2013; Haghshenas et al. 2016). Dai and You (2007) and Aragao et al. (2009) used a different sieve to separate the coarse portion from the fine portion of the asphalt mixture, 2.36 mm, and 0.6 mm, respectively. The details of the different aggregate gradations studied are presented in Table 2.1.

Table 2.1 Details of different aggregate gradations adopted in FAM specimens

	Friere et al. 2017			Masad et al. 2008	
	Cumulative % by weight of total aggregate passing				
Sieve size, mm	HMA	FAM (1.18 mm)	Sieve size, mm	HMA	FAM (1.18 mm)
25	100	-	25	100	-
19	100	-	19	100	-
12.5	95	-	12.5	98	-
9.5	80	-	9.5	88	-
4.75	50	-	4.75	60	-
2.36	32	-	1.18	47	100
1.18	21	100	0.3	22	62
0.6	19	42	0.075	9	28
0.3	16	36	Pan	0	0
0.15	13	22			
0.075	8	16			
Pan	0	0			

Selection of Asphalt Content: Many studies have been carried out for the selection of asphalt content by trial and error methods for the preparation of FAM mixtures. While selecting the asphalt content, it should not be very high or very low as it causes flow and stiff mixtures respectively. First attempt has been made by Kim et al. (2003) by adopting a fixed value of 8 % of asphalt content, which represents an asphalt film thickness of 10 μ. Branco et al. (2008) and Branco (2008) determined the

FAM asphalt content based on the asphalt content of fine aggregate matrix of the HMA mixture which is smaller than 1.18 mm. Karki (2010) adopted the same assumption presented by Kim et al. (2003) and proposed calculations based on a film thickness of 12 μ. Later, Coutinho (2012) and Sousa et al. (2013) suggested experimental methods such as solvent extraction binder method and ignition method respectively. Both methods calculate the FAM asphalt content based on only the fine portion of the mixture, regardless of the amount of fine aggregate matrix adhered to the coarse aggregate. Freire (2015) and Freire et al. (2017) proposed a correction in the calculations presented by Coutinho (2012), in order to include the fine matrix adhered to the coarse aggregate particles in the calculations.

The major concerns related to the determination of the FAM asphalt content based on above methods are higher asphalt content, no proportionality in asphalt content between FAM and HMA mixtures when modified asphalt binders are used, poor repeatability of both extraction and fractionation method when modified binders are used, because of the difficulty in separating mixture particles by hand. To overcome the above concerns, Ng (2017) and Ng et al. (2018) adopted the alternative FAM design method based on the procedure developed by Arrambide and Duriez in 1959 to estimate the HMA asphalt content using surface area or specific surface (Ss). Based on this surface area concept, they developed different equations to find asphalt content of FAM mixtures (Pb_{FAM}). In order to find asphalt content for the FAM mixtures prepared with the modified asphalt binders, the asphalt content was multiplied by the ratios between the asphalt contents of the HMA mixtures prepared with the modified asphalt binders and the conventional binder. The use of such ratios is based on the known trend of obtaining higher asphalt contents in the design of HMA and FAM mixtures using modified binders due to higher viscosity and higher film thicknesses. In Table 2.2., the results of asphalt content for FAM mixtures using different methods are shown.

Table 2.2 Binder contents of the HMA and FAM mixtures according to some proposed methods in the literature

Sl. No	Mixture Types	BC for HMA, %	BC for FAM, % By Proposed Methods			
		HMA mix design	Branco (2008)	Coutinho (2012) and Freire (2015)	Sousa (2010)	Ng (2017)
1	AC mix	4.4	10.8	6.3	7.3	7.4
2	AC+PPA mix	4.7	11.5	6.4	8.0	7.8
3	AC+SBS mix	5.0	12.1	6.1	7.8	8.3
4	AC+Rubber mix	5.5	15.3	6.1	9.8	9.3

Note: BC= Binder Content, AC= Asphalt Concrete

Air Voids: The air voids content that best represents the FAM is not well known. The methods developed to determine the binder content of the fine aggregate matrix tend to be empirical, and based on the binder content obtained in the asphalt concrete design. FAM samples extraction from the SGC specimens prepared with loose FAM mixture with known air voids is used as the criterion to find the air void content of the FAM mixtures. Zollinger (2005) has made an attempt to find air voids of 11% in FAM samples using SGC sample of height 85mm. Further, to evaluate the effect of air void content on healing properties of FAM samples, Bhasin et al. (2008) prepared the SGC samples containing 13% air voids with a height of 75mm. Due to the torque limitations of the DSR, less stiff FAM samples have been prepared with higher air void range of 10%-13% (He et al. 2016; Zhu et al. 2017). However, the researchers have made an assumption that there is no difference in the air voids content present in the asphalt mixtures and its FAM phase (Branco et al. 2008; Branco 2008; Im et al. 2015; Freire et al. 2017).

Karki et al. (2015) concluded that the air voids are randomly distributed throughout the asphalt mixture samples which are present between FAM phase and aggregate phase. In his study, air voids were determined based on the compaction density. This density was determined by dividing the total weight of the FAM phase by its volume. The weight of the FAM in the compacted asphalt concrete mixture is calculated by subtracting the weight of the aggregate phase and the weight of the asphalt binder absorbed by the aggregates and coated on the aggregates from the total weight of the compacted mixture. Similarly, the volume of the FAM is obtained by subtracting the volume of the aggregate phase and asphalt binder filling and covering the aggregates from the maximum volume of the compacted asphalt concrete mixture. With this assumption Karki et al. (2015) produced the FAM samples with different air voids (1.0% and 5.5 %) and simulated the dynamic modulus for asphalt mixtures. FAM samples with 1% air voids gave good agreement based on experimental modulus and the simulated modulus. This concludes that 1% air voids in FAM samples can represent the matrix phase in the asphalt mixtures. To evaluate the effect of air voids on the linear viscoelastic dynamic shear modulus of FAM, Underwood and Kim (2011) considers the air voids present in FAM samples with 50, 75 and 100% of asphalt mixtures and this study concludes that reduction in air voids content can cause the increase in the linear viscoelastic shear modulus of FAM at the rate of 7% by reduction in 1% air void content. Due to presence of higher binder content, FAM mixture showed more susceptibility to air void variation.

2.3 FABRICATION OF FAM SPECIMENS

FAM specimen preparation is not as standardized or well outlined as the binder process. For this reason, two different methods have been used by many researchers to fabricate FAM specimens, i) Superpave Gyratory Compaction (SGC) and cutting specimens out of a larger cylindrical sample, ii) specimens preparation using direct compaction method.

2.3.1 Superpave gyratory compactor method

FAM specimens have been fabricated using Superpave Gyratory Compactor (SGC) Zollinger (2005). This method is utilized more often and has more of a standardized process such as the one used for fabricating the binder samples. Most of the researchers have been used this method for preparing the FAM samples. The researchers selected different asphalt binders (Conventional and Modified binders) and different size of aggregates. There are two different methods of FAM sample preparation.

a) Cylindrical FAM Sample Preparation by Coring of SGC Sample: Cylindrical FAM samples were initially prepared by cylindrical SGC mould of diameter 100mm (Palvadi et al. 2012; Sousa et al. 2013; Masad et al. 2014; Karki et al. 2015; Sadeq et al. 2016; Freire et al. 2017) and 150mm (Underwood et al. 2011,2013; Caro et al. 2012,2015; Tong et al. 2013,2015; Karki et al. 2015,2016; Zhu et al. 2017), these samples were cored using a coring bit refrigerated by water to obtain the FAM samples. The samples are prepared using different size of aggregates. Some authors have used the Maximum Aggregate Size (MAS) 0.6mm, 1.18mm, 2mm, 2.36mm, 4mm and 4.75mm. The MAS varies from 0.6mm to 4.75mm. Height of the SGC samples varies from 70mm to 90mm with respect to the targeted air voids. Aragao et al. (2012) used the MAS 0.6mm for his FAM study. There are many authors used 1.18mm as MAS for preparing the FAM samples (Veronica et al. 2008; Bhasin et al. 2011; Palvadi et al. 2012; Karki et al. 2014, 2015, 2016; Caro et al. 2008, 2012, 2014; Tong et al. 2013, 2015; Sanchez et al. 2017; Masad et al. 2008,2014; Im et al. 2015; Sousa et al. 2013; Sadeq et al. 2016; Freire et al. 2017). Few authors have used the 2.36mm as MAS for the preparation of FAM samples (Zhu et al. 2017, Underwood et al. 2011, 2013) and only one author used MAS 4mm and 2mm for preparation of FAM samples (Freire et al. 2017). FAM samples have prepared with different dimensions, height of the sample varies from 45mm to 50mm and diameter of the sample varies from 12mm to 20mm. Figure 2.1 represents the procedure for preparation cylindrical FAM samples.

b) Rectangular FAM Sample Preparation by Cutting of SGC Sample: Rectangular FAM samples were initially prepared by SGC mould of diameter 100mm, the rectangular sample of size: i) 50x10x6mm (Smith and Hesp, 2000) and ii) 50x10x10mm (Li et al. 2017) and from mould of diameter 150mm, the rectangular sample of size 50x12x10mm (Reinke et al. 2006) were prepared by cutting the SGC sample. Although it may seem that the SGC method is more standardized, this method has its own complexities. It should also be mentioned that even though an SGC standard exists it does not include details for FAM mixes or for cutting the samples. Therefore details regarding the mix and the cutting procedure are experiment or lab specific. Figure 2.2 represents the procedure for preparation cylindrical FAM samples.

2.3.2 Direct compaction method

The idea of a direct compaction method to fabricate FAM samples is a new process. Every idea or new process starts with a purpose or intent for experimenting with the general procedure. There are several major reasons for implementing a sample preparation process. High quality materials are essential for small scale lab testing and can be limited for research purposes. Using these materials in the most efficient way, this process would help to cut down on wasted material as well as make the most of the resources provided. Not only it will save material use, it would also save the fabricator time as well. The exact number of samples needed for a test matrix could be fabricated without making more than necessary, again it saves precious resources. Saving the fabricator time is meaningful because their time can be spent running tests on the samples rather than fabricating a large number of samples that may not be needed.

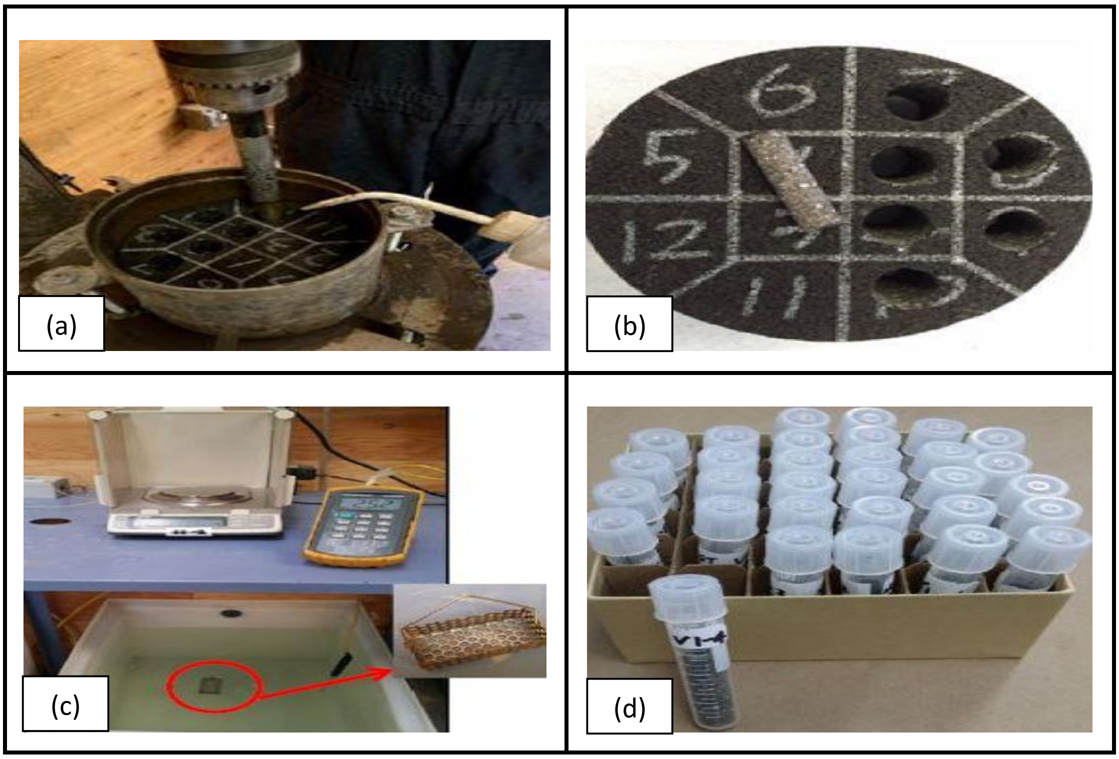


Figure 2.1 Procedure for preparation of cylindrical FAM specimens
(a) Coring (b) FAM specimen (c) Weigh station to measure air voids (d) Storage of FAM specimens (He et al. 2016)

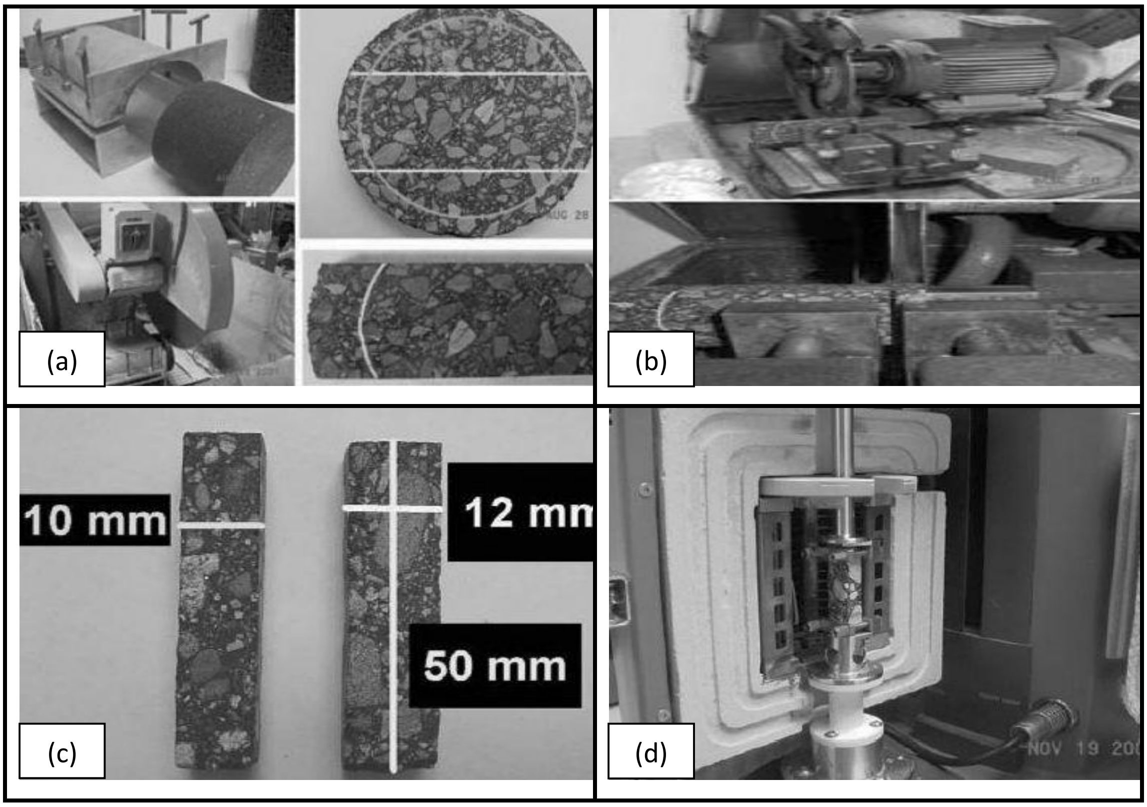


Figure 2.2 Procedure for preparation of rectangular FAM specimens (a) SGC Specimen (b) Cutting of SGS Specimen (c) FAM Specimen (d) FAM Specimen in DSR (Rienke et al. 2005)

Lastly this direct compaction process would save significant lab space. The mixing, compaction and cutting procedure uses large equipment and machinery to accomplish the sample fabrication process. Each loose FAM mixture was compacted in a specially fabricated mould. The inside area of the mould was machined to produce a smooth surface on the compacted sample without significant defects. This treatment helps to obtain repeatable test results since the smooth surface is an important factor in minimizing random behaviour in terms of fatigue crack initiation and propagation in the torsional loading mode. (Kim et al. 2003). There are two different methods of FAM sample preparation.

FAM samples are prepared by using direct compaction method is used by many authors. Authors have considered the samples shape in two different ways i) Cylindrical ii) Rectangular. All cylindrical FAM samples are of size (Height varies from 30mm to 75mm and Diameter of FAM samples varies from 12mm to 12.5mm) are prepared using loose fine aggregate asphalt mixtures as shown in Figure 2.3(a).

Authors selected the maximum aggregate size of aggregates from 0.6mm (Martono et al. 2007) to 1.18mm (Nabizadeh et al. 2017; Kim et al. 2003; Aragao et al. 2010; Haghshenas et al. 2016) and rectangular shape of FAM samples of size (Length varies from 50mm to 60mm, width of the sample varies from 10mm to 12.5mm, Height varies from 6mm to 6.5mm) are prepared using loose mix with fabricated mould as shown in Figure 2.3(b) (Kim et al. 2001; Yang et al. 2017). Summary on preparation methods of FAM specimens is presented in Table 2.3.

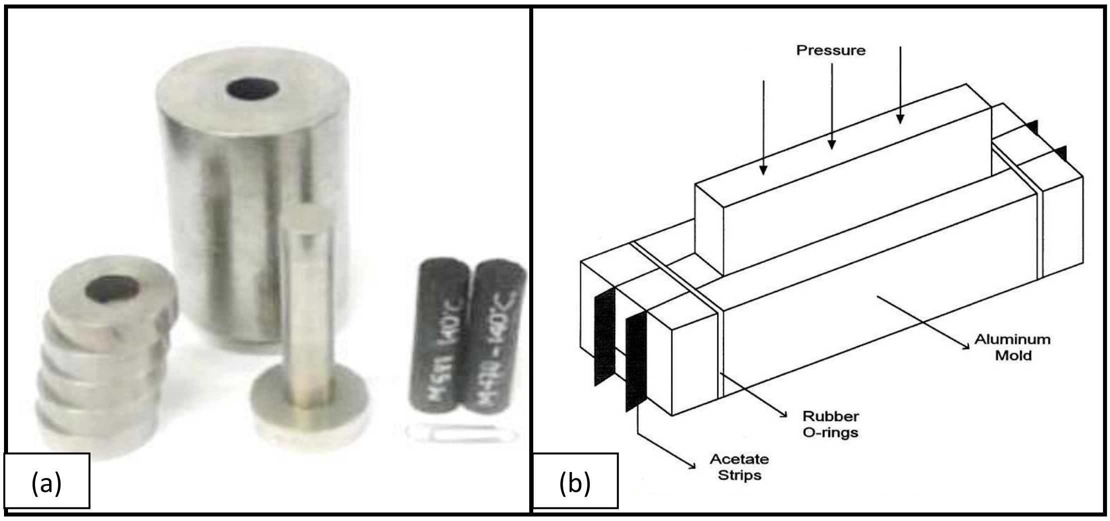


Figure 2.3 (a) Cylindrical FAM specimen mould (Caro et al. 2014), (b) Rectangular FAM specimen mould (Kim et al. 2001)

Table 2.3 Summary on preparation methods of FAM specimens

Sl. No	Authors	Year	Type of HMA sample	Aggregates passing (mm)	Method of preparation	Shape of FAM specimen	Size of FAM specimen (mm)
1	Caro et al.	2008	SGC	1.18	Coring	Cylindrical	50x12.5
2	Bhasin et al.	2011	SGC	1.18	Coring	Cylindrical	50x12.5
3	Arago et al.	2012	SGC	0.6	Coring	Cylindrical	45x12.5
4	Palvadi et al.	2012	SGC	1.18	Coring	Cylindrical	50x20.0
5	Underwood et al.	2013	SGC	2.36	Coring	Cylindrical	45x12.0
6	Sousa et al.	2013	SGC	1.18	Coring	Cylindrical	50x12.5
7	Masad et al.	2014	SGC	1.18	Coring	Cylindrical	50x12.0
8	Kanaan et al.	2014	SGC	2.36	Coring	Cylindrical	50x12.45
9	Im et al.	2015	SGC	1.18	Coring	Cylindrical	45x12.25
10	Karki et al.	2016	SGC	1.18	Coring	Cylindrical	45x12.0
11	Sadeq et al.	2016	SGC	1.18	Coring	Cylindrical	50x12.0
12	Zhu et al.	2017	SGC	2.36	Coring	Cylindrical	50x12.5
13	Freire et al.	2017	SGC	4, 2, and 1.18	Coring	Cylindrical	50x12.0
14	Sanchez et al.	2017,19	SGC	1.18	Coring	Cylindrical	50x12.5
15	Caro et al.	2020	SGC	1.18	Coring	Cylindrical	50x12.5
16	Smith	2000	SGC	4.75	Cutting	Rectangle	50x10x6
17	Reinke et al.	2005	SGC	1.18	Cutting	Rectangle	50x12x10
18	Li et al.	2017	SGC	4.75	Cutting	Rectangle	50x10x10
19	Kim et al.	2001	Loose mix	1.18	Mould	Rectangle	60x10x6
20	Yang et al.	2016	Loose mix	1.18	Mould	Rectangle	50x12.5x6.5
21	Kim et al.	2003	Loose mix	1.18	Mould	Cylindrical	50x12.0
22	Martono et al.	2007	Loose mix	0.60	Mould	Cylindrical	30x12.0
23	Arago et al.	2009	Loose mix	1.18	Mould	Cylindrical	50x12.0
24	Motamed et al.	2013	Loose mix	2.36	Mould	Cylindrical	75x12.5
25	Haghshenas et al.	2016	Loose mix	1.18	Mould	Cylindrical	50x12.0
26	Nabizadeh et al.	2017	Loose mix	1.18	Mould	Cylindrical	50x12.0

Note: SGC = Compacted HMA specimen with height of different size

2.4 VISCOELASTIC PROPERTIES OF FAM MIXTURES

To evaluate the LVE region of the FAM mixtures under both strain/stress controlled mode at different temperatures and frequency helps to conduct further tests on DSR by giving the LVE of the FAM mixtures. The linear viscoelastic characteristics are fundamental properties of asphalt mixtures and are widely used in the design and modeling of mixtures and pavement structures. Therefore, the ability to understand the changes in viscoelastic properties of asphalt mixtures caused by aging is beneficial to track and quantify the effect of aging on mixture performance that is of general concern.

The majority of the fatigue damage is concentrated in FAM phase of full asphalt mixture. The understanding of LVE region of this mixture becomes of utmost importance. This region is where the stiffness value is independent of the load (stress/strain) being applied on FAM. This means there is no damage occurrence in this particular region. When the stress/strain level crosses this LVE range, the cracks start to appear in the mixture (Initiation of fatigue damage).

In order to link this to practical performance of asphalt mixture in the field, where the stress/strain coming on unit area of the pavement is lower (within LVE region), the fatigue damage may not be appearing (or); the number of cycles to fatigue failure (50% reduction in initial modulus value) is indefinite (NCHRP 646). Consequently, an aged asphalt mixture has higher cracking susceptibility and potentially decreases the serviceability of the pavement, lowering ride quality, and requires a considerable amount of taxpayer’s money on frequent maintenance or rehabilitation of the pavement (Zhang et al. 2020).

Strain Sweep Test: Strain sweep tests are performed at different temperature to determine strain levels that satisfy the homogeneity principle of linear viscoelasticity and corresponding linear viscoelastic stiffness of each FAM mixture. The authors usually consider the LVE region of FAM mixtures at 10% drop in the initial value of complex shear modulus. This test can be conducted to identify the strain levels that should be used for the subsequent oscillatory tests (Nabizadeh et al. 2017; Haghshenas et al. 2016; Kim et al. 2003; Aragao et al. 2009). Motamed et al.

(2012) conducted the study on FAM samples to evaluate the viscoelastic properties of FAM mixtures. They have considered the strain value less than 0.035% is the material response within the linear viscoelastic limit, by using this strain conducted creep and recovery tests on FAM samples to obtain linear viscoelastic properties. A torsional shear strain sweep tests were conducted to know the strain levels producing maximum shear stress and peak phase angle (Kim et al. 2003). Kim et al. (2001) carried out strain sweep tests on FAM mixtures to find the strain value 0.2%, which is the LVE strain range value that does not induce any damage to the FAM mixtures while testing. Zhu et al. (2017) carried out strain sweep test from 0.002%-0.6% to get the LVE limit for the FAM mixtures by observing breakage of samples over this strain range. With this observation they concluded that, shear stress increased with increasing shear strain and after reaching to its maximum value it decreased drastically.

There are some authors fixed the LVE strain limit value 0.0065% (Caro et al. 2008, 2012) by conducting the strain sweep test. Caro et al. (2014) conducted the strain sweep test with strain ranges 0.001%-0.1% to determine the threshold from the non-linear viscoelastic zone to the zone where fatigue damage initiates. Sanchez et al. (2017) conducted the strain sweep test with the strain range 0.001%-0.15%. They have given 2 minutes duration at each strain level to observe the modulus value. By this, they identified the strain level that should be used to conduct fatigue tests. Kanaan et al. (2014) varies the strain values while conducting the strain sweep test, and then they observed the complex shear modulus of FAM samples. There are no such differences in modulus values. So, they selected the LVE limit of FAM mixtures as 0.01%. Masad et al. (2008) conducted both strain sweep test and stress sweep test to identify the material properties in the linear viscoelastic range and concluded that 0.0065% strain is the lowest strain value within which complex shear modulus of FAM samples are undamaged. Strain sweep test conducted by Li et al. (2017) on warm-mix recycled asphalt binder, mastic, and FAM to establish the LVE limits and strain levels used for the fatigue tests. They have selected the strain range for FAM mixes of 0.001%-1% and identified the LVE strain value by considering strain within the 10% complex shear modulus reduction. Underwood et al. (2011) carried out a strain sweep test on FAM with different strain levels and finally they have selected the LVE range within the 0.06% strain. LVE strain level used by Yang et al. (2016) was 0.01% strain. This strain level was recommended by ASTM D 7552-2009, they considered directly this strain level as LVE limit for further tests.

Stress Sweep Test: Stress sweep test can be conducted to determine the maximum value of stress amplitude that produces the nonlinear viscoelastic response without causing damage to the FAM samples during the fatigue loading (Masad et al. 2014). Stress sweep test conducted to find the permanent strain level 5% or number of loading cycles up to 10000 to induce fatigue damage to the FAM samples using 135 kPa stress level (Nabizadeh et al. 2017). Stress sweep test can be conducted to monitor the complex modulus with different loading frequencies at 25°C on FAM samples as increase in the stress level (Kim et al. 2003). They find the stress level within the LVE limit by observing the 10% reduction in the initial value of complex modulus. Nonlinear viscoelasticity found by conducting the stress sweep test on FAM mixtures. FAM mixture shows the LVE limit of stress level within 15 kPa (Im et al. 2015). Masad et al. (2014) carried out stress sweep test with stress range 1.1 kPa to 110 kPa swept at equal intervals to find the LVE limit for the stress levels which do not cause any damage to the FAM samples. Differentiating between linear and nonlinearity of FAM materials, stress sweep test carried out to find the LVE region for the FAM samples (Sadeq et al. 2016). They used the stress levels range from 1 kPa to 589 kPa with the stress level increased each time by 25 kPa. After conducting this test they concluded that, stress level within 150 kPa considers the linear viscoelastic region of the materials. Any stress level above the 150 kPa indicates the materials to nonlinearity and then damage.

2.5 PERFORMANCE EVALUATION OF FAM MIXTURES

2.5.1 Fatigue properties of FAM mixtures

Fatigue failure occurs in the FAM mixtures due to progression of load applications or number of load cycles applied on the specimen continuously without any rest periods. The fatigue failure of FAM mixtures can be characterising by using both strain controlled and stress controlled mode. Fatigue failure can be detected by an abrupt and simultaneous decrease in both complex modulus value and phase angle. Many researchers have considered the different damage levels in the FAM samples as final damage generated within the FAM mixtures at the end of the cyclic loading test.

Time Sweep Test: In order to evaluate fatigue cracking potential of FAM mixture, time sweep tests carried out at different testing temperature with strains greater than the LVE limit level of strain satisfying linear viscoelasticity. The larger strains are considered to cause nonlinear behaviour (such as fatigue damage) (Kim et al. 2001; Kim et al. 2003). The strains greater than the linear viscoelastic range are used for conducting the time sweep test to determine the fatigue cracking potential of FAM mixtures (Nabizadeh et al. 2017). Number of loading cycles at the maximum phase angle considers the fatigue failure of FAM mixtures at larger strain value 0.25%. Motamed et al. (2013) conducted the time sweep test on FAM mixture to study the fatigue cracking property of FAM mixtures by considering torsional shear stress 275 kPa applied on FAM samples till 500 minutes or 300000 cycles. This criterion has given to find the fatigue failure of FAM samples. To understand the fatigue damage in the FAM mixture, Kim et al. (2003) selected the larger strain values of 0.4%-0.71% to cause complete fatigue failure on FAM samples. They considers the fatigue failure of FAM samples with longer time when many hairline cracks observed on the surface of FAM samples or macro cracks observed at the end of testing.

Smith and Hesp (2000) adopted 0.2% strain in time sweep test to find the fatigue failure of rectangular shape of FAM samples by considering the 50% loss in the initial value of stiffness. Kim et al. (2003) studied the effect of mineral fillers used in FAM samples by conducting the time sweep test to study the fatigue failure of FAM samples. In this study they have selected the different levels of the strain values (0.20%, 0.28%, 0.40%, and 0.56%) to cause the fatigue damage in the FAM samples. According to Kim et al. (2003), the phase angle peak represents fatigue failure because the material can no longer maintain a high phase angle at failure. The time sweep tests on cylindrical FAM samples to characterise fatigue and healing properties by using strain controlled mode. Constant strains 0.018, 0.022, 0.027, and 0.033% induced with different (40, 10, 10, and 5 min) rest periods introduced intermittently at decreasing order of stiffness levels (Karki et al. 2016). Karki et al. (2014) conducted the time sweep test at different stress modes from 225 kPa-400 kPa without any rest period. They define the fatigue failure of FAM samples at different percentage (80%, 70% and 50%) reduction in the initial stiffness values.

Zhu et al. (2017) and Caro et al. (2008,2012,2014) carried out the time sweep test performed using strain controlled cyclic loading with the strain values of 0.15%. Also, they compared the strain sweep test and time sweep test on finding the fatigue life of FAM samples and concluded that the number of tests and the duration per test for strain sweep testing method are less than those required for the time sweep testing method. The fatigue damage of FAM samples defines, number of cycles at which G* decreased 40% of its initial value selected as the parameter to compare the final damage generated within the FAM mixtures at the end of the cyclic loading test (Sanchez et al. 2017). They conducted the time sweep test with 0.09% as strain value about 4 hours to induce the fatigue failure in the FAM mix samples. The time sweep can be conducted in both stress controlled and strain controlled mode (Freire et al. 2017). They studied the fatigue damage of FAM samples using strain value of 0.065% and stress of 418 kPa with duration of 48 hours. Fatigue failure criteria considered is phase angle achieves highest value, which indicates the sample failure.

Kanaan et al. (2014) carried out a time sweep test under both strain controlled and stress controlled mode. Failure of specimen identified in strain control mode is the strain reaches until 4% and in stress controlled mode, test continues till G* value reaches 1000 MPa. Time sweep test conducted using both strain (low and high) controlled mode and stress (low and high) controlled mode to study the fatigue failure of FAM mix samples. They have used different low and high stress levels 8 kPa and 107 kPa respectively to conduct time sweep test. Strain levels used for this study are 0.0065% and 0.2%. They concluded that controlled-strain test requires more loading cycles than controlled-stress test to cause the same level of damage when both tests begin at the same stress level. Sousa et al. (2013) used the high strain level 0.35% to characterise the fatigue failure of FAM samples.

Sadeq et al. (2016) studied the fatigue behaviour of FAM samples using time sweep test by considering the 75 kPa and 400 kPa stress levels to cause the fatigue damage to the FAM samples with longer duration or up to 200000 cycles. Failure criteria used in this study is 50% reduction in initial shear modulus of FAM samples. Li et al. (2017) considers the three different strain levels (0.1%, 0.15% and 0.20%) to cause fatigue damage to the FAM samples by conducting the time sweep test. Failure criteria define here that 70% reduction in initial shear modulus. Transition point is considered as fatigue failure point. Transition point is where Mixture stiffness (The ratio of stress output to the applied strain input) reduces drastically (Aragao et al. 2009). They used the strain value to conduct the time sweep test was 0.3%. To evaluate the fatigue cracking of FAM mixture, time sweep test conducted using strain levels 0.15%, 0.20% and 0.25% which are greater than the strain level satisfying the linear viscoelasticity. The number of loading cycles at maximum phase angle (or the number of loading cycles at the transition point) was considered as the fatigue life of the mixture (Haghshenas et al. 2016).

According to these studies, the transition point between two inflection points in the stiffness and the loading cycle plot is the most appropriate measure when fatigue failure occurs as it represents the shift from microcracking to macrocracking. The rate of stiffness reduction drastically increased at that transition point when the macrocracks started to form. The authors also showed good agreement between the number of loading cycles at the transition point and at the peak phase angle. This failure criterion has been considered a more logical and better estimate of fatigue failure of asphalt mixtures than arbitrarily using the 50% reduction in stiffness as a failure criterion. As an example plot, Figure 2.4 presents the failure criterion determined by the transition point.

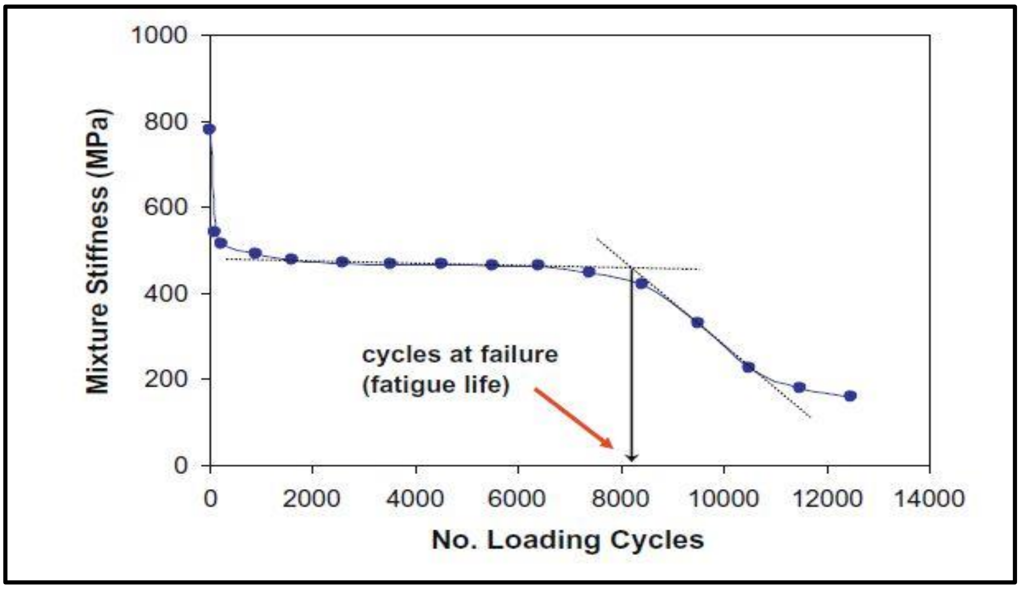


Figure 2.4 The strain controlled time sweep test for determining fatigue failure (Aragao et al. 2009)

Table 2.4 Studies on fatigue properties of FAM mixtures

Sl. No	Authors	Time Sweep Test/Cyclic Fatigue Test		
		Stress Controlled, kPa	Strain Controlled, %	Fatigue Failure Criteria, (No. of loading cycles at)
1	Smith et al. (2000)	-	0.2	50% reduction in $\|G^*\|_o$.
2	Kim et al. (2003)	-	0.2-0.56	δ_{max}.
3	Kim et al. (2003)	-	0.4-0.7	δ_{max} & different damage levels.
4	Aragao et al. (2010)	-	0.3	δ_{max}.
5	Haghshenas et al. (2016)	-	0.15-0.25	δ_{max}.
6	Nabizadeh et al. (2017)	-	0.25	δ_{max}.
7	Zhu et al. (2017)	-	0.15	δ_{max}.
8	Sanchez et al. (2017)	-	0.09	40% reduction in the $\|G^*\|_o$.
9	Freire et al. (2017)	418	0.065	δ_{max}.
10	Motamed et al. (2012)	275	-	Up to 300,000 cycles/ δ_{max}.
11	Karki et al. (2014)	225 and 400	-	60% reduction in the $\|G^*\|_o$.
12	Sadeq et al. (2016)	75 and 400	-	50% reduction in the $\|G^*\|_o$.

Note: $|G^*|_o$= Initial stiffness value, δ_{max}= Maximum phase angle

The fatigue failure criterion changed from one work to another work, because the sample may not fail fully within the test duration or at particular failure cycles considered for the test. So, the researchers have been used some damage levels and maximum phase angle as a failure criterion to find the fatigue life of FAM mixtures.

The detailed descriptions of fatigue failure criterion used in the fatigue test on FAM mixtures are shown in Table 2.4.

2.5.2 Rutting properties of FAM mixtures

Rutting characteristics of FAM mixtures is a function of the duration of the rest period, and level of the stiffness preceding the rest period. Studies have shown that, duration of rest period and the stiffness preceding the rest period significantly affected healing behaviour of the materials. To investigate the rutting properties of FAM samples, researchers are being used the different loadings (strain mode or stress mode) as creep loading. Also, they have used the different rest periods at different damage levels. By observing the stiffness value of FAM mixtures before and after rest periods, they used to find the percentage recovery in FAM mixtures. FAM mixture recovers more during the longer rest periods than the lesser rest periods. Also, researchers observed that, the percentage of recovery of FAM mixtures is more when rest periods introduce at lower level of damage than higher level of damage (Karki et al. 2014). The DSR has been successfully used to characterise the permanent deformation and healing potential of FAM mixtures with and without rest periods in several studies.

Creep and Recovery Test on FAM Mixtures: Creep recovery test can be carried out to determine the amount of creep strain and irrecoverable strain of FAM mixtures subjected to different stress levels and at different temperatures in order to evaluate the permanent deformation characteristics of FAM mixtures (Nabizadeh et al. 2017). Also, this test carried out to characterise the healing potential of FAM mixtures with and without rest periods in several studies. Creep loading time of 30 sec and recovery time of 300 sec given for conducting the creep and recovery test at different stress levels 15 kPa, 25 kPa, 50 kPa and 75 kPa (Nabizadeh et al. 2017). From this study, they found out the irrecoverable strain of the FAM mixtures at the end of 300 sec. This test can also be carried out using different strain levels (Smith and Hesp 2000). Bhasin et al. (2011) used the 4 min rest period for nine times while conducting the fatigue test on the FAM samples. Each 4 min rest period applied corresponding to the 2.5, 5, 10, 15, 20, 30, 40 and 50% of the fatigue life value for particular FAM samples measured without any rest period. Motamed et al. (2013)

carried out a creep and recovery test to determine the viscoelastic properties of FAM samples. The test conducted using stress controlled mode 30 kPa stress with creep loading time 3 sec and recovery time of 300 sec. Creep loading is limited only up to strain reaches 0.035%. This indicates the material's response most likely within the viscoelastic limit.

Smith and Hesp (2000) used the two different strain levels i.e, 0.1% and 0.2% to conduct the creep recovery test. Test continues till 50% reduction in the initial stiffness value of rectangular shape with size 50 mm long, 6 mm thick and 10 mm wide of FAM samples, and then rest period of 18 hrs provided for recovery in FAM mixture stiffness. From this test, they determined the percent recovery in fatigue life of FAM samples over 18 hrs rest period. Controlled shear strain cyclic test conducted on rectangular bar FAM samples of size 60 mm long, 6 mm thick and 12 mm wide. Rest periods are used in this study 1, 2, 1 and 4 mins at different levels of loading cycles 600, 6000, 12000 and 24000 respectively. Test continues till 30000 load cycles and finally they concluded that the recovered pseudo stiffness after the rest periods can be considered due to the micro damage healing. Palvadi et al. (2012) and Karki et al. (2014) studied the effect of different rest periods at different levels of initial stiffness of FAM samples with stress controlled mode 220 kPa. By this study they quantify the healing at a specific level of pseudo stiffness and duration of rest period. Karki et al. (2016) conducted the creep and recovery tests on cylindrical FAM samples to characterise healing properties by using strain controlled mode. Constant strain 0.027% induced with different rest periods introduced intermittently at decreasing order of stiffness levels. Static creep recovery test carried to characterise the stress dependent nonlinear viscoelastic properties of FAM mixtures. Creep stresses 15, 20, 30, 40, 50 and 75 kPa for a time 30 sec followed by 500 sec recovery time applied on the FAM samples (Im et al. 2015).

An ideal trend for pseudo stiffness versus the number of cycles before and after a rest period is shown in Figure 2.5 (Kim et al. 2001). In Figure 2.5, the curve OBCD represents the reduction in the pseudo stiffness due to damage growth without a rest period, and the curve AB′D′ depicts the reduction in the pseudo stiffness due to damage growth after the rest period. The pseudo stiffness increased from Point B to

Point A after the rest period due to the micro damage healing, and it decreased as the loading continued after the rest. Therefore, it can be concluded that the rest periods and corresponding micro damage healing contributed to an increase in fatigue life by an amount equal to ΔNf.

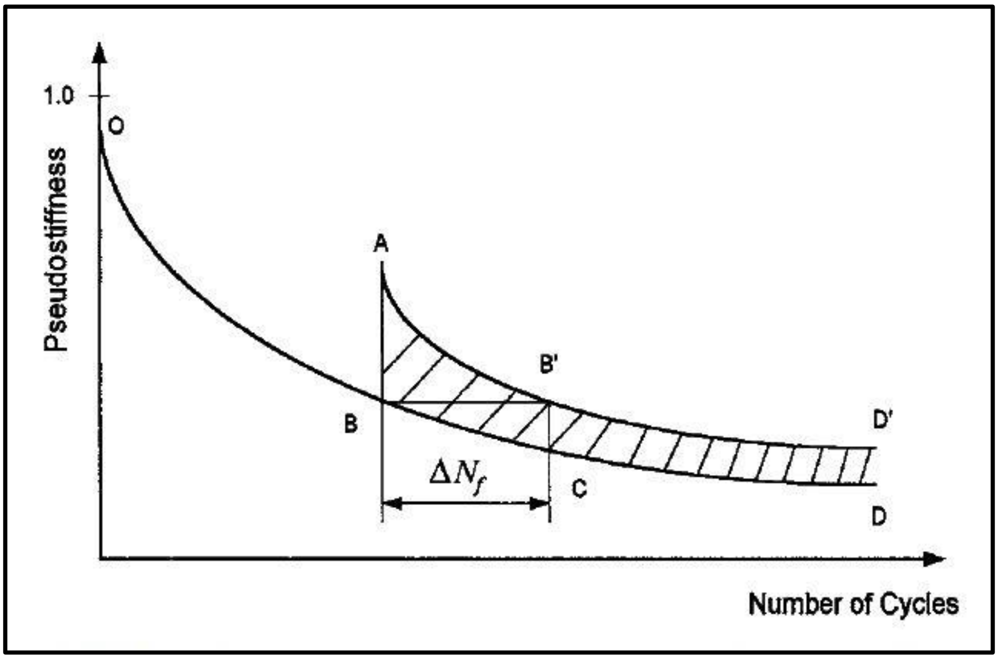


Figure 2.5 Ideal trend, which is conceptual not real, before and after rest period (Kim et al. 2001)

2.5.3 Complex shear modulus and dynamic modulus of FAM and full asphalt mixtures

FAM mixture is a representative of fine portion of full asphalt mixture. There are less available instruments to find the complex shear modulus of full asphalt mixtures which are also more expensive, time consuming, larger samples required to carry out test. From the literature Harvey et al. (2000), Brown et al. (2001), Azari et al. (2005), Druta et al. (2008), and Visintine et al. (2013), the instrument Superpave Shear Tester (SST) (Figure 2.6(a)) is used for finding the complex shear modulus of full asphalt mixture as per ASTM D7312. While, complex shear modulus (|G*|) of FAM mixture is determined using DSR (Figure 2.6(b)) in laboratory which is defined by the ratio of shear stress to shear strain. In recent years, researchers Aragao et al. (2010), Caro et al. (2012), Motamed et al. (2012), Sadeq et al. (2016), and Zhu et al. (2017) are being used the DSR to find the complex shear modulus of FAM mixtures as per ASTM D7552. This method of finding complex shear modulus of FAM mixtures is much easier, economical and consumes less material than the full asphalt mixtures. The test parameters like strain value, frequencies and temperatures used to find the complex shear modulus are same for both instruments. From Table 2.5, complex shear modulus (|G*|) of FAM mixtures and full asphalt mixtures compared at intermediate temperature range from 15-30°C where in the range of 2.5×10^{8} Pa to 2.96×10^{9} Pa and are not similar. However, |G*| as determined by using DSR at a strain of 0.01 % as per ASTM D7552 produces results comparable to those obtained on the Superpave Shear Tester (SST) performing the frequency sweep at constant height with other similar test conditions.

Table 2.5 Complex shear modulus and dynamic modulus of FAM and full asphalt mixtures

Sl. No	Authors	SST Specimen Results			Authors	FAM Specimen Results		
		Freq, Hz	Temp, °C	|G*| (MPa)		Freq, Hz	Temp, °C	|G*| (MPa)
1	Harvey et al. (2000)	10	20	2280	Aragao et al. (2010)	10	25	800
2	Azari et al. (2003)	10	25	2960	Motamed et al. (2012)	10	16	1560
3	Azari et al. (2005)	10	25	825	Caro et al. (2012)	10	28	250
4	Visintine et al. (2013)	10	20	2070	Sadeq et al. (2016)	10	25	1240
5	Druta et al. (2008)	10	25	600	Zhu et al. (2017)	10	20	700

Further, researchers have studied the dynamic modulus and the phase angle of FAM and full asphalt mixtures and concluded that, the FAM mixtures shows sensitivity that is more in line with that observed for full asphalt mixture under all of the tested conditions (Underwood and Kim 2011). This correspondence between the FAM and full asphalt mixture properties was also observed for the moisture characterisation and fatigue cracking and permanent deformation characterisation (Caro et al. 2008; Motamed 2012; Coutinho 2012; Nabizadeh 2015; Im et al. 2015). Motamed et al. (2012) compared the fatigue cracking resistance between FAM and full asphalt mixtures via fatigue life (number of cycles to achieve 50 % of the initial modulus), and observed that the FAM presented the same rank order for fatigue life of the full asphalt mixtures produced with the same modified asphalt binders. It can be concluded that the FAM is able to characterise the full asphalt mixtures in a qualitative way.

Figure 2.6(a) SST (Brown et al. 2001)

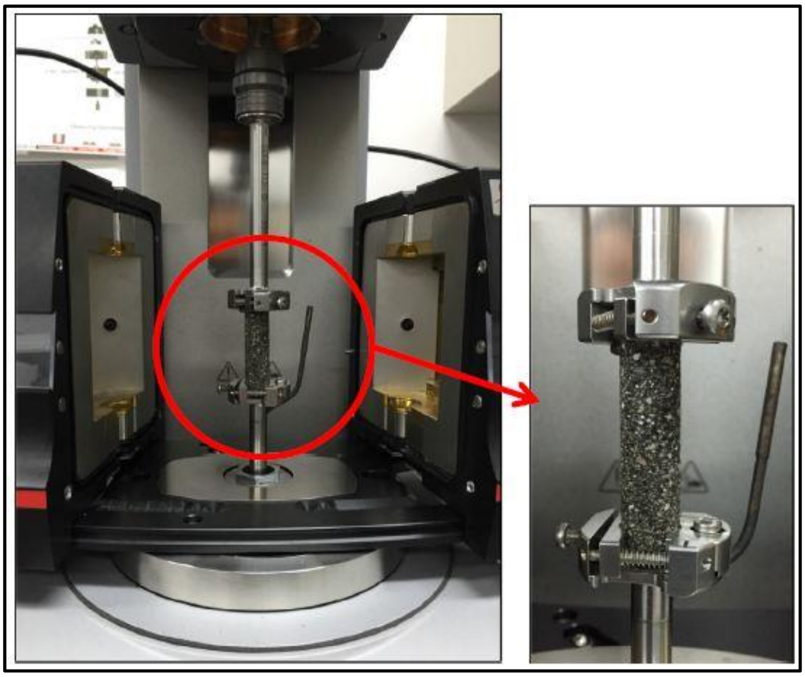


Figure 2.6(b) DSR torsion bar fixture (He et al. 2016)

2.6 SUMMARY OF LITERATURE REVIEW

The utilisation of smaller FAM specimens rather than the HMA specimens to assess viscoelastic, fatigue, rutting, and moisture induced damage performance of FAM mixtures in road construction industries is gaining more popularity worldwide due to its simplicity and rational approach. This review presents utilization of test conducted on FAM mixtures to evaluate viscoelastic, fatigue, rutting, and moisture induced damage properties. However, several studies are available in the domain of viscoelastic, fatigue, rutting, and moisture induced damage characterisation of FAM asphalt mixtures based on the monotonic FAM test technique, the combined discussion provides a comprehensive understanding of the review for completeness purposes.

The first part of the review focused on the FAM material characterisation. In this section, the preparation of FAM mixtures was studied which includes, different gradations, asphalt content and air voids distribution. The different aggregate gradations with respect to the maximum aggregate sizes of 4.75 mm, 2.36 mm, 2 mm, 1.18 mm and 0.6 mm was adopted. Further, selection of asphalt content was based on aggregate surface area method. In addition, varying air voids of 1% (Karki et al. 2015) to 15% (Motamed et al. 2012) was adopted for the preparation of FAM mixtures. However, there is no standard protocol to use maximum size of aggregates, asphalt content and air voids to prepare the FAM mixtures. Hence, characterisation of these will lead to better representation of HMA. The second part of this review focused on the different methods for fabrication of FAM specimen. In this section, review has concentrated on studies carried out using different methods in preparing the FAM specimens. The characterisation of viscoelastic, fatigue, rutting, and moisture induced damage properties of FAM mixtures was done usually with DSR by adopting rectangular and cylindrical specimens with different dimensions.

The major part of the review focused on the tests carried out in characterisation of viscoelastic, fatigue, rutting, and moisture induced damage properties of FAM mixtures using DSR. The main tests studied to characterise the viscoelastic properties are strain sweep and stress sweep tests. Next, to characterise the fatigue properties, time sweep test was conducted with strain controlled and stress controlled mode. Here, the researchers find out the number of cycles to failure or the fatigue failure is considered based on the reduction in the initial stiffness of the FAM mixtures. Then the rutting properties are characterised by conducting the creep and recovery test by introducing different rest periods at different intervals using both strain controlled and stress controlled mode. From this test, researchers evaluated the percentage recovery in the FAM mixtures. Furthermore, to analyse the impact of moisture on creep recovery response of FAM mixtures, the creep recovery test conducted on dry and wet conditioned FAM specimens at different stress levels and temperatures were considered. From this test, researchers evaluated the decrease in percent recovery or increase in in non-recoverable creep compliance by conducting creep recovery test on moisture conditioned FAM specimens. Further, |G*| as determined by using DSR at a strain of 0.01 % as per ASTM D7552 produces results comparable to those obtained on the Superpave Shear Tester (SST) performing the frequency sweep at constant height with other similar test conditions. Also, the dynamic modulus of full asphalt mixture shows sensitivity that is more in line with that observed for FAM mixtures. Overall, the FAM mixture is able to characterise the full asphalt mixtures in a qualitative way for characterising the viscoelastic, fatigue, rutting, and moisture induced damage properties.

CHAPTER 3

3.0 MATERIALS AND METHODOLOGY

3.1 MATERIALS

The FAM mixture is a blend of asphalt binder, fine aggregates and fillers having of size less than 0.075 mm (Kim et al. 2003). Following sections includes brief information on the basic properties of various materials utilized in this research work.

3.1.1 Asphalt binder

Two Viscosity Graded (VG) base asphalt binders and one Polymer Modified Binder (PMB) designated as PMB(S) 'S' indicates Styrene-Butadiene-Styrene (SBS) were considered for this research work. As per Indian Road Congress (IRC) recommendation, if the expected traffic level is less than 30 msa, VG-30 should be used. Similarly for expected traffic level more than 30 msa, VG-40 is recommended. Further, VG-40 asphalt binder is well suited where the locations such as intersections, near tolls booths, and truck parking lots experience the higher pressure from heavy traffic loads. Also, due to high viscosity of this asphalt binder, it is more appropriate for improving the resistance to shoving and other problems associated with higher temperatures and heavy traffic loads. Therefore, considering the wider range of traffic, both VG-30 as well as VG-40 was chosen for this research work. Viscosity graded VG-30 and VG-40 asphalt binders were obtained from the local refinery, Mangaluru, India. Additionally, asphalt binder modified with SBS was also considered for this research to incorporate one of the asphalt binder modifiers in this research. The asphalt binders were used in this study confirmed the IS: 73-2013 requirement for grades VG-30 and VG-40. Similarly, PMB(S) also satisfied the IS: 15462-2019 requirements. The basic properties of VG-30, VG-40, and PMB(S) are presented in Table 3.1, Table 3.2, and Table 3.3 respectively.

Table 3.1 Basic properties of asphalt binder (VG-30)

Property	Test Results	Limiting value IS 73:2013
Penetration at 25°C, 0.1 mm	64	Min. 45
Softening point (R&B) (°C)	52	47
Absolute viscosity at 60°C (poise)	2700	2400-3600
Kinematic viscosity at 135°C (cSt)	438	Min. 350
Flash Point (°C)	≥220	Min. 220
Tests on residue from RTFO test:		
Viscosity ratio at 60°C	1.78	Max. 4.0

Table 3.2 Basic properties of asphalt binder (VG-40)

Property	Test Results	Limiting value IS 73:2013
Penetration at 25°C, 0.1 mm	41	Min. 35
Softening point (R&B) (°C)	57	50
Absolute viscosity at 60°C (poise)	3340	3200-4800
Kinematic viscosity at 135°C (cSt)	497	Min. 400
Flash Point (°C)	≥220	Min. 220
Tests on residue from RTFO test:		
Viscosity ratio at 60°C	1.93	Max. 4.0

Table 3.3 Basic properties of modified asphalt binder (PMB(S))

Property	Test Results	Limiting value IS 15462:2019
Softening point (R&B) (°C)	61	Min. 60
Viscosity at 150°C (Pa.s)	0.62	Max. 1.2
Flash Point (°C)	≥230	Min. 230
Separation, difference in softening Point (R&B) (°C)	0.8	Max. 3.0
Tests on residue from RTFO test:		
Loss in mass (%)	0.6	Max. 1.0
High temperature PG grade (°C)	PG 64-XX	-
Intermediate failure temperature (°C)	17.60	-

3.1.2 Aggregates and aggregate gradation for FAM mixtures

The single source granite fine aggregate was collected from Kinnigoli Quarry, Mangaluru, India. The fine aggregates smaller than 2.36 mm sieve size found to have specific gravity of 2.67. Similarly, aggregate water absorption value was found to be 0.54% which satisfied the requirements set by the Ministry of Road Transportation and Highways, (MoRTH 2013) requirement (≤ 2%).

3.1.3 Aggregate gradation for FAM mixtures

The FAM aggregate gradation was designed based on the dense graded asphalt mixture with a nominal maximum aggregate size of 19.0 mm. The FAM consists of the fine portion of the full asphalt mixture with aggregates passing sieve 2.36 mm (Underwood and Kim 2011; He et al. 2016; Zhu et al. 2017). The usage of too smaller aggregates passing 1.18 mm is not practical to prepare FAM specimens because, large amount of fine materials are needed to prepare FAM specimens (He et al. 2016; Zhu et al. 2017). Also, FAM specimens prepared using larger size aggregates passing 4.75 mm may cause variability in test results (He et al. 2016; Zhu et al. 2017). Therefore, aggregates passing through 2.36 mm sieve were used for the preparation of FAM specimens in this study. The HMA mix design and FAM gradation (Branco et al. 2008; Sousa et al. 2013; Freire et al. 2017) are shown in Figure 3.1. The optimum binder content for the FAM mixtures was determined with the help of surface area method (Li et al. 2017; Ng et al. 2018). Considering homogeneously coated aggregates with asphalt binder having film thickness of 10 µ (Kim et al. 2003; Karki et al. 2015; sadeq et al. 2016), the optimum binder content (7.3% by weight of total mix) was kept same for all type of FAM specimens so that the additional effect of change in asphalt binder content could be avoided and a reasonable comparison could be made. The target air void for various FAM specimens was varied from 4-6% (±1%). It is to be noted that the proportioning of fine aggregates present in the FAM mixtures were kept the same as in the full HMA mixture aggregate gradation. However, the amount of finer proportion of aggregate (smaller than 2.36 mm) was normalized with respect to the largest size of aggregate used in the FAM (=2.36 mm) (Eq. 3.1). Further, the aggregate gradation for HMA and FAM mix design are presented in Table 3.4.

$$\text{Percent passing sieve x in FAM}=\frac{\text{Mass of aggregate passing sieve x in full mixture}}{\text{Mass of aggregate passing sieve 2.36 in full mixture}}X100 \quad (3.1)$$

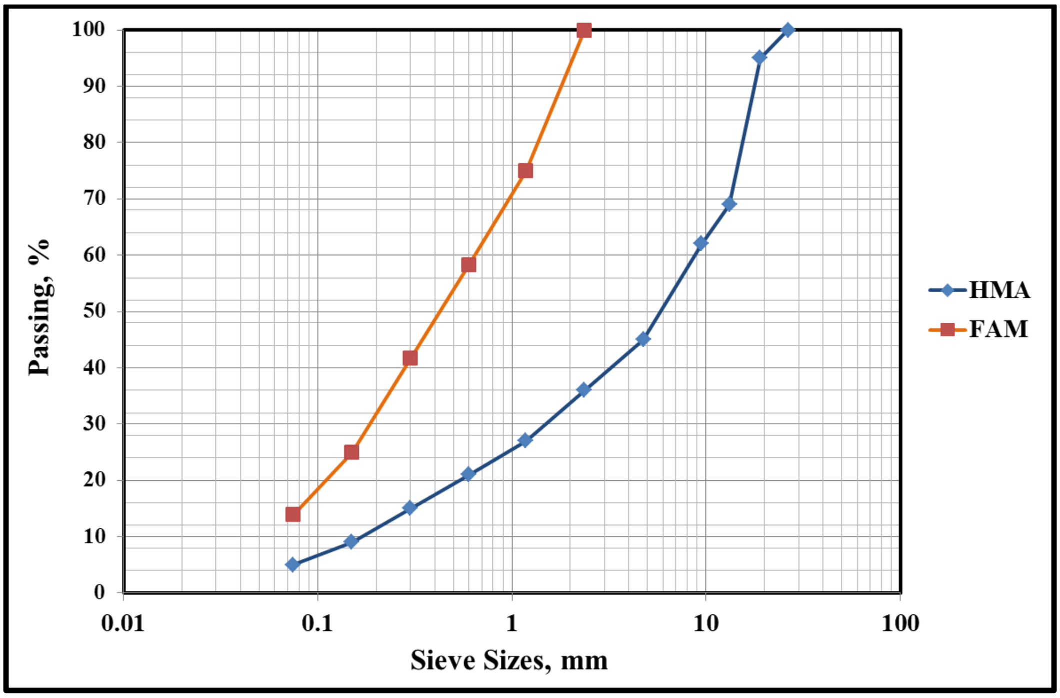


Figure 3.1 Aggregate gradations for HMA and FAM mix design

Table 3.4 Aggregate Gradations for HMA and FAM Mixtures

Sieve size, mm	HMA			FAM		
	Cumulative % by weight of total aggregate passing					
	Maximum	Adopted	Minimum	Maximum	Adopted	Minimum
26.5	100	100	100	-	-	-
19	100	95	90	-	-	-
13.2	79	69	59	-	-	-
9.5	72	62	52	-	-	-
4.75	55	45	35	-	-	-
2.36	44	36	28	100	100	100
1.18	34	27	20	77	75	71
0.60	27	21	15	61	58	54
0.30	20	15	10	45	42	36
0.15	13	9	5	30	25	18
0.075	8	5	2	18	14	7
Pan	0	0	0	0	0	0

3.2 FAM SPECIMEN PREPARATION BY DIRECT COMPACTION METHOD

Based upon the availability of resources and other laboratory constraints, either cylindrical or rectangular FAM specimens have been used by different researchers (Kim et al. 2001; Caro et al. 2015; He et al. 2016). Rectangular shaped FAM specimens were prepared in this research work. Getting uniform, homogeneous and smooth surface of FAM specimen is important as it helps in obtaining repeatable results in the laboratory (Kim et al. 2001; Suresha and Ningappa 2018). Such an approach for FAM specimen preparation not only produces specimens having smooth surfaces, but also save (a) significant lab space, (b) minimizes material wastage, and (c) saves significant time in mixing, compaction and cutting process. Initially, rectangular beam mould having a dimension of 50 mm x 12 mm x 10 mm as per ASTM D7552 guideline was fabricated. Subsequently, FAM specimens were prepared using a direct compaction method as recommended by Aragao et al. (2010) and Nabizadeh et al. (2017).

Equiviscous approach was used for calculating mixing temperature for VG-30 and VG-40, and found to be 153°C and 162°C respectively. Additionally, the mixing temperature equal to 174°C was used for polymeric modified asphalt binder as per manufacturer's recommendation. The minimum compaction temperature equal to 140°C was used in this research work as per MoRTH 2013 recommendation. Fine aggregates and asphalt binders were heated to mixing temperature and mixed manually until fine aggregates is thoroughly coated to obtain a loose FAM mixture. Subsequently, the loose FAM mixture was placed in a conditioning oven for Short Term Aging (STA) as per AASHTO R30 for about 4 hours at specified compaction temperature 135℃. Further, maximum density of FAM mixtures was determined (ASTM D2041). The specially fabricated moulds are kept for half an hour in oven at compaction temperature. After heating of moulds, the hot FAM loose mixture mass determined were poured evenly into the moulds. Then the compaction of FAM loose mixture is conducted at compaction temperature by applying the static pressure (Kim et al. 2001; Aragao et al. 2010; Nabizadeh et al. 2017).

Figure 3.2 shows the various stages adopted during FAM specimen preparation. Specially provided fixture with Dynamic Shear Rheometer (DSR) was used to characterize each FAM specimens (Figure 3.3). Utmost care was taken for FAM specimen while assembling in the DSR rectangular fixture so that it is well aligned and centred to avoid inconsistency of the obtained results.

Figure 3.2 Rectangular FAM specimen preparation and dynamic shear rheometer (MCR 502) Setup

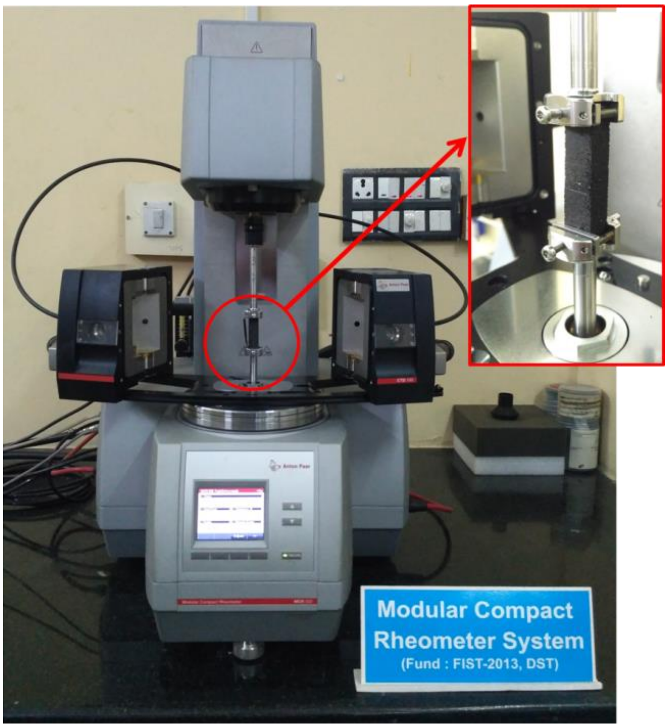


Figure 3.3 Dynamic Shear Rheometer (MCR 502) setup

3.3 SHORT TERM OVEN AGING (STA) AND LONG TERM OVEN AGING (LTA)

Laboratory aging was conducted in an air draft oven. Short-term oven aging on FAM loose mixture at 135°C for 4 hrs recommended by AASHTO R30 before compaction process have been carried out. To simulate long-term oven aging, current protocol 5 days at 85°C (AASHTO R30) on compacted FAM specimens is used. The 5 days of long term aging at 85°C will not ensure steady state condition. Because, the current AASHTO R30 protocol did not age the material as severely as field exposure does. Moreover, this method may not be appropriate to simulate the field aging under all conditions. The AASHTO procedure only includes a single conditioning time and temperature which is considered to match field aging at any location, regardless of the temperature history and climatic region of the pavement of interest. Furthermore, aging on the compacted specimen leads to the development of an aging gradient from the specimen's center to its periphery, which violates the representative volume element requirement for performance testing. Aging compacted specimen can also result in different aging extents for different geometry specimens. (Houston et al. 2005; Newcomb et al. 2019/NCHRP 919; Zhang et al. 2020). Recently, researchers have been working to develop improved methods that rely on aging loose asphalt mixtures instead of compacted specimens to reflect field aging more accurately (Blankenship et al. 2010/AAPT 06-01; Kim et al. 2018/NCHRP 871).

To overcome this problem, oven aging on loose FAM mixture was selected from the recent findings. One aging procedure (24 hrs 135°C) recommended by Asphalt Institute, the other protocol, as recommended by the Wisconsin Department of Transportation (DOT) specifications, consisted of aging the loose FAM mixtures for 12 hrs at 135°C prior to compaction, others loose mixture aging at (5 and 12 days 95°C) of asphalt mixture recommended by NCHRP 9-54. Further, 6 hrs and 12 hrs for 135°C selected to understand the lower aging level and intermediate level of aging effect on viscoelastic properties of FAM mixture. The findings from this project depicts that loose mixture aging is more severe and uniform compared to current long-term oven aging procedure on compacted specimen AASHTO R 30. The details of method to fabricate FAM specimens in this study adopted are shown in Table 3.5.

Table 3.5 Details of method to fabricate FAM specimens

Steps	STA/LTA	Temperature	Duration
Pre-heating of fine aggregates and asphalt binder		153°C	40 min
Mixing of loose FAM mixture			
Loose FAM mixture	STA	135°C	4 hrs
Loose FAM mixture	LTA	135°C	6, 12, and 24 hrs
Loose FAM mixture	LTA	95°C	5, and 12 days
Pre-heating of moulds		135°C	1 hr
Pre-heating		135°C	2 hrs
Compacting			
Compacted specimens	LTA	85°C	5 days
Cooling		AC room at 18°C	2 hrs
Extraction of specimens from the moulds			
Equilibration		Room temperature	24 hrs

3.4 TESTS CONDUCTED

3.4.1 Strain sweep test

Strain sweep test was carried out on both STA and LTA FAM specimens to determine the linear viscoelastic region of each FAM mixture (Marasteanu and Anderson 2007; Aragao et al. 2010; Nabizadeh et al. 2017). This test was conducted at a single temperature and frequency level of 25°C and 10 Hz respectively by changing the strain levels from 0.0001% - 0.1%. The idea behind choosing a single temperature (25°C) was due to the fact that as the testing temperature increases, the strain corresponding to Linear Viscoelastic (LVE) range increases. This approach ensured that this test was conducted at a selected strain level at subsequently higher temperatures (higher than 25°C) are well within the LVE range. Strain corresponding to a 10% drop in the |G*| was considered as maximum strain level under LVE range.

3.4.2 Temperature and frequency sweep test

Temperature and frequency sweep test was conducted to determine the viscoelastic properties of each FAM mixtures. Based on the LVE test results, constant strain level selected well within LVE range was selected (=0.006%). The temperature was varied from 15°C to 65°C at the interval of 10°C, whereas, frequency level was varied from 0.1 Hz to 25 Hz. The master curve for average complex shear modulus |G*| and phase angle δ was subsequently drawn. Logarithm sigmoidal model was further used for drawing the master curve for |G*| at the reference temperature (Underwood and Kim 2011; Yusoff et al. 2013; Yang et al. 2016; Nobakht and Sakhaeifar 2018; Sahebzamani et al. 2018; Sanchez et al. 2019). Eq. 3.1 shows the mathematical form of the logarithmic sigmoidal model of |G*|. In this study, the Lorentzian peak equation was used to model the δ master curve accurately. Eq. 3.2 shows the Lorentzian peak model equation for drawing the master curve for δ (Rahbar-Rastegar et al. 2018; Nemati and Dave 2018; Nemati 2019). Although a variety of time–temperature shift factor equations have been employed to construct the master curves as indicated in the literature (Pellinen et al. 2002; Pellinen et al. 2004; Rowe and Sharrock 2011; Rema and Swamy 2019). Some examples are (1) free-shifting of experimental results, (2) Williams-Landel-Ferry (WLF) equation, (3) Arrhenius- type equation, (4) Log-linear equation, (5) Viscosity-Temperature Susceptibility (VTS), and (6) the Kaelble shift function. From these equations, the Williams-Landel-Ferry (WLF) equation was proved to be the most appropriate shift factor equation for constructing the master curves, as it provides the most accurate predictions in a fairly wide frequency range and test temperatures that are higher than the glass transition (Tg) temperature (Williams et al. 1955; Levenberg and Shah 2008; Liu and Luo 2017; Luo and Liu 2017). Accordingly, the WLF equation was selected for the |G*| and δ master curves, as presented in the thesis Eq. (3.3). Also, studies carried out on FAM mixtures used the WLF equation while constructing the |G*| and δ master curves (Underwood and Kim 2011, 2013; Elkashef et al. 2019). Based on this background, the WLF equation was utilized for finding out the reduced frequency at the reference temperature 25°C (Eq. 3.3).

From this test, the master curve for response parameters can be plotted at each temperature as a function of frequency in log-log scale. The different curves obtained at each temperature were horizontally shifted along the logarithmic frequency axis to form a smooth master curve at reference temperature. In this study, the reference temperature is considered as 25°C. The temperature dependent horizontal shift for constructing master curve is the t-T shift factor. Further, the solver module in Microsoft Excel® is used for minimizing the sum of squares of error between the measured and predicted values.

With respect to the sigmoidal function it is an S-shaped curve with four parameters that either directly or indirectly define four important shape characteristics; the upper asymptote, the lower asymptote, the maximum slope, and the inflection point wherein the shape transforms from one with increasing slope to one with decreasing slope (as one moves left to right). In this case a parametric analysis is useful in interpreting how well the optimisation process proceeds since variations in data quality can interfere with the rationality of these physically related characteristics. This process is first facilitated by taking the frequency as infinity or as zero. Since multiple forms of the sigmoidal function exist both in general terms and within the asphalt concrete literature one must be careful in performing this task with the exact sigmoidal function of interest. In doing this analysis on Eq. 3.1, the β and α parameters are related to the glassy modulus (upper asymptote) and the equilibrium modulus (lower asymptote) of the master curve, respectively. The κ value controls the width of relaxation spectra, and the frequency of the inflection point can be calculated from $10^{-\gamma/\kappa}$, which describes the elastic-viscous transition exhibited as a result of a shift between behavior dominated by the aggregate structure and the binder. These shape parameters from dynamic modulus master curves are described and illustrated in Figure. 3.4. Generally, κ increases when aging level increases, while $-\gamma/\kappa$ decreases as aging level increases, which means the asphalt mixtures will become more elastic as the elastic-viscous transition point moves to a lower frequency, resulting in a flatter dynamic modulus curve.

$$\log|G^*| = \alpha + \frac{\beta}{1+e^{\gamma+\kappa(\log\omega_r)}}, \qquad (3.1)$$

Where, α, β, γ, κ are the sigmoidal fitting coefficients which describe the shape of the $|G^*|$ master curve and ω_r is the reduced frequency.

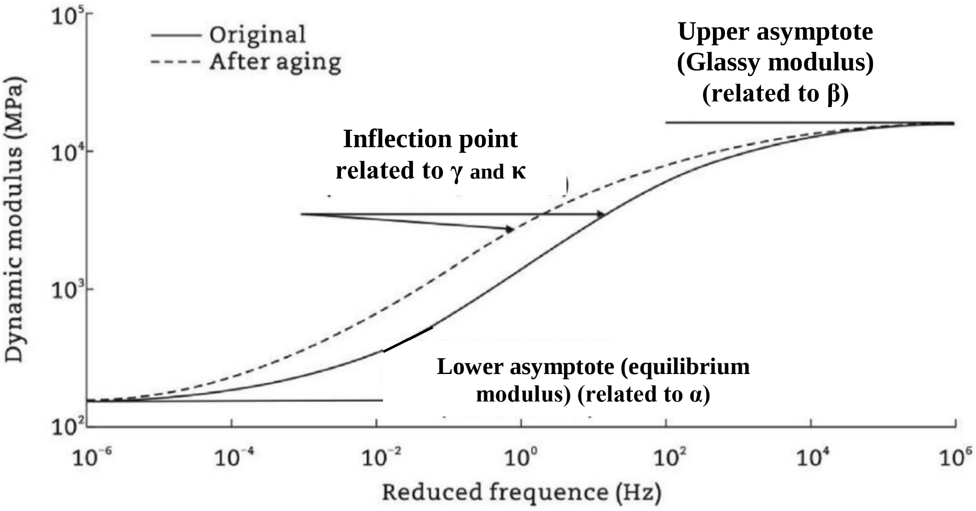


Figure 3.4 Shape parameters from |G*| master curve (Zhang et al. 2020)

$$\text{Phase angle } (\delta) = \frac{a*b^2}{[(\log \square_r - c)^2 + b^2]}, \tag{3.2}$$

The fit coefficients are a, b, and c as follows: 'a' indicates the peak value, 'b' controls the transition length, and 'c' is connected to the peak point horizontal position of the peak point (the frequency of the peak point can be calculated from 10^c), δ is phase angle and ω_r is the reduced frequency. The 'a' and 'c' values typically decrease as aging level increases, moving the curve to the bottom left of the plot. The parameters are called vertical peak and horizontal peak instead of 'a' and 'c' in thesis. The parameters results are explained briefly in section 4.3.2. Figures 3.5 describe and illustrate the shape parameters from phase angle master curves.

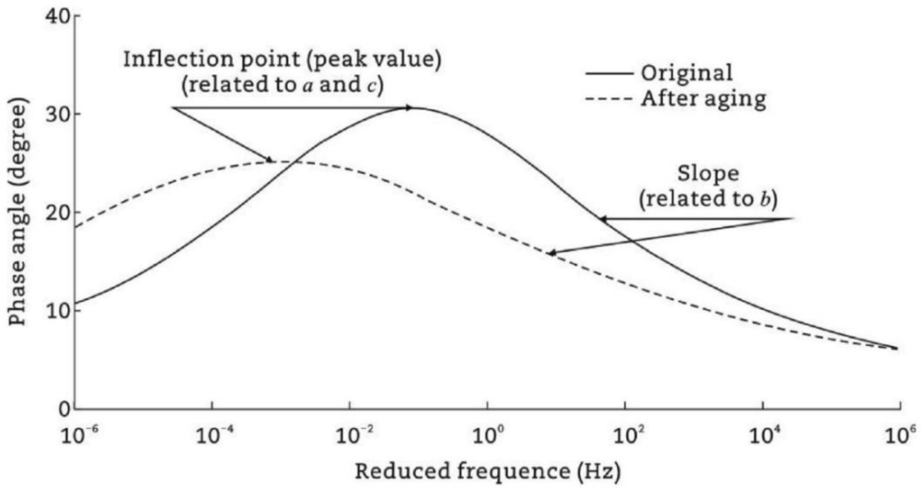


Figure 3.5 Shape parameters from δ master curve (Zhang et al. 2020)

$$\log a_T = \frac{C1(T - T_R)}{C2 + T - T_R}, \tag{3.3}$$

Where, T refers testing temperature (°C), T_R is the reference temperature (25°C) and C_1, C_2 are the fitting coefficients.

3.4.3 Time sweep test

The strain controlled time sweep test was carried out on STA and LTA FAM specimens to characterise the fatigue cracking potential of FAM mixtures (Smith 2000; Kim et al. 2003; Kim 2005; Zollinger 2005; Aragao et al. 2010; Karki 2010; Motamed et al. 2012; Kanaan et al. 2014; Haghshenas et al. 2016; Karki et al. 2016; Li et al. 2017; Nabizadeh et al. 2017; Zhu et al. 2017). This test was conducted at three different strain levels (0.09%, 0.12% and 0.15%) (Considering temperature = 25°C, and frequency = 10 Hz) in non LVE range to cause sufficient fatigue damage to the FAM mixture (Zollinger 2005; Nabizadeh 2015; Yang et al. 2017; Freire et al. 2017). Number of cycles at 50% reduction in the |G*| value was considered to be fatigue failure of FAM specimens (Palvadi 2011; Underwood 2016; Rodriguez 2017). Considering three replicate specimens, time sweep test was conducted on FAM specimens to examining the fatigue potential of FAM mixtures. Fatigue test results can be described by a phenomenological regression model as described by Eq. 3.4. (Kim et al. 2003).

$$N_f = a(\gamma)^b \tag{3.4}$$

Where, N_f= Fatigue life, γ = Applied non-LVE strain level, and a, b= Regression coefficients.

3.4.4 MSCR test

The MSCR standard was adopted to evaluate the rut performance of the three different FAM mixtures (F1, F2, and F3) under repeated loading and unloading conditions as per ASTM D7405 under constant stress mode at three different temperatures (30°C, 40°C, and 50°C). The stress levels used in this present research were selected based on the referred literature (Im et al. 2017; Nabizadeh et al. 2017; Montañez et al. 2020). The MSCR test was performed at two different stress levels (15 kPa, and 55 kPa) while keeping the creep and recovery period constant as mentioned earlier. At the end of the tenth cycle for a 15 kPa creep stress level, an extra recovery period of five minutes was chosen before continuing with the 55 kPa creep stress level. This extra recovery duration was considered in this study based on the recommendation provided by Elnasri et al. (2016) to avoid the delayed viscoelastic effect of the material. A graphical representation of MSCR test is shown in Figure 3.6.

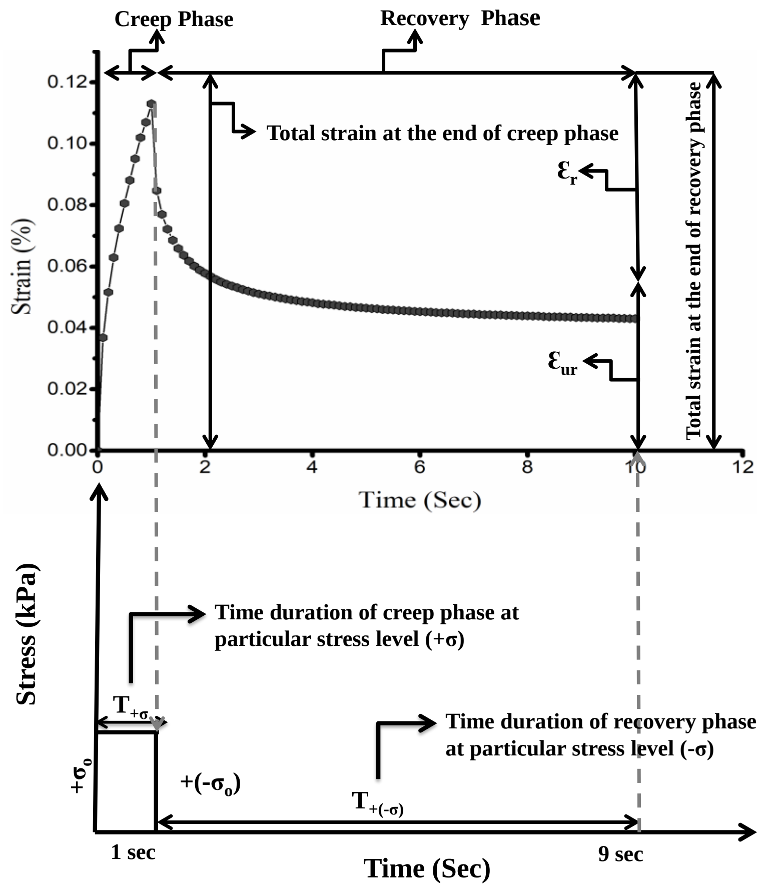


Figure 3.6 Graphical representation of creep and recovery phase

The strain responses of each FAM mixtures were obtained by conducting the MSCR test. Thereafter, the average percent recovery value (%R) and non-recoverable creep compliance (J_{nr}) values at the end of tenth load cycle for different temperatures and stress levels were determined using Eq. 3.5 and Eq. 3.7 respectively. Further, to examine the stress sensitivity of different FAM mixtures, the $\%R_{diff}$ and J_{nr_diff} values were calculated using Eq. 3.8 and Eq. 3.9.

$$R_{(\sigma)}(\%) = \frac{\sum_{i=10}^{10} \varepsilon_r}{10} \times 100, \tag{3.5}$$

Where,

$$\varepsilon_{(r)} = \sum_{i=1}^{10} \left(\frac{\varepsilon_1 - \varepsilon_{10}}{\varepsilon_1}\right) i \times 100, \tag{3.6}$$

Likewise, the average percent non-recoverable creep compliance (J_{nr}) at different stress levels was determined as

$$J_{nr(\sigma)}(kPa^{-1}) = \frac{\sum_{i=1}^{10}(\frac{\varepsilon_{10}}{\sigma})i}{10}, \tag{3.7}$$

$$J_{nr\_diff}(\%) = \frac{J_{nr\ 55\ kPa} - J_{nr\ 15\ kPa}}{J_{nr\ at\ 15\ kPa}} \times 100, \tag{3.8}$$

$$R_{diff}(\%) = \frac{R_{55\ kPa} - R_{15\ kPa}}{R_{15\ kPa}} \times 100, \tag{3.9}$$

R (%) = Percent recovery, J_{nr} (kPa^{-1}) = non-recoverable creep compliance value, ε_1= strain at the end of 1 sec creep loading period, ε_{10}= strain at the end of 10 sec recovery period, σ (kPa) = applied shear stress during each creep loading phase.

3.4.5 Rheological modeling of FAM mixtures using Burgers model

In addition to the evaluation of %R and J_{nr} values for different combination of FAM mixtures, an attempt was made to conduct Burgers modeling of the strain response obtained from the MSCR test. The Burgers model consists of Kelvin-Voigt unit (One-spring and One-dashpot are connected in parallel) and Maxwell unit (One-spring and One-dashpot are connected in series). By adding a strain response of Kelvin-Voigt and Maxwell independently for creep and recovery response, the constituting equation of the Burgers model for the evaluation of strain response can be established. Burgers model consists of four element components as shown in Figure 3.6. The complete strain ε_B at time t is a sum of the strains in these three elements (ε_{m1}, ε_{m2}, and ε_k) as shown in Figure 3.7. The subscripts B, m, and k indicate Burgers model, Maxwell and Kelvin elements, respectively.

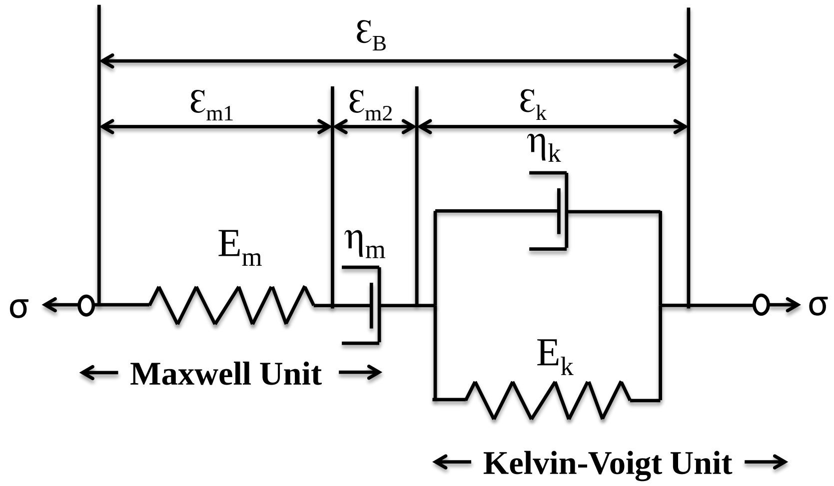


Figure 3.7 Schematic representation for Burgers four elements model

The strain response for creep phase can be obtained from Eq. 3.10. Similarly, the corresponding strain response can be obtained from Eq. 3.11 during recovery phase.

$$\varepsilon_t = \sigma\left[\frac{1}{E_m} + \frac{1}{\eta_m} + \frac{1}{E_k}\left(1 - e^{\frac{-E_k \times t}{\eta_k}}\right)\right] \tag{3.10}$$

$$\varepsilon_t = \sigma\left[\frac{t_0}{\eta_m} + \frac{1}{E_k}\, e^{\frac{-E_k \times t}{\eta_k}}\left(e^{\frac{E_k \times t_0}{\eta_k}} - 1\right)\right] \tag{3.11}$$

Where,

σ = Creep stress level, t_o= time interval at which creep load was removed, t = time period.

E_m, η_m, E_k, and η_k are the four elements Burgers model parameters. Whereas, η_m and η_k are the dashpots representing the viscous behavior and E_m and E_k are the spring elements representing elastic behavior. In comparison with the measured values ($\varepsilon_{measured}(t_i)$) in the N-measurement points, Eq. 12 and Eq. 13 were used to determine the average absolute errors (AAE) and sum of squared errors (SSE) respectively for the predicted strain values ($\varepsilon_{predicted}(t_i)$) using Burgers four element model parameters (Domingos and Faxina 2015; Liu and You 2008).

$$\mathrm{AAE} = \frac{1}{N}\sum_{i=1}^{N}\frac{\varepsilon_{predicted}(t_i) - \varepsilon_{measured}(t_i)}{\varepsilon_{measured}(t_i)} \tag{3.12}$$

$$\mathrm{SSE} = \sum_{i=1}^{N}(\varepsilon_{predicted}(t_i) - \varepsilon_{measured}(t_i))^2 \tag{3.13}$$

Different parameters for the Burgers model were obtained by minimizing the sum of the square of errors between the model and experimental values from the MSCR test using the solver function available with Microsoft Excel.

3.4.6 Static creep and recovery test

The static creep-recovery test was adopted to investigate impact of moisture on stress dependent permanent deformation characteristics of three different FAM mixtures (F1, F2, and F3) in dry and wet condition at temperature 40°C. Creep loading time 30 sec and recovery time 300 sec were considered in the test are based on the referred literature (Im et el. 2017; Nabizadeh et al. 2017). Test was carried out in a wide range of creep stresses 15kPa, 35kPa, 55kPa, and 75kPa.

3.4.7 Moisture conditioning of FAM specimens

To determine the moisture susceptibility of FAM mixtures, a conditioning process that has been used in the past for FAM mixtures to assess moisture damage (Masad et al. 2006; Caro et al. 2008; Caro et al. 2012; Montanez et al. 2020) was selected. The process consisted of submerging the FAM specimens for one hour in distilled water under vacuum saturation (27 in. Hg) at 25°C. Further, the FAM specimens were allowed at room temperature for four hours. At the end of the conditioning process, the static creep recovery test was conducted on both dry and wet conditioned FAM specimens. The moisture conditioning process of FAM specimens is shown in Figure 3.8.

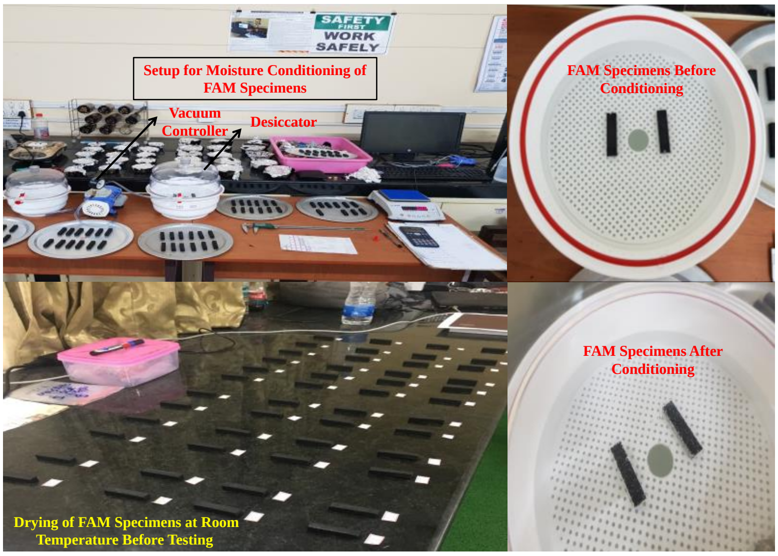


Figure 3.8 Moisture conditioning of FAM specimens

The strain responses of each FAM mixtures in both dry and wet condition were obtained by conducting the static creep recovery test. Thereafter, the average percent recovery value (%R) and non-recoverable creep compliance (J_{nr}) values at the end of recovery period (300 sec) for testing temperature of 40°C and stress levels were determined using Eq. 3.5 and Eq. 3.7 respectively. Further, the deformed and undeformed FAM specimens are shown in Figure 3.9.

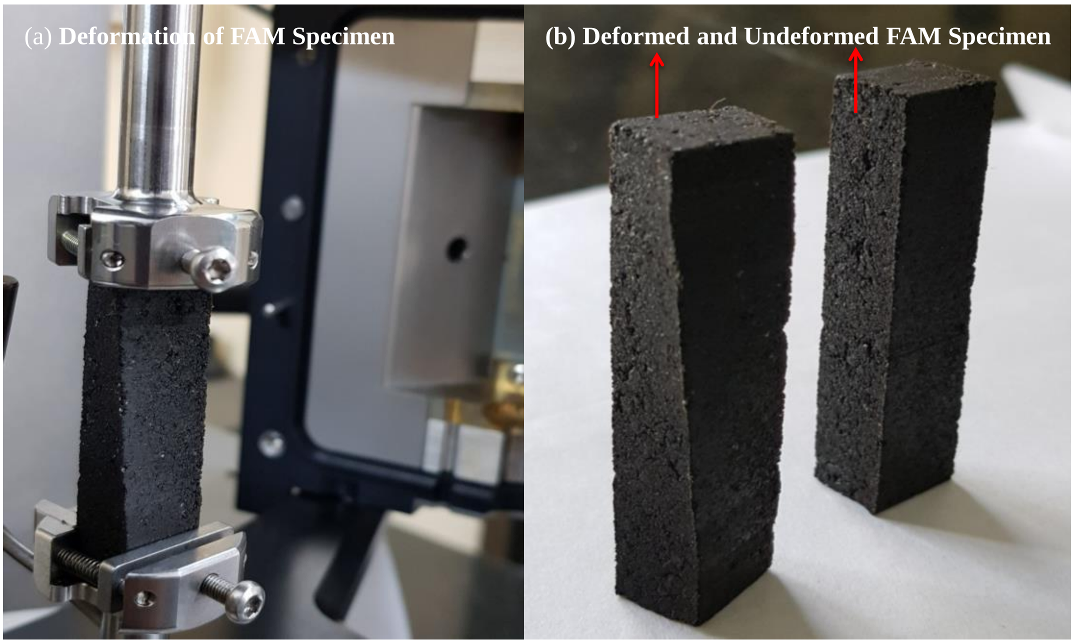


Figure 3.9 Deformed and Undeformed FAM specimens

3.4.8 Statistical analysis

ANOVA (Analysis of variance) was performed for statistical analysis to determine the significance of the responses (Saboo et al. 2020; Nainegali et al. 2020). To determine the impact of independent variables on the responses, statistical parameters are estimated. The low p-values ($p<0.05$) are significant for 95% confidence level and these terms are statistically significant for the responses. In this study, the ANOVA was conducted using MINITAB (Release 17, trial version) to examine the significance of different temperatures and stress levels on creep and recovery behavior of FAM mixtures prepared with different types of asphalt binders such as VG-30 (F1), VG-40 (F2), and PMB (F3) in both dry and wet conditions.

CHAPTER 4

4.0 EFFECT OF LONG TERM AGING ON VISCOELASTIC AND FATIGUE PROPERTIES OF FAM MIXTURES

4.1. GENERAL

In this chapter, aging is considered as one of the major factor which causes an increase in stiffness and brittleness to asphaltic mixture. This chapter aimed at evaluating the effect of different aging protocol on viscoelastic and fatigue properties of Fine Aggregate Matrix (FAM) mixtures which represents the finer portion (passing 2.36 mm sieve size) of asphalt concrete mixtures. To evaluate the effect of aging on viscoelastic and fatigue properties of three FAM mixtures (F1, F2, and F3), six different long-term aging levels (6 hrs at 135°C, 12 hrs at 135°C, 24 hrs at 135°C, 5 days at 95°C, and 12 days at 95°C aging on FAM loose mixture and 5 days at 85°C on compacted FAM specimens) were considered. Linear Visco-Elastic (LVE) limit of each FAM mixtures was initially determined by conducting strain sweep test. Viscoelastic properties ($|G^*|$ and δ) and master curve shape parameters of FAM mixtures were further determined from temperature and frequency sweep test. Fatigue properties of FAM mixtures at different aging levels were evaluated using strain controlled time sweep test.

4.2 LABORATORY EXPERIMENTAL PLAN

This study aimed at evaluating the effect of different aging (loose mix aging and compacted specimen aging) levels on viscoelastic and fatigue properties of FAM mixtures. It is a usual practice to carry out aging in the laboratory using different temperatures and aging periods to simulate the field aging of asphaltic mixtures. Short term aging on FAM loose mixture was carried out at 135°C for 4 hrs before compaction as per AASHTO R30 recommendation. To simulate long term aging in the laboratory, AASHTO R30's current protocol recommends carrying out aging for 5 days at 85°C on compacted FAM specimens. Additionally, unlike AASHTO R30 recommendation, NCHRP 9-54 recommends long term aging on loose FAM for different aging duration and temperature (6 hrs at 135°C, 12 hrs at 135°C, 24 hrs at 135°C, 5 days at 95°C and 12 days at 95°C). Therefore, along with AASHTO R30's recommended protocol, long term aging of loose FAM was also carried out as per NCHRP 9-54 recommendation.

Table 4.1 Details of test specimens of F1 mixture

Binder Type	Properties	Test Name	Loose Mixture Aging						Compacted Specimen Aging	Number of Specimens
			A	A1	A2	A3	B1	B2	C	
VG-30	Viscoelastic	Strain sweep	3	3	3	3	3	3	3	3x7=21
		Temp. and freq. sweep	3	3	3	3	3	3	3	3x7=21
		Frequency sweep	3	3	3	3	3	3	3	3x7=21
	Fatigue	Time sweep @ 3 strain levels	3x3	3x3	3x3	3x3	3x3	3x3	3x3	3x3x7=63
									Total	**126**

Note: A=4 hr at 135°C, A1=6 hr at 135°C, A2=12 hr at 135°C, A3=24 hr at 135°C, B1=5 days at 95°C, B2=12 days at 135°C, C=5 days at 85°C, VG= Viscosity Grade

Table 4.2 Details of test specimens of F2 mixture

Binder Type	Properties	Test Name	Loose Mixture Aging						Compacted Specimen Aging	Number of Specimens
			A	A1	A2	A3	B1	B2	C	
VG-40	Viscoelastic	Strain sweep	3	3	3	3	3	3	3	3x7=21
		Temp. and freq. sweep	3	3	3	3	3	3	3	3x7=21
		Frequency sweep	3	3	3	3	3	3	3	3x7=21
	Fatigue	Time sweep @ 3 strain levels	3x3	3x3	3x3	3x3	3x3	3x3	3x3	3x3x7=63
									Total	**126**

Note: A=4 hr at 135°C, A1=6 hr at 135°C, A2=12 hr at 135°C, A3=24 hr at 135°C, B1=5 days at 95°C, B2=12 days at 135°C, C=5 days at 85°C, VG= Viscosity Grade

Table 4.3 Details of test specimens of F3 mixture

Binder Type	Properties	Test Name	Loose Mixture Aging						Compacted Specimen Aging	Number of Specimens
			A	A1	A2	A3	B1	B2	C	
PMB	Viscoelastic	Strain sweep	3	3	3	3	3	3	3	3x7=21
		Temp. and freq. sweep	3	3	3	3	3	3	3	3x7=21
		Frequency sweep	3	3	3	3	3	3	3	3x7=21
	Fatigue	Time sweep @ 3 strain levels	3x3	3x3	3x3	3x3	3x3	3x3	3x3	3x3x7=63
									Total	**126**

Note: A=4 hr at 135°C, A1=6 hr at 135°C, A2=12 hr at 135°C, A3=24 hr at 135°C, B1=5 days at 95°C, B2=12 days at 135°C, C=5 days at 85°C, PMB= Polymer Modified Binder

To study the viscoelastic, and fatigue properties of FAM mixtures (F1, F2, and F3), a total number of 378 specimens were used for characterising FAM mixtures at different aging levels. Details of different FAM combinations, binder type, name of the test conducted, number of test specimens prepared and properties of FAM mixtures are shown in Table 4.1, Table 4.2, and Table 4.3. A, A1, A2, A3, B1, B2 refers to loose mixture aging, whereas, C’ refers to compacted specimen aging. Design of experiments for viscoelastic and fatigue properties of FAM mixtures are shown in Table 4.4.

Table 4.4 Design of experiments for viscoelastic, and fatigue properties of FAM mixtures

Test Name	Test Parameters	Responses	Criteria for Responses
Strain sweep test	Strain-0.0001-0.1% Temperature-25°C Frequency-10Hz	LVE region.	10% reduction in initial $\|G^*\|$ value.
Temperature and frequency sweep test	Strain-0.006% Temperature-15-65°C Frequency-0.1-25Hz	Viscoelastic Properties $\|G^*\|$ and δ.	Master curve for each FAM mixture at reference temperature 25°C.
Time sweep test	Strain levels-0.09, 0.12 and 0.15% Temperature-25°C Frequency-10Hz	Fatigue life.	No. of loading cycles (N_f) at 50% reduction in initial $\|G^*\|$ value.

Flowchart for the experimental research plan of viscoelastic and fatigue properties of FAM mixtures is shown in Figure 4.1. Three different types of strain controlled tests (strain sweep test, temperature, and frequency sweep test and time sweep test) were carried out on STA and LTA FAM specimens in this research work. Strain sweep test helped in demarcating the boundary line between linear and non-linear viscoelastic zone. It is important to note that the temperature and frequency sweep test needs to be conducted by applying strain level in the linear viscoelastic range. Likewise, strain level in time sweep test for fatigue life analysis should be applied in non-linear viscoelastic range. Therefore, strain sweep test helped in selecting the appropriate strain level for temperature and frequency sweep and time sweep test.

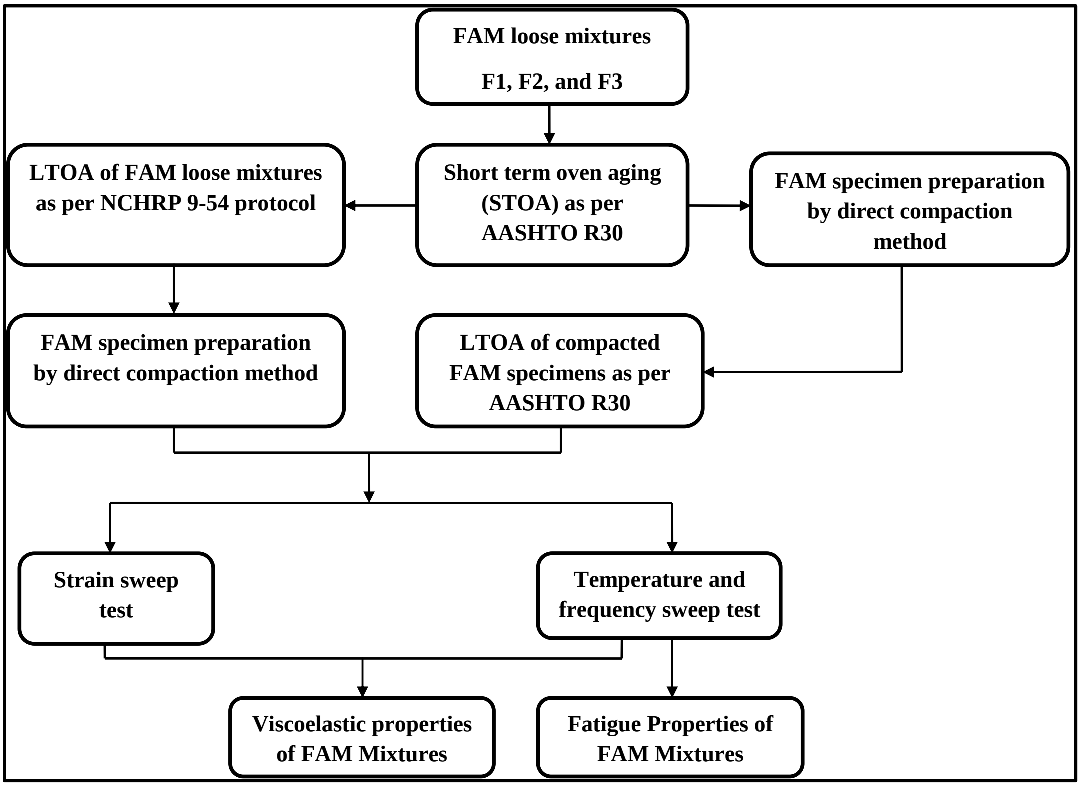


Figure 4.1 Flowchart for experimental research plan of viscoelastic and fatigue properties

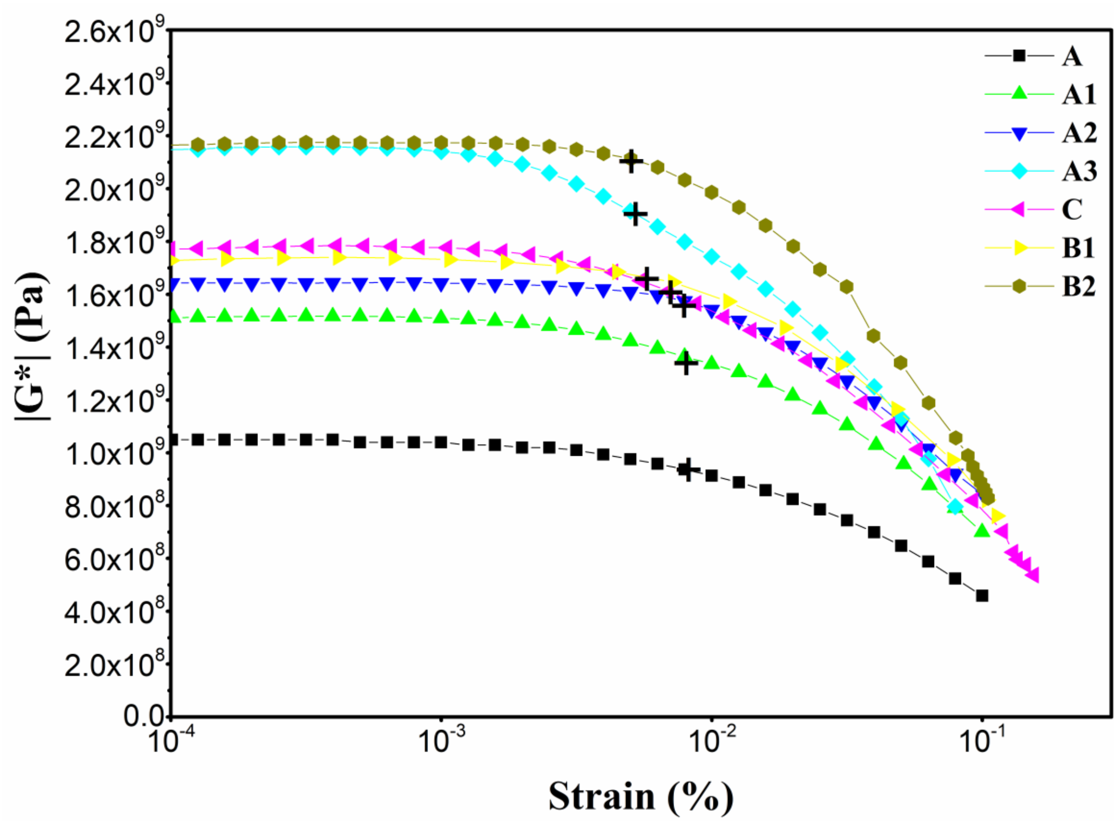
4.3 RESULTS AND DISCUSSIONS

The results and discussions of the present investigations are discussed in the following sections.

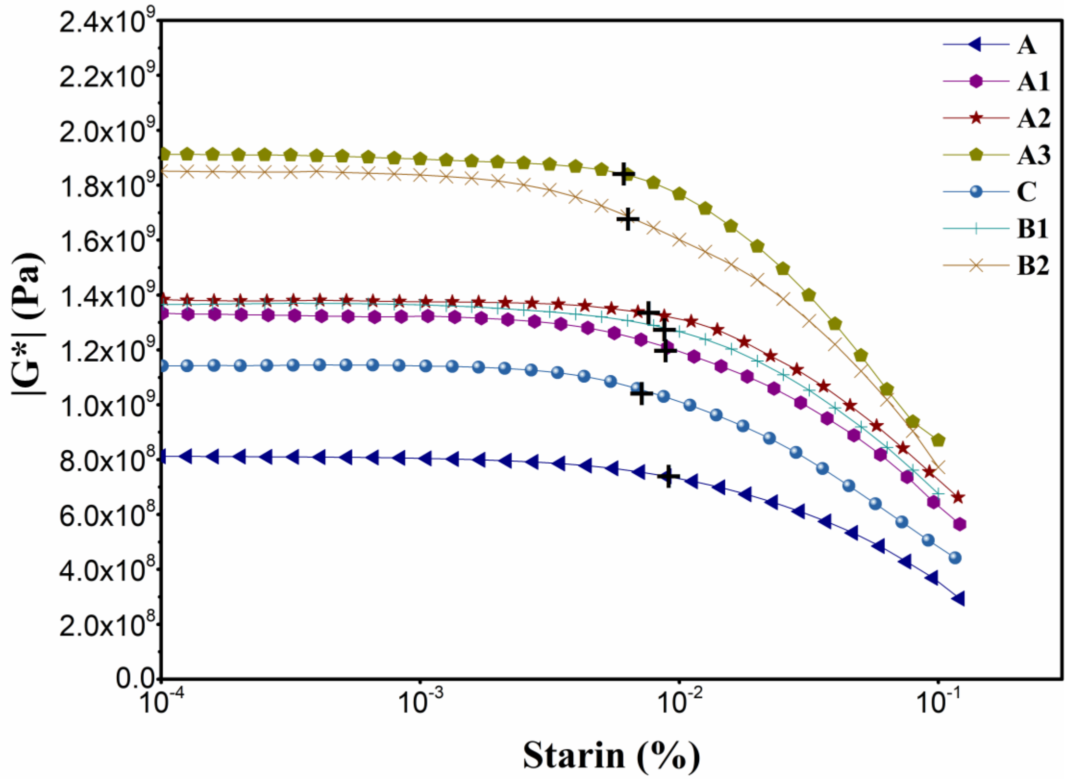
4.3.1 Linear viscoelastic region

This test has been reported by various researchers for different types of FAM mixtures which helped in determining the LVE range for three different FAM mixtures (F1, F2 and F3). FAM specimens of F1 mixture are prepared with 4% air voids. Similarly, FAM specimens of F2 and F3 mixtures are prepared with 6% air voids in this research work. The results of the strain sweep test on various FAM specimens are presented in Figure 4.2(a), Figure 4.2(b), and Figure 4.2(c). The curves of |G*| versus strain from the strain sweep test has been plotted for three FAM mixtures with different aging levels. It is clear from the plot that as the aging level increased, the stiffness value also increased in all three type of FAM mixtures irrespective of the different air voids present in the specimens. For example, the stiffness value within LVE range can be observed to be increased by approximately 2.0, 2.3, and 3.7 times for F1, F2, and F3 mixture respectively, with a change in aging protocol from A (short term aging at 135°C for 4 hrs) to B2 (12 days aging at 95°C) (refer Table 4.1, Table, 4.2, and Table 4.3 for specimen nomenclature). While comparing the stiffness of F2 and F3 mixtures, the specimens of F3 mixtures observed to be lesser compared to specimens of F2 mixture for all different aging protocols. This comparison was done due to presence of similar air voids maintained in these two mixtures. Decrease in stiffness due to softer SBS binder used in F3 mixture. Moreover, it is also to be noted that the |G*| plot for specimen aged for 12 days at 95°C overlapped with the corresponding plot with specimen aged at 135°C for 24 hrs (A3) within the LVE range for all the FAM mixtures. Such a response indicates the equivalency of aging level of FAM between (a) 12 days at 95°C and (b) 135°C for 24 hrs. The stiffness of B2 and A3 mixtures was observed similar. Even though the aging temperature and duration were different, equivalency in aging was observed at only strain level within the LVE range. However, stiffness is independent at lower stress/strain levels within the LVE range. When the strain levels cross the LVE range, the failure damage starts to appear. As the aging temperature and duration are different for B2 and A3 mixture, the damage was observed differently. The same findings were observed while conducting the fatigue analysis at higher strain levels (Refer 4.3.3). This result is important in the sense that the aging period can be significantly reduced from 12 days to just 24 hrs just by increasing the conditioning temperature from 95°C to 135°C.

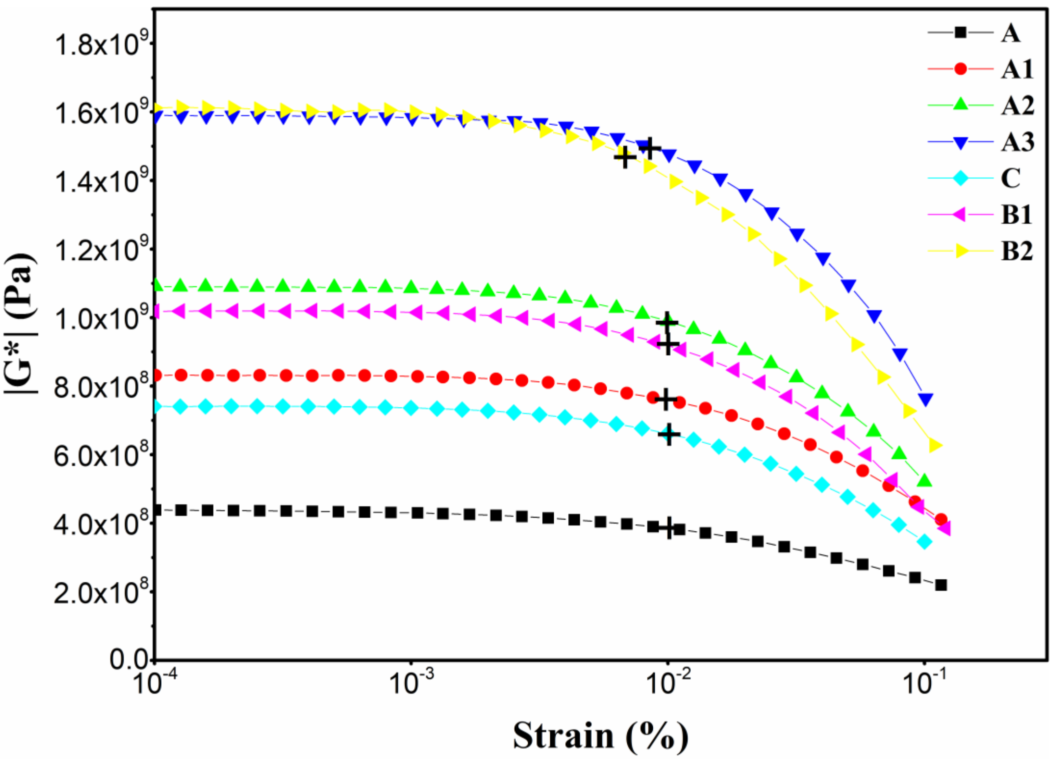
It can be further seen that the |G*| value remained constant when the applied strain level is within the LVE range. However, as soon as strain level increased above the corresponding LVE range of specimen, the decrease in |G*| became apparent as expected. Such a response clearly indicates the requirement of amplitude strain level above the respective LVE limit to induce damage to the material. The LVE range was not exactly same for all the FAM mixtures that were considered in this study. But, only a small variation in LVE range was observed (0.008-0.01%) irrespective of the aging level applied to all the FAM specimens. The '+' sign in Figure 4.2(a), Figure 4.2(b), and Figure 4.2(c) clearly represents the variation of LVE range. In this study, constant strain level well within LVE region was selected (=0.006%). The results are in line with the findings reported by Aragão and Kim (2012), and Li et al. (2017) where LVE strain upper limit is only sensitive to material scale and insensitive to aging level to the specimens of all the three type of FAM mixtures.



(a) Mixture type=F1



(b) Mixture type=F2



(c) Mixture type=F3

Figure 4.2 Strain sweep test results for FAM mixtures. (a) F1 (b) F2 (c) F3

4.3.2 Temperature and frequency sweep test

Based on the outcome obtained from strain sweep test as discussed earlier, temperature and frequency sweep test was carried out by applying an amplitude strain level within the LVE range. The master curve for average |G*| value of three replicate specimen results of three FAM mixtures with STA and LTA (A, A1, A2, A3, C, B1 and B2) was drawn at a reference temperature of 25°C with the help of time-temperature superposition principle and logarithmic sigmoidal model. Various model parameters which control the shape of the master curve were obtained from the solver function available with Microsoft Excel through optimization technique. The various model parameters obtained from the optimization technique for sixty three different specimens of three FAM mixtures are presented in Table 4.5.

The γ value in the generalized sigmoidal model governs the horizontal positioning of turning point (Yousoff et al. 2013). It is clear from the table that as the aging level increased, the γ value correspondingly decreased. For example, the γ value for A1 specimen of F1 mixture is -0.33 which decreased to -0.43 and -0.56 with an increase in aging duration from 6 hrs to 12 and 24 hrs respectively. Similarly, the γ value for A1 specimen of F2 mixture is -0.25 which decreased to -0.67 and -0.96. Such a response can be attributed to the stiffening effect to the FAM specimens due to increase in the relative proportion of asphaltene and a corresponding decrease in maltene in asphalt binder used in FAM mixtures with an increase in aging temperature and/or corresponding aging duration (Yousoff et al. 2013). Likewise, other parameters of the logarithmic sigmoidal model also seem to be affected by different aging protocol to the FAM specimen. For example, κ and β value can be seen to be increasing with an increase in aging level.

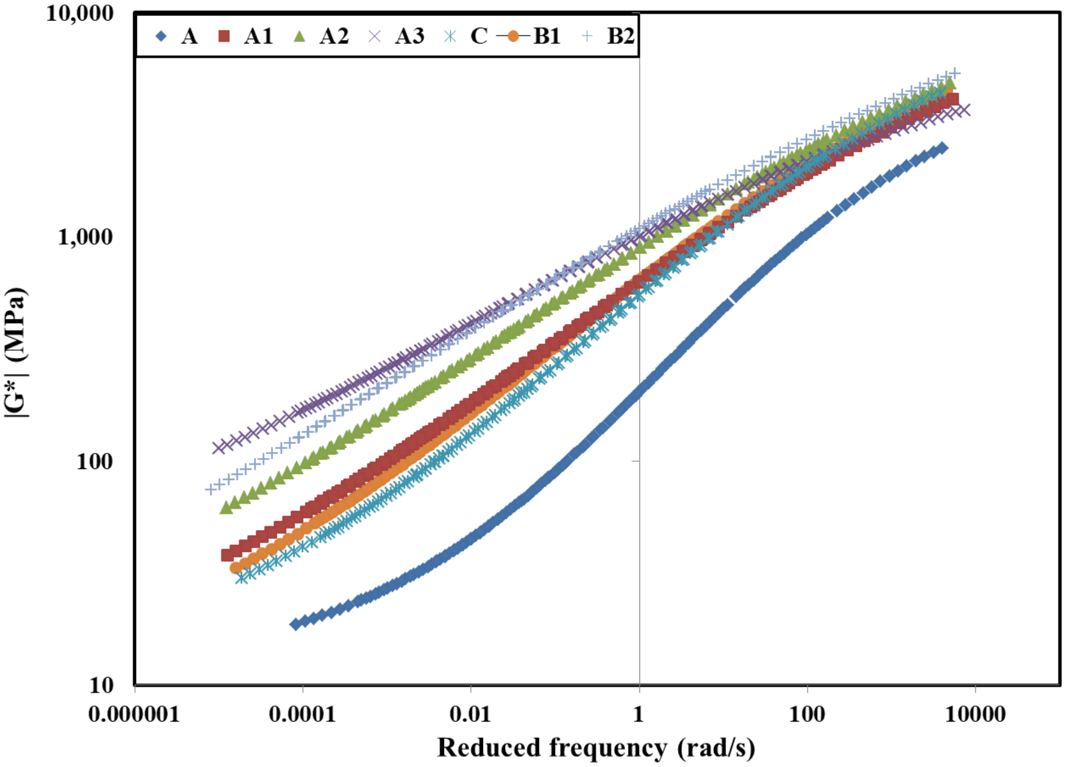
Table 4.5 Complex shear modulus |G*| master curve parameters of FAM mixtures

Mixture Type	Specimen Type	α	β	γ	κ
F1	A	7.04	2.73	-0.15	-0.55
	A1	6.78	3.47	-0.33	-0.31
	A2	6.79	3.58	-0.43	-0.28
	A3	7.32	2.65	-0.56	-0.30
	C	6.97	3.19	-0.22	-0.40
	B1	6.84	3.35	-0.35	-0.36
	B2	6.33	4.23	-0.57	-0.22
F2	A	6.82	2.74	-0.25	-0.52
	A1	6.58	3.16	-0.67	-0.40
	A2	6.13	3.76	-0.89	-0.30
	A3	6.84	4.01	-0.96	-0.23
	C	6.81	2.82	-0.48	-0.48
	B1	6.40	3.23	-0.69	-0.38
	B2	5.35	4.61	-1.19	-0.24
F3	A	6.99	2.48	-0.44	-0.64
	A1	6.86	2.77	-0.18	-0.53
	A2	6.77	2.96	-0.45	-0.45
	A3	5.68	4.29	-1.03	-0.26
	C	6.94	2.62	-0.11	-0.59
	B1	6.86	2.80	-0.32	-0.50
	B2	6.03	3.89	-0.96	-0.31

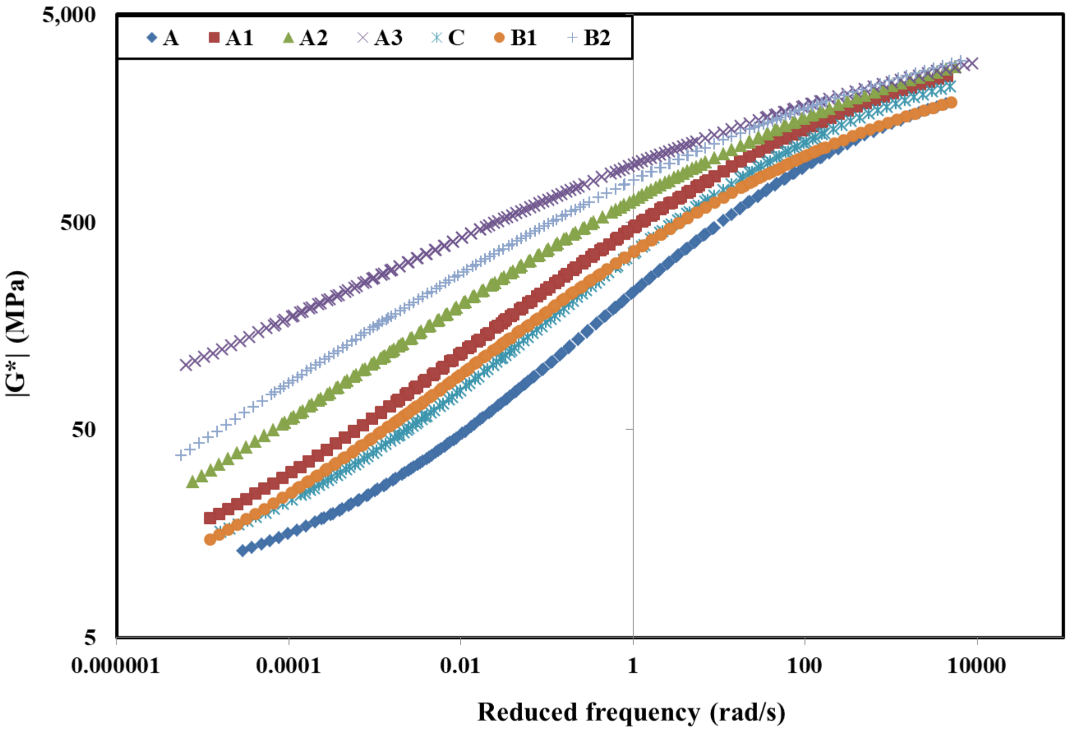
Figure 4.3(a), Figure 4.3(b), and Figure 4.3(c) shows the master curve for F1, F2, and F3 mixtures respectively. Increase in |G*| value with increase in frequency level can be observed as expected. Each plot can be seen as approaching towards a single value at higher frequency level which can be attributed to attainment of glassy state of the mixture and in line with findings on FAM mixtures reported by different researchers (Rastegar et al. 2018; Li et al. 2018; Sanchez et al. 2017). On the other hand, the apparent effect of aging can be clearly seen in relatively lower frequency zone. The lowest value of |G*| can be observed for STA specimen which subsequently increased with the increase in different aging level. For example, the |G*| value for A3 specimen of F1 mixture aged at 24 hrs at 135°C is about 8.8 times more than the STA FAM specimen at a frequency level of (0.00005 rad/s). Similarly, |G*| value of specimen aged for 5 days at 95°C (B1) loose mixture aged FAM specimen showed 2.5 times stiffer compared to STA FAM specimen at a frequency level of (0.00005 rad/s). Further, |G*| value for A3 specimen of F2 mixture aged at 24

hrs at 135°C is about 4.7 times more than the STA FAM specimen at a frequency level of (0.00005 rad/s). Similarly, |G*| value of specimen aged for 5 days at 95°C (B1) loose mixture aged FAM specimen showed 1.5 times stiffer compared to STA FAM specimen at a frequency level of (0.00005 rad/s). Similar results were observed for FAM specimens of F3 mixtures too. Moreover, the specimen C (conditioned at 85°C for 5 days) found to have almost similar response as that of specimen B1 (conditioned at 95°C for 5 days) of all the three type of FAM mixtures. Also, the similar findings have been reported by Rastegar et al. (2018) for asphaltic mixture with different degree of aging.

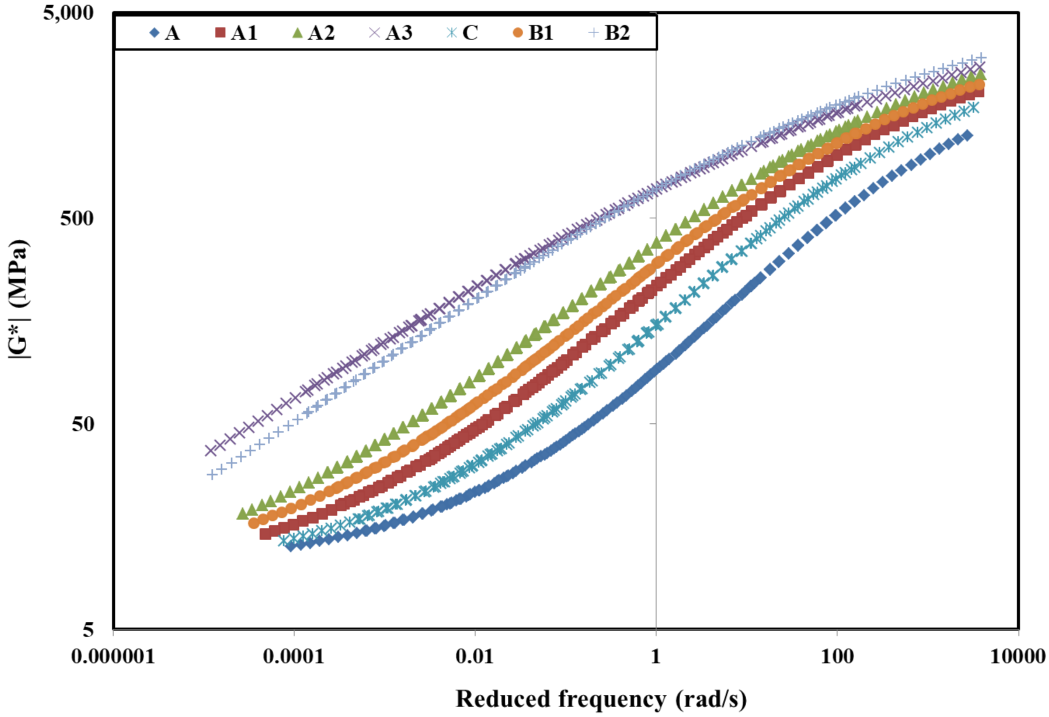
Further, as in the case of amplitude sweep test (conducted at a frequency level of 10 Hz), where |G*| variation for specimen B2 (conditioned at 95°C for 12 days) and specimen A3 (conditioned at 135°C for 24 hrs) in LVE range was found to be almost similar. Response for the corresponding specimens can be seen to be in close proximity at a reduced frequency level of 10 Hz which is in agreement with findings obtained from strain sweep test as discussed in Section 4.3.1. However, at a relatively lower frequency and higher frequency level, the response can be seen as different. The |G*| value for A3 is relatively higher than B2, whereas, the corresponding value at a higher frequency level for B2 is higher than A3. This indicates that specimen A3 may perform better than B2 in high temperature condition (equivalent to low frequency), whereas, the specimen A3 may perform better than B2 in low to intermediate temperature conditions. These findings are observed same for all the three type of FAM mixtures used in this research. Figure 4.4(a), Figure 4.4(b), and Figure 4.4(c) shows the variation of |G*| values for FAM mixtures (F1, F2, and F3) at 0.001 Hz to demonstrate the effect of different aging level on corresponding parameter in lower frequency zone.



(a) Mixture type=F1

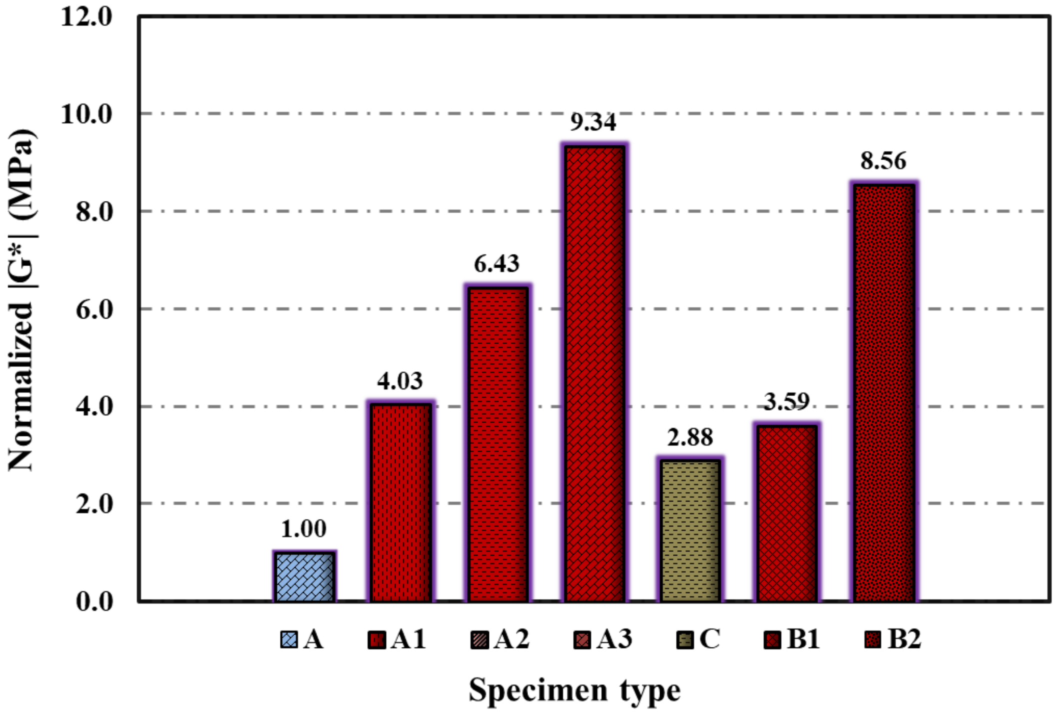


(b) Mixture type=F2

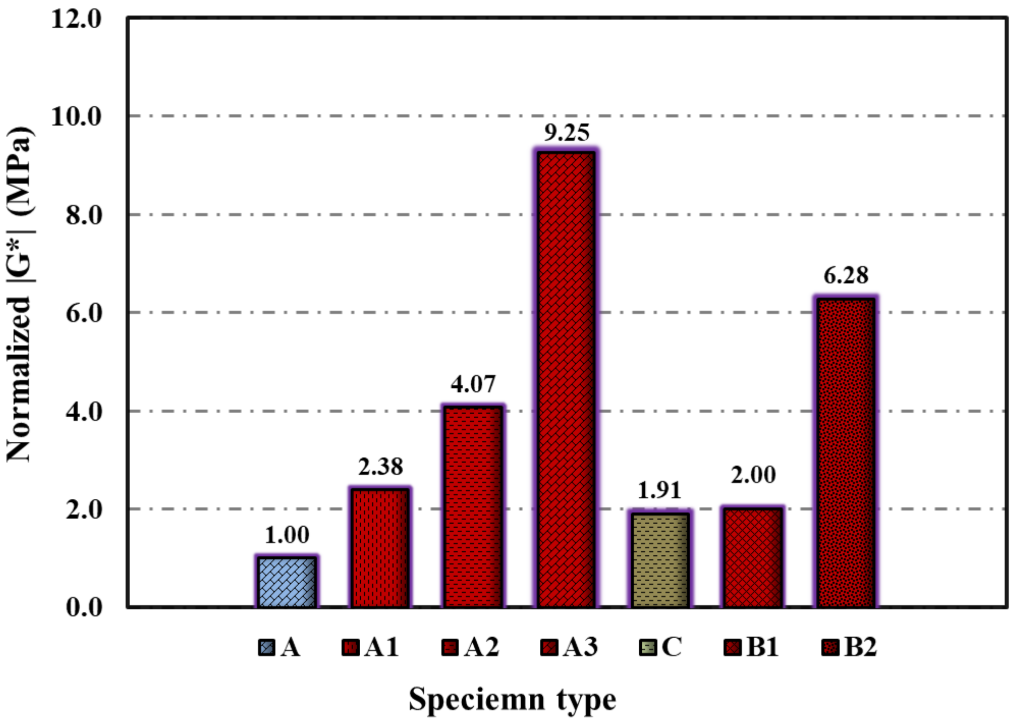


(c) Mixture type=F3

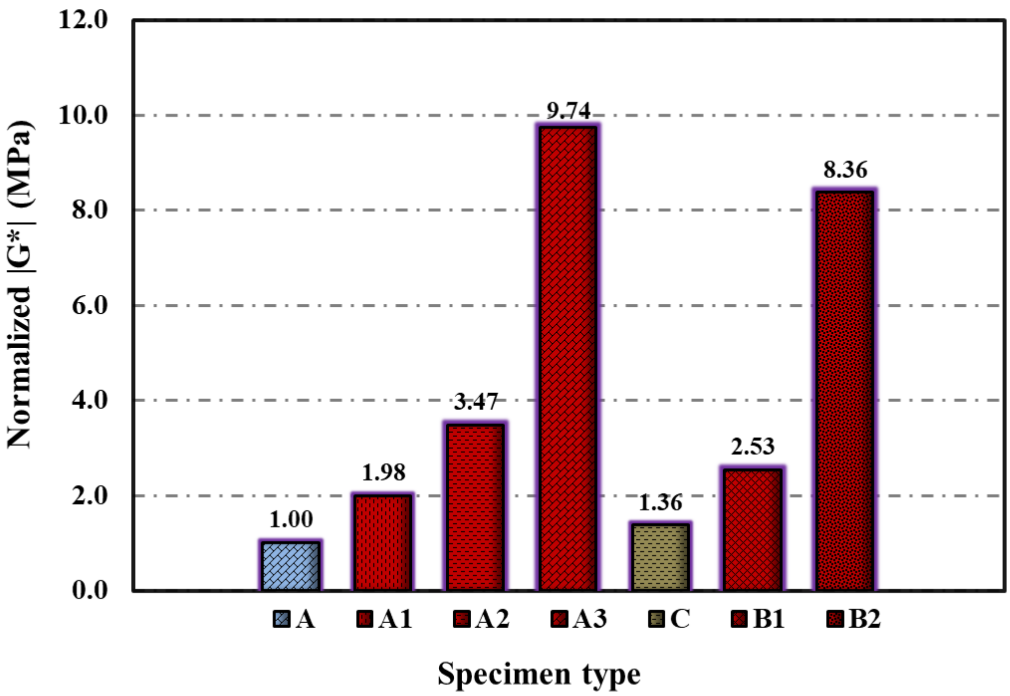
Figure 4.3 Complex shear modulus |G*| of STOA and LTOA FAM specimens at reference temperature 25°C. (a) F1 (b) F2 (c) F3



(a) Mixture type=F1



(b) Mixture type=F2



(c) Mixture type=F3

Figure 4.4 Normalised |G*| of FAM specimens at 0.001Hz and 25°C. (a) F1 (b) F2 (c) F3

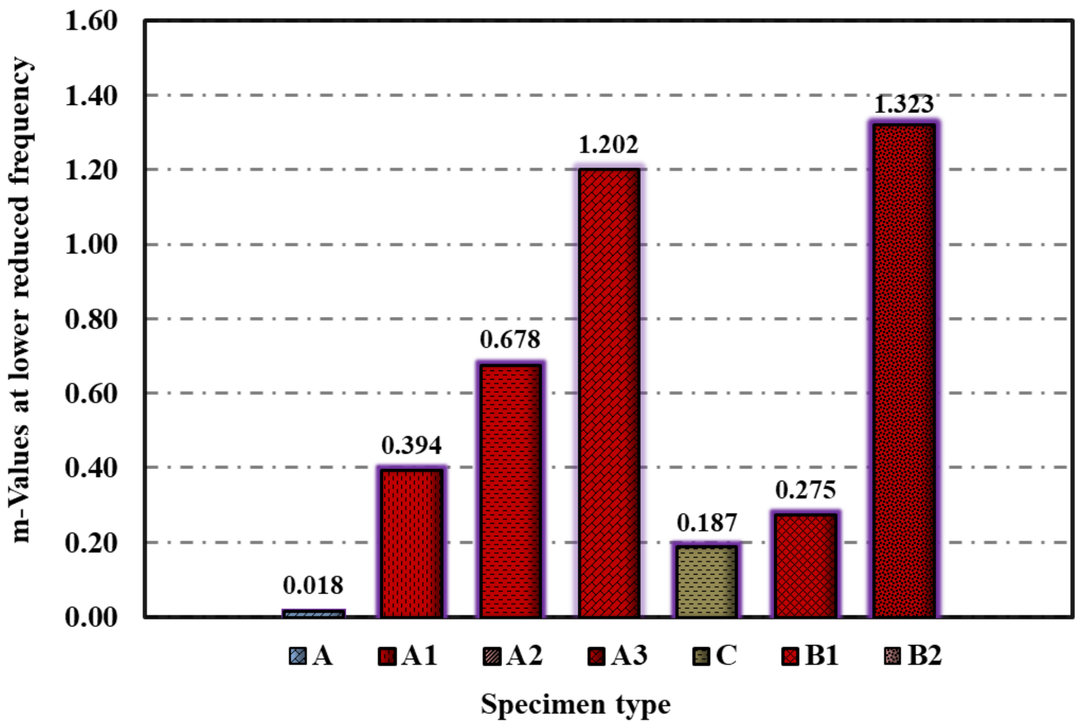
The |G*| master curve exhibit a characteristic flattening effect that can be quantified by the slope (m) of the logarithmic plot between |G*| and frequency (known as relaxation modulus) Nabizadeh et al. (2015) and Sanchez (2018) was also determined as shown in Table 4.6, m-values between each FAM mixtures at different frequency levels has been compared. The values in Table 4.6 clearly demonstrate the influence of aging on the m-values at higher temperature (or lower frequencies). The long-term aged FAM specimens found to have distinctively different relaxation time compared with the STA FAM specimens.

Table 4.6 Slope between each FAM specimens at different frequency levels

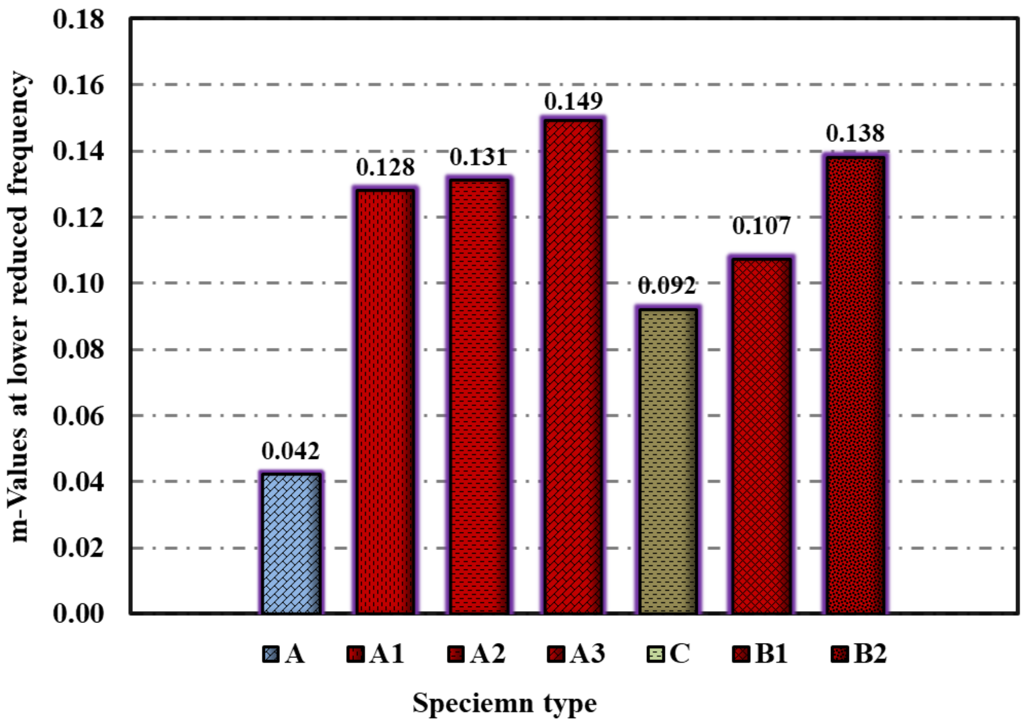
Mixture Type	Specimen Type	Slope, m		
		At lower reduced frequency (0.00005 rad/s)	At intermediate reduced frequency (1.5 rad/s)	At higher reduced frequency (5250 rad/s)
F1	A	0.018	0.069	0.170
	A1	0.394	0.158	0.190
	A2	0.678	0.197	0.222
	A3	1.202	0.167	0.078
	C	0.187	0.158	0.297
	B1	0.275	0.177	0.240
	B2	1.323	0.217	0.205
F2	A	0.042	0.079	0.090
	A1	0.128	0.225	0.090
	A2	0.131	0.640	0.108
	A3	0.149	1.915	0.044
	C	0.092	0.113	0.087
	B1	0.107	0.185	0.071
	B2	0.138	1.252	0.075
F3	A	0.007	0.328	0.311
	A1	0.030	0.812	0.322
	A2	0.088	1.143	0.362
	A3	0.574	1.572	0.395
	C	0.013	0.556	0.313
	B1	0.051	0.978	0.379
	B2	0.433	1.400	0.419

Generally, the aged FAM specimens take more stress relaxation time than the STA specimens (Nabizadeh et al. 2017). The increase in m-values may be attributed to increase in aging level to FAM specimens. For example, m-value for A3 specimen of all FAM mixtures aged at 24 hrs at 135°C is observed higher compared to STA

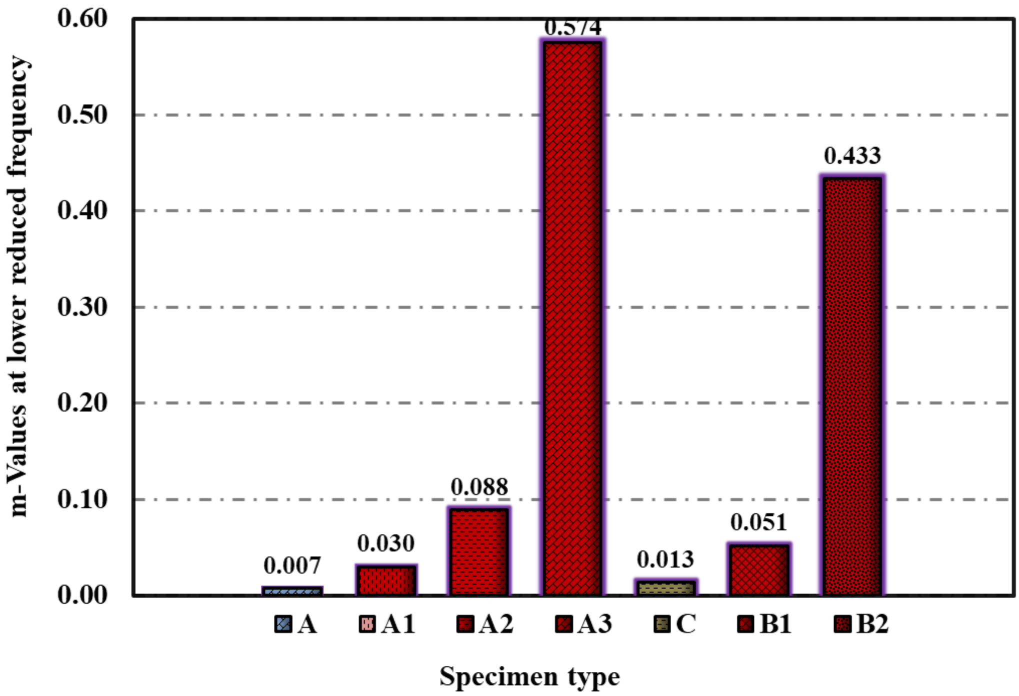
FAM specimens at a lower side of reduced frequency level. Similarly, 5 days at 95°C (B1) loose mixture aged FAM specimen showed higher m-value compared to STA FAM specimen at a lower side of reduced frequency level. Further, m-values increase at intermediate side of reduced frequency levels. Moreover, the effect of aging levels at low temperature or high loading frequencies was not distinguishable. This indicates that highly aged FAM specimens can be more susceptible to early stage fatigue damage due to lack of relaxation capability. The results are in line with findings reported by Sanchez et al. (2019) for different FAM mixtures. Figure 4.5(a), Figure 4.5(b), and Figure 4.5(c) shows the variation of m-values for FAM mixtures (F1, F2, and F3) to demonstrate the effect of different aging level in lower frequency zone (0.00005 rad/sec).



(a) Mixture type=F1



(b) Mixture type=F2

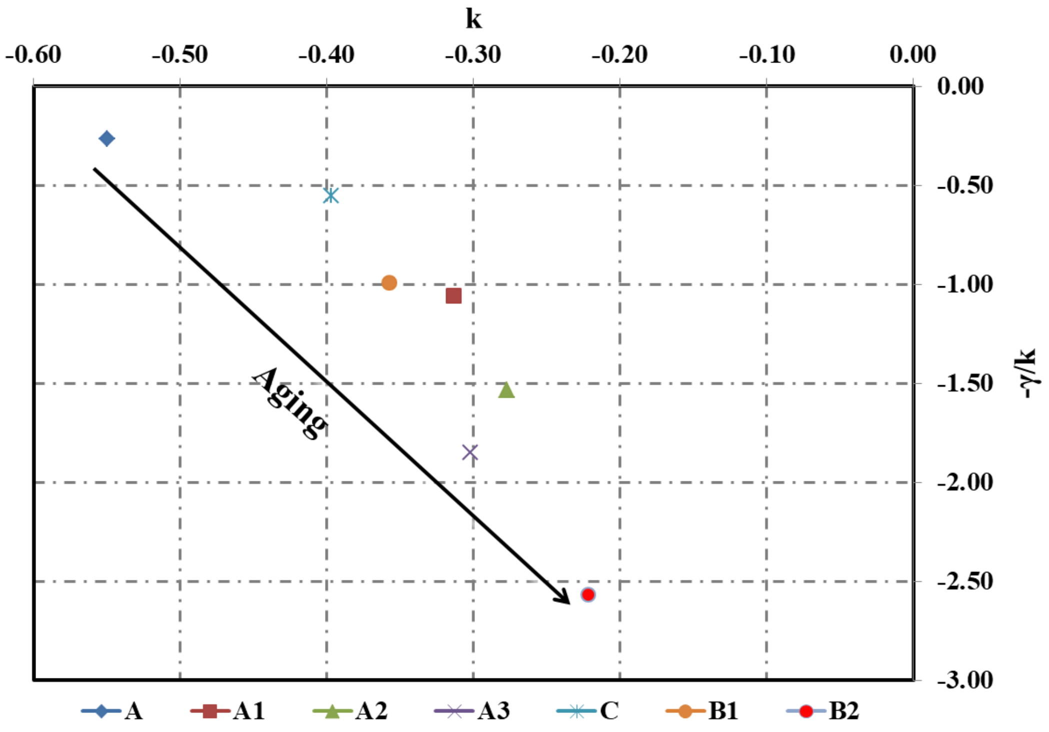


(c) Mixture type=F3

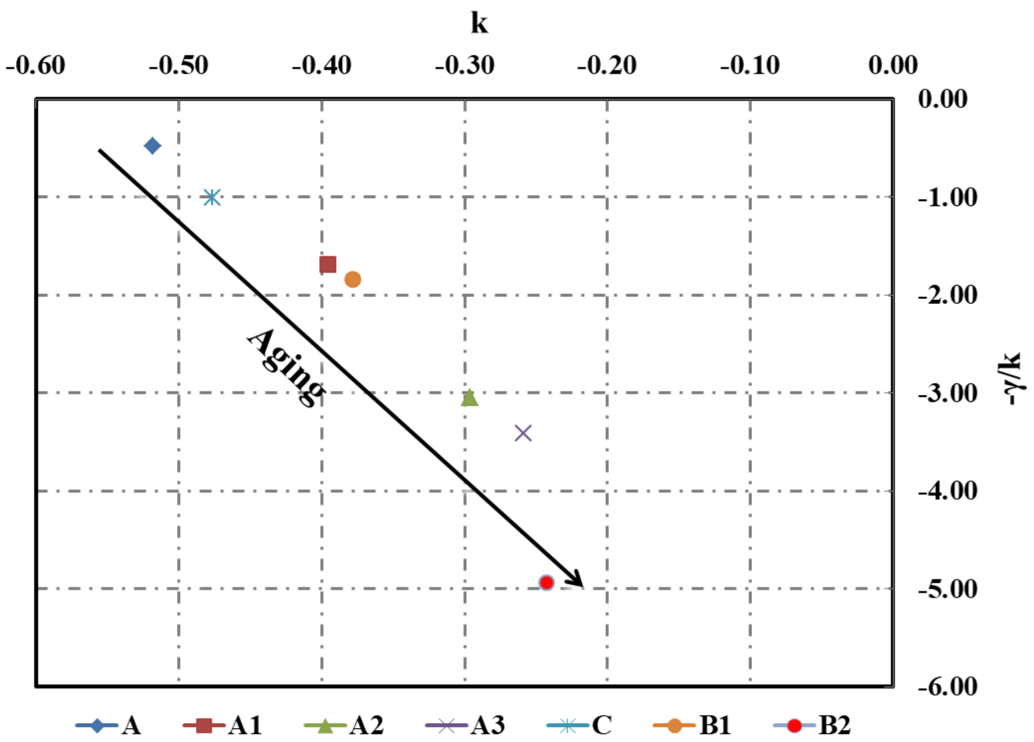
Figure 4.5 m-values at lower reduced frequency level at 0.00005 rad/sec. (a) F1 (b) F2 (c) F3

Furthermore, inflection point parameter (-γ/κ) and relaxation width parameter (κ) from the |G*| master curve plot are considered to analyse the relationship between aging duration and temperature. However, the 'κ' value influences the length of the relaxation spectra and it is possible to calculate the frequency of the inflection point from $10^{-\gamma/\kappa}$. As the asphalt material ages, the |G*| master curve tends to flatten and the inflection point shifts to lower frequencies (Menching et al. 2017). The (-γ/κ) parameter for STA FAM specimen (A) is almost equal to zero for F1 and F2 mixtures and equal to one for F3 mixture. Similarly, -γ/κ value of specimen aged for 5 days at 95°C (B1) loose mixture aged FAM specimen showed 3.97, 1.37, and 1.27 times more compared to STA FAM specimen of F1, F2 and F3 mixtures respectively. Moreover, the specimen C (conditioned at 85°C for 5 days) found to have almost similar response as that of specimen B1 (conditioned at 95°C for 5 days) in all the three type of FAM mixtures. The corresponding value for B1 of F1 mixture (-0.991) can be seen as slightly higher than C (-0.553).

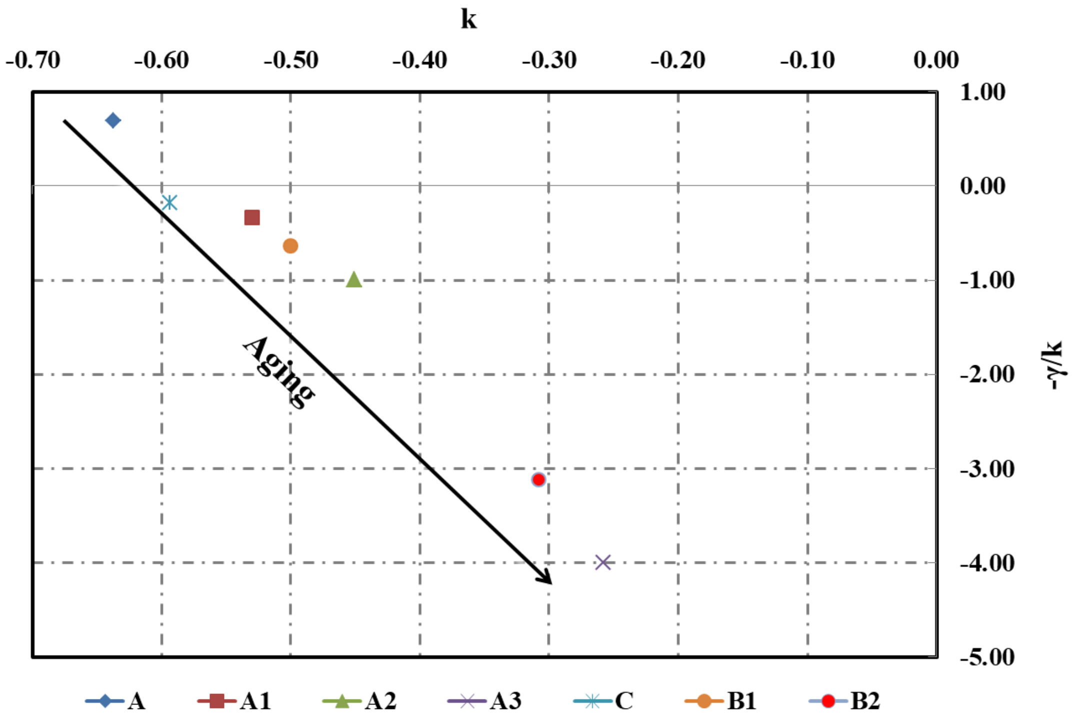
Similarly, B1 of F2 and F3 mixtures have higher values (-1.835 and -0.636) compared to specimen C. Further, similar observations have been reported by Rastegar et al. (2018) for asphaltic mixture with different degree of aging. A higher value of -γ/κ for B1 in can be attributed to correspondingly higher conditioning temperature leading to a relatively higher degree of aging. It is clear from the Figure 4.6(a), Figure 4.6(b), and Figure 4.6(c) that as the aging level increased, the -γ/κ value correspondingly increased. For example, the -γ/κ value for A1 specimen of F1 mixture is -1.058 which increased to -1.531 and -1.847 with an increase in aging duration from 6 hrs to 12 and 24 hrs respectively. Further, -γ/κ value for A1 specimen of F2 mixture in is -1.689 which increased to -3.049 and -3.415. A1 specimen of F3 mixture has also showed similar results. The -γ/κ parameter decreases and κ increases, as more aging happens, pushing points further towards the bottom right. Such a response can be attributed to the stiffening effect to the FAM specimens with an increase in aging temperature and/or corresponding aging duration. These can also indicating that FAM specimens with higher κ values are expected to be more susceptible to cracking (Zhou et al. 2019; Menching et al. 2017).



(a) Mixture type=F1



(b) Mixture type=F2

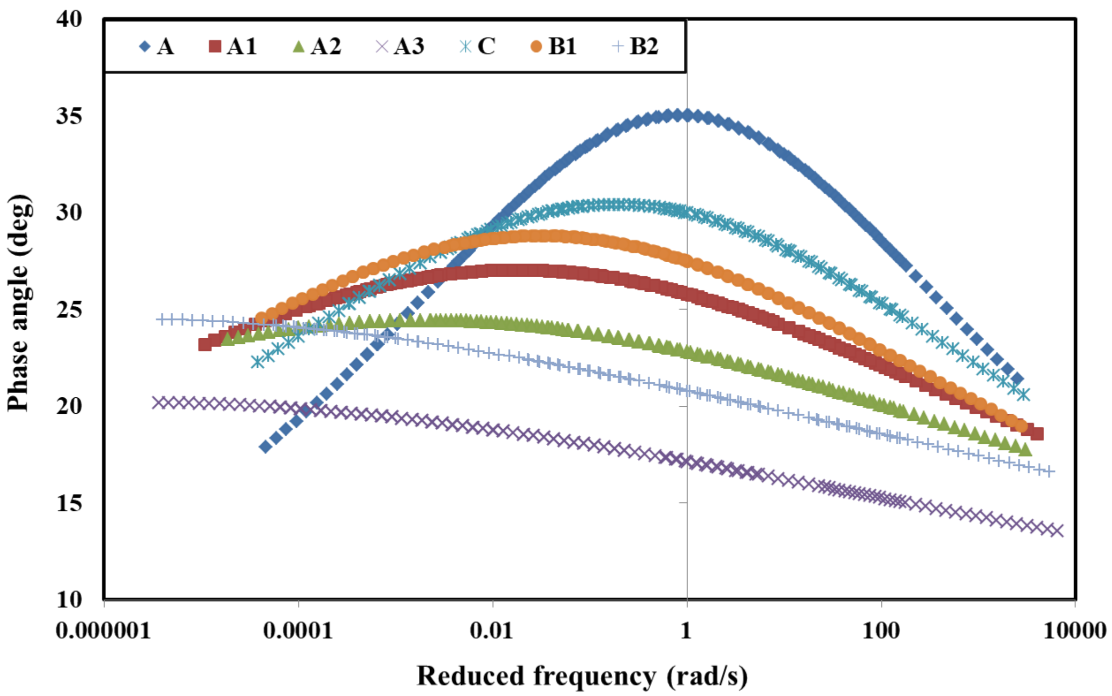


(c) Mixture type=F3

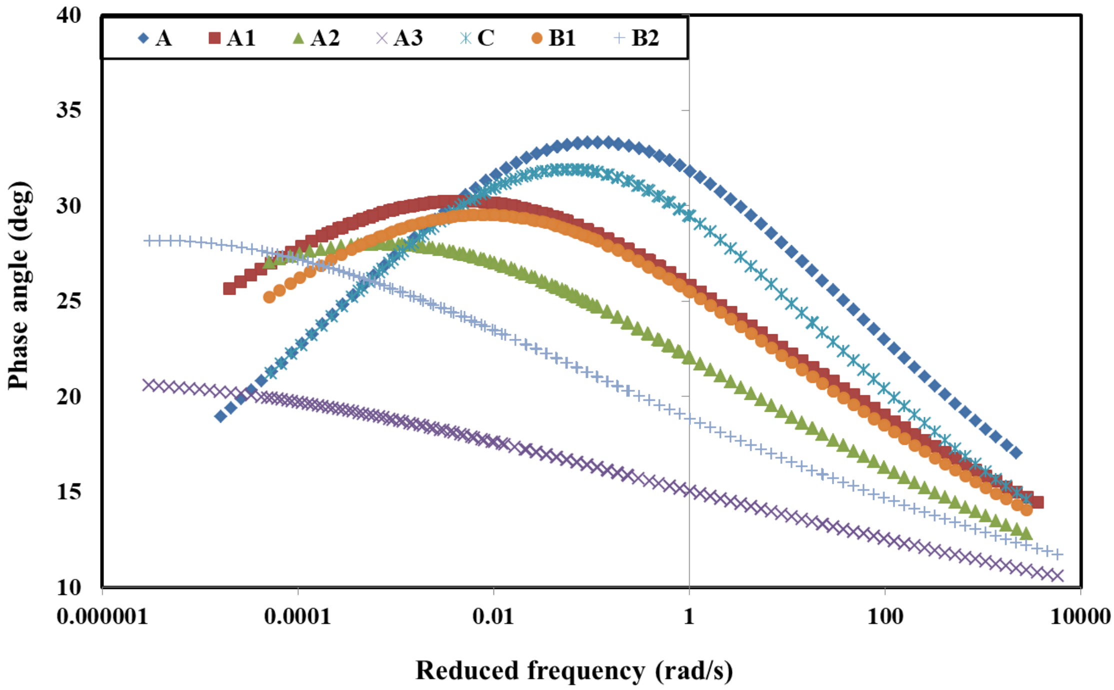
Figure 4.6 Variations of |G*| master curve shape parameter with different aging levels at a reference temperature of 25°C. (a) F1 (b) F2 (c) F3

The master curve of δ for each STA and LTA specimen of F1, F2, and F3 mixtures was also drawn as shown in Figure 4.7(a), Figure 4.7(b), and Figure 4.7(c). Unlike the variation of |G*|, a distinct change in δ with a change in reduced frequency can be seen. It is clear from the plots that as the aging level increased to the FAM specimens, the corresponding value at a particular frequency level decreased, indicating decreases in relaxation property of the FAM specimen. Such a response can be attributed to the viscoelastic nature of the FAM mixture which further indicates the increase in susceptibility of FAM towards cracking with an increase in aging level. For example, the maximum value of δ of specimen A is approximately twice the corresponding maximum value of specimen A3 of all the FAM mixtures. Likewise, a similar decrease in δ value can be obtained with different aging levels. In the majority of the cases, δ value can be seen as increasing with the increase in reduced frequency which subsequently decreased with a further decrease in reduced frequency level. It indicates the importance of loading frequency in the behavior of the FAM mixtures.

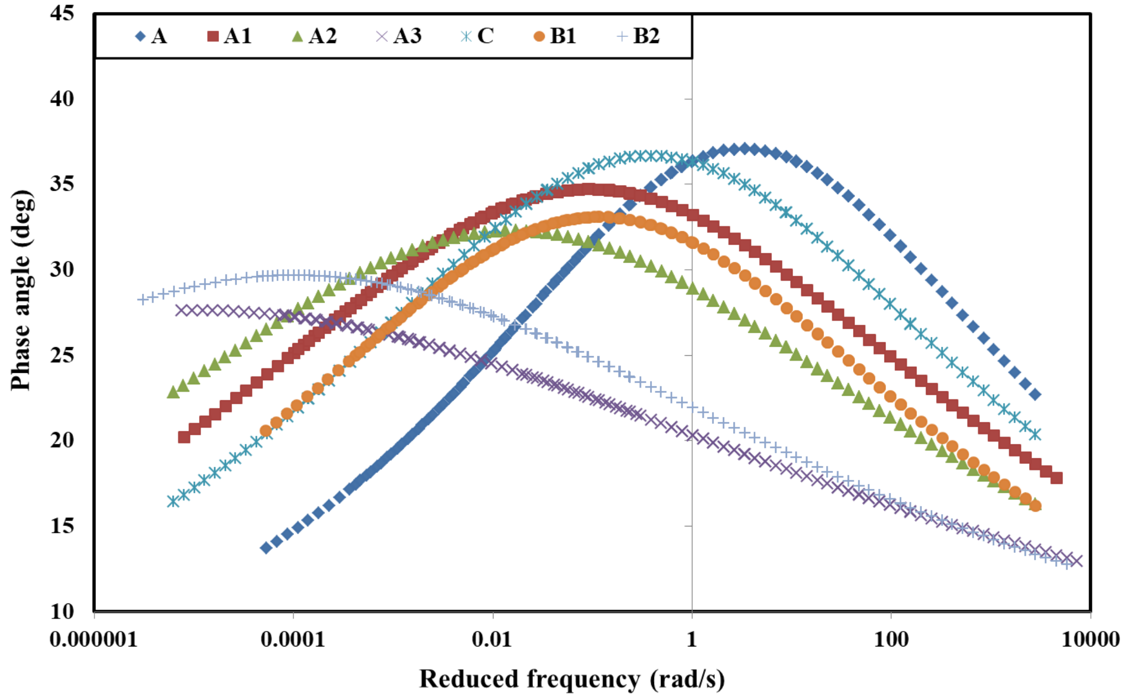
Such a response for the variation of δ over the wide range of frequency is in agreement with findings on FAM mixtures reported by Rastegar et al. (2018) and Underwood and Kim (2011). It is also interesting to note that as the aging level increased to the FAM specimen, the flatness of the corresponding plot for δ value increased. In other words, the increase in an aging level decreased the degree of dependency of δ value on loading frequency. For example, among A, A1, A2, and A3 specimen, the flatness of δ plot over reduced frequency is highest for A3 specimen of all the FAM mixtures. Similar response for δ can be seen between specimen C and B1. Such a response may be attributed to the increased effect of elastic aggregate structure in overall material response; however, it could also be related to the limitations of linear viscoelastic principle in describing the behavior of FAM mixtures, especially for highly aged specimens. Similar to the case of |G*|, the statistical analysis for the variation of δ was also carried out and variation was found to be within an acceptable range.



(a) Mixture type=F1



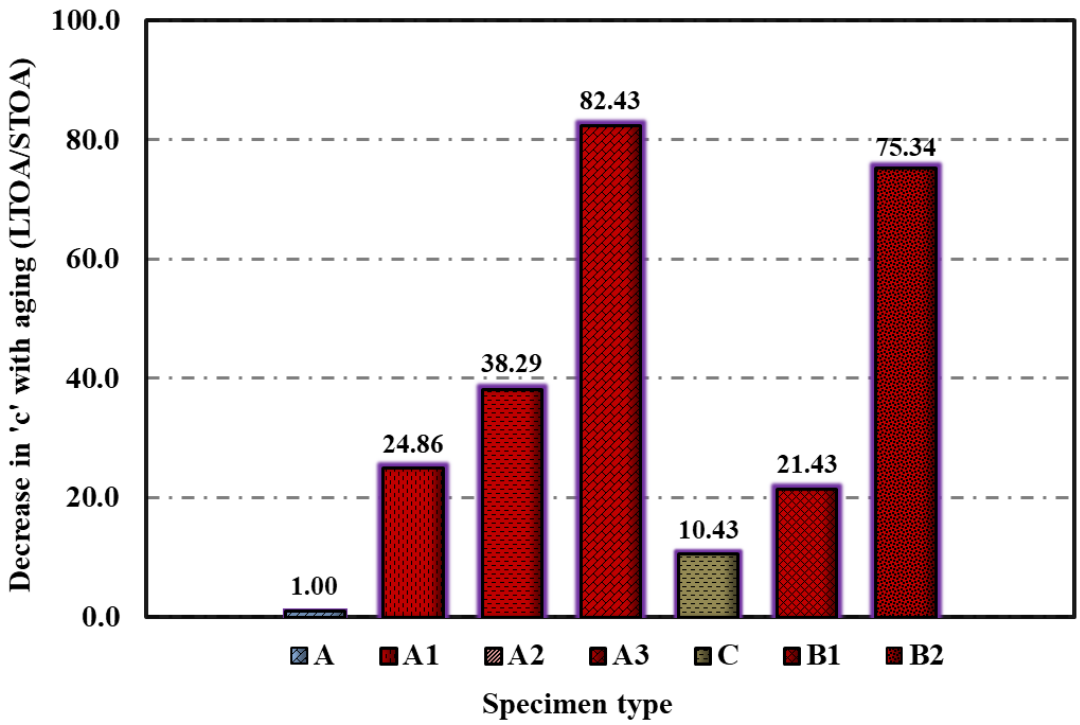
(b) Mixture type=F2



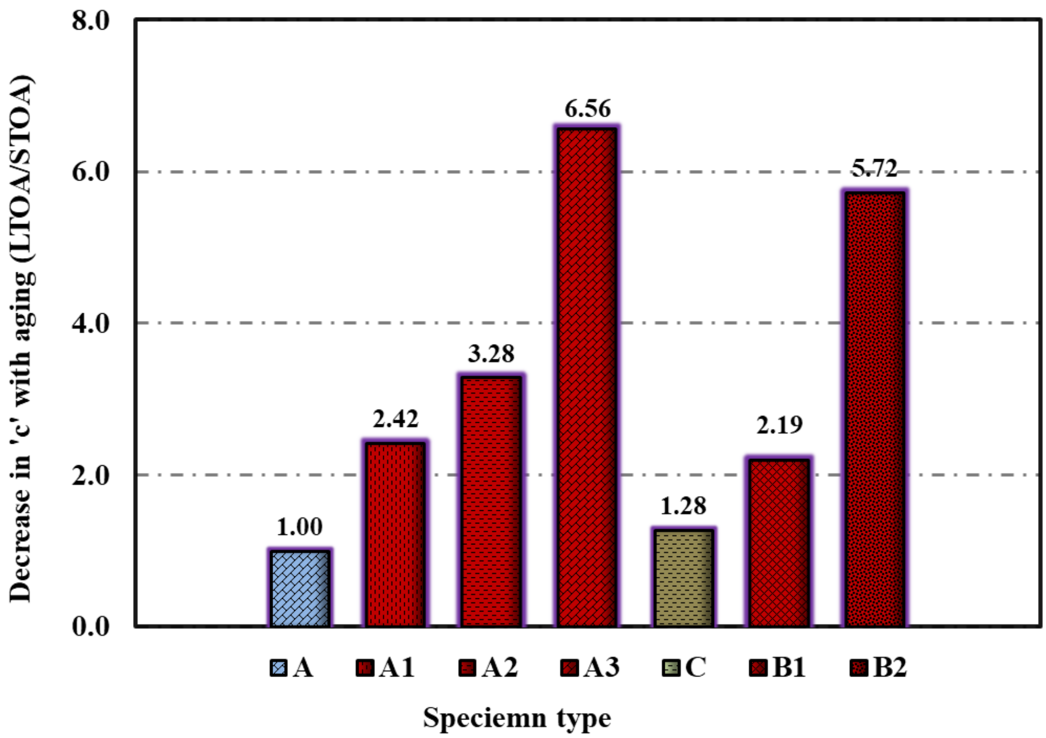
(c) Mixture type=F3

Figure 4.7 Phase angle of STOA and LTOA FAM specimens at reference temperature of 25°C. (a) F1 (b) F2 (c) F3

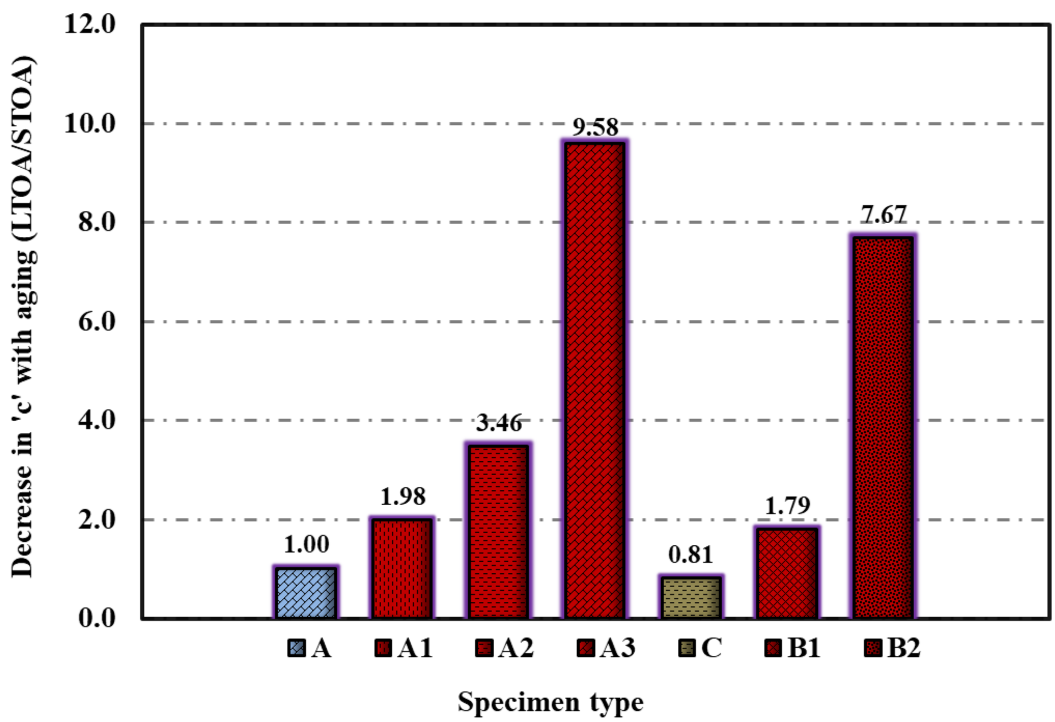
Figure 4.8(a), Figure 4.8(b), and Figure 4.8(c) shows the decrease in shape parameter c for all FAM mixtures (F1, F2, and F3) aged at different duration and temperature levels. Generally, c value decreases as aging level increases. The long-term aged FAM specimens found to have distinctively different c-value compared with the other FAM specimens. The decrease in c-value may be attributed to increase in aging level to FAM specimens. For example, the ratio (c-LTOA/c-STOA) for A3 specimen of all FAM mixtures aged at 24 hrs at 135°C is observed higher compared to STA FAM specimens. This indicates that highly aged A3 FAM specimens of all FAM mixtures (F1, F2, and F3) can be more susceptible to early stage fatigue damage due to lack of relaxation capability. However, these A3 specimens showed higher impact from aging as evaluated by the decrease in c value with aging.



(a) Mixture type=F1



(b) Mixture type=F2



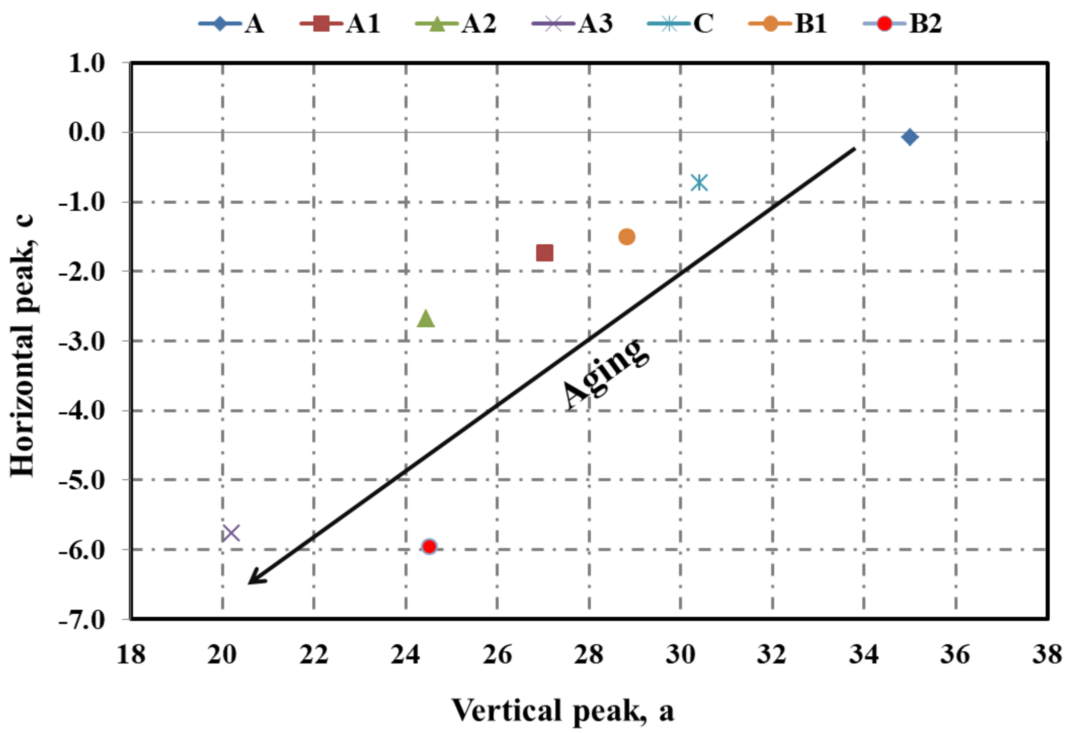
(c) Mixture type=F3

Figure 4.8 Decrease in c value with aging. (a) F1 (b) F2 (c) F3

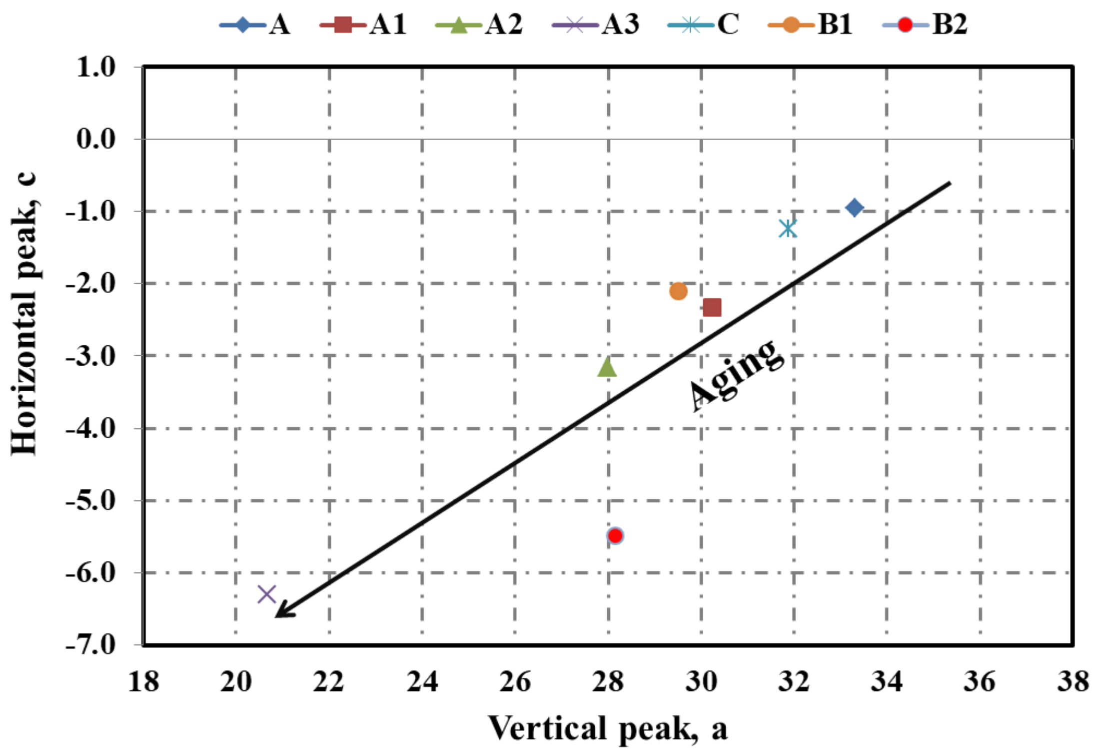
Further, for more analysis of relation between aging duration and temperature used in this study, the variation of the vertical position of peak (a) and the parameter related to the horizontal position of peak (c) with aging were selected. Figure 4.9(a), Figure 4.9(b), and Figure 4.9(c) can be an indicator for the relaxation potential of the FAM mixtures (F1, F2, and F3) aged at different duration and temperature levels. Further, figures clearly showed that how both vertical and horizontal peak values decline as the aging level increases, shifting the points to the plot's lower left. FAM specimens with higher horizontal and vertical peak values are expected to have higher relaxation capability and better fatigue behaviour. 'A' has higher vertical peak values (a) and horizontal peak (c). This indicates that, specimen 'A' has higher relaxation capability and better fatigue behaviour compared to specimen A3 of all corresponding FAM mixtures considered in this study. The various model parameters obtained from the optimization technique for different FAM specimens are presented in Table 4.7. Each plot represents the average of three replicates specimens.

Table 4.7 Phase angle master curve parameters of FAM mixtures

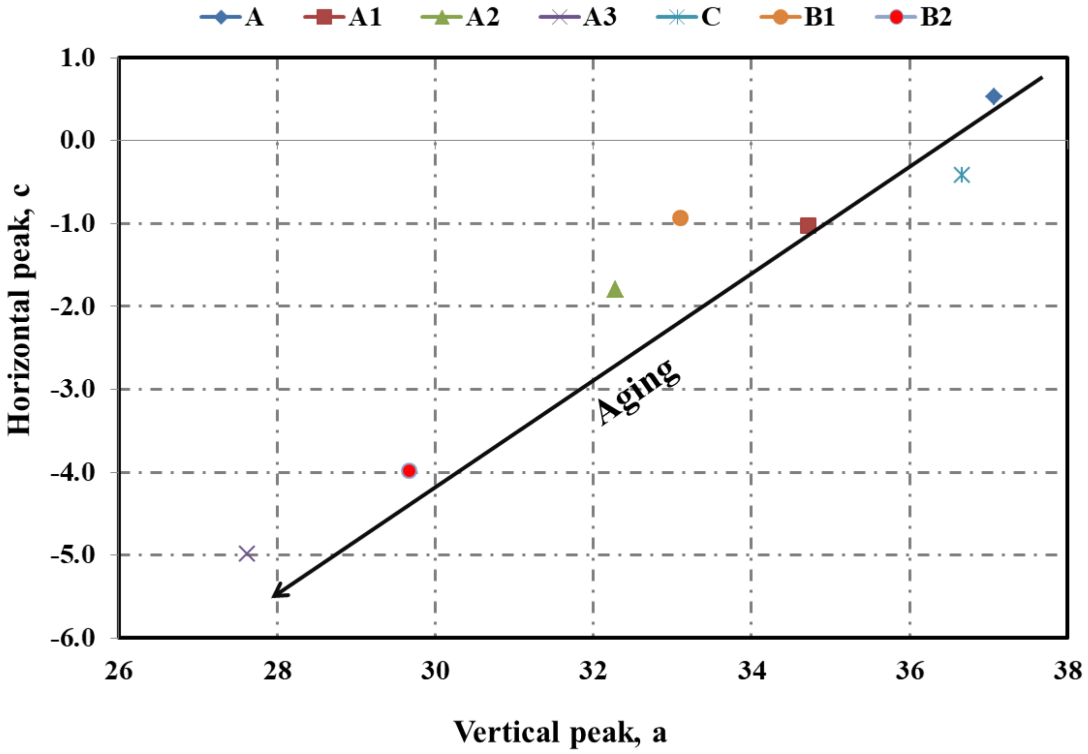
Mixture Type	Specimen Type	a	b	c
F1	A	35.02	-4.36	-0.07
	A1	27.04	-7.91	-1.74
	A2	24.44	-10.05	-2.68
	A3	20.21	-13.64	-5.77
	C	30.42	-6.08	-0.73
	B1	28.81	-6.88	-1.50
	B2	24.52	-14.01	-5.95
F2	A	33.31	-4.40	-0.96
	A1	30.24	-5.62	-2.32
	A2	27.98	-6.07	-3.15
	A3	20.68	-10.27	-6.30
	C	31.89	-4.29	-1.23
	B1	29.51	-5.29	-2.10
	B2	28.16	-7.80	-5.49
F3	A	37.08	-3.67	-0.52
	A1	34.72	-4.81	-1.03
	A2	32.28	-5.29	-1.80
	A3	27.63	-8.32	-4.98
	C	36.66	-4.29	-0.42
	B1	33.10	-4.31	-0.93
	B2	29.67	-6.72	-3.99



(a) Mixture type=F1



(b) Mixture type=F2



(c) Mixture type=F3

Figure 4.9 Variations of δ master curve shape parameters with different aging levels at a reference temperature of 25°C. (a) F1 (b) F2 (c) F3

Finally, the various values obtained from the modeling were statistically compared with the corresponding experimental values and the goodness of fit was evaluated for all the FAM mixtures (F1, F2, and F3) of each FAM specimen aged at different aging protocol. The statistical analysis results are provided in Table 4.8. It can be clearly seen that the goodness of fit parameters obtained for different FAM mixtures are well within the acceptable range. Mixtures are well within the acceptable range.

Table 4.8 Goodness-of-fit results of |G*| and δ from master curve analysis

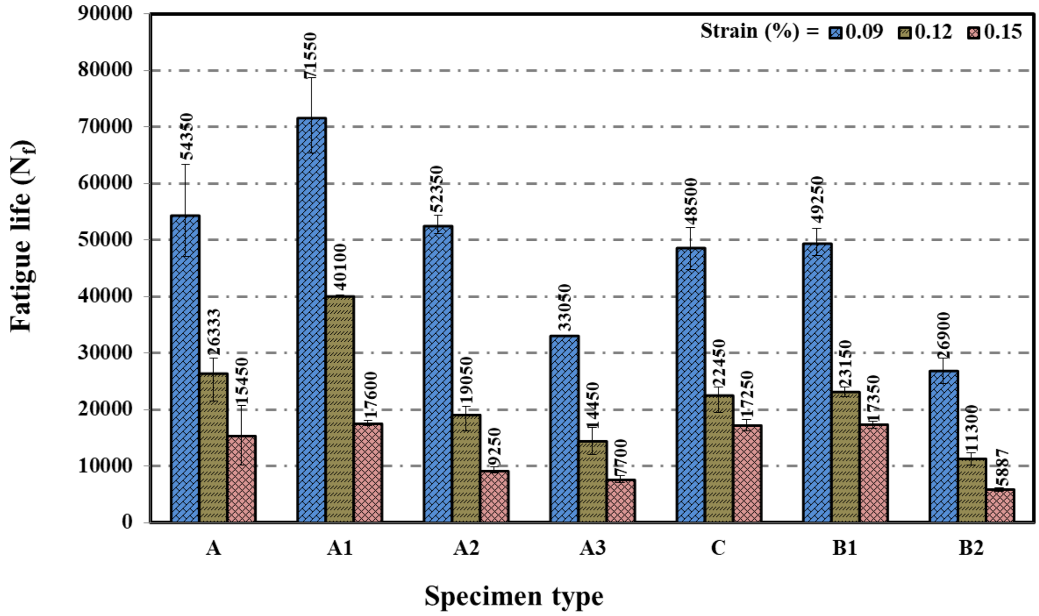
	F1				F2		F3	
	|G*|, R^2	Acceptance criteria, Yousoff et al. (2013)	δ, R^2	Acceptance criteria, Yousoff et al. (2013)	|G*|, R^2	δ, R^2	|G*|, R^2	δ, R^2
Specimen Type	Coefficient of determination	Coefficient of determination	Coefficient of determination	Coefficient of determination				
A	0.997	Excellent (≥0.90)	0.872	Good (0.70-0.89)	0.996	0.876	0.998	0.932
A1	0.990	Excellent (≥0.90)	0.714	Good (0.70-0.89)	0.997	0.910	0.997	0.896
A2	0.827	Good (0.70-0.89)	0.716	Good (0.70-0.89)	0.999	0.946	0.997	0.912
A3	0.900	Excellent (≥0.90)	0.932	Excellent (≥0.90)	0.998	0.984	0.999	0.863
C	0.975	Excellent (≥0.90)	0.730	Good (0.70-0.89)	0.996	0.872	0.997	0.915
B1	0.974	Excellent (≥0.90)	0.700	Good (0.70-0.89)	0.998	0.911	0.997	0.895
B2	0.990	Excellent (≥0.90)	0.840	Good (0.70-0.89)	0.999	0.987	0.999	0.972

4.3.3 Time sweep test results

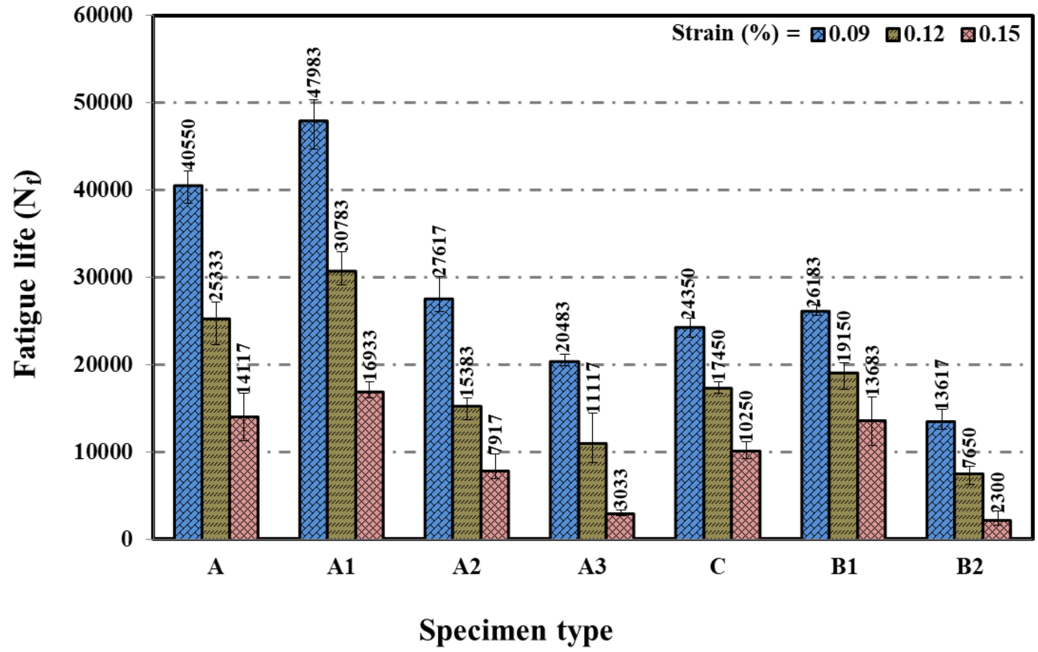
To examine the effect of different aging protocols on fatigue life, time sweep test under strain controlled (0.09%, 0.12% and 0.15%) condition was carried out at 25°C using constant frequency level of 10Hz (Kim et al. 2003). Reduction in |G*| value by 50% of its initial value is widely accepted criteria for defining the end of the fatigue life of the specimen and the same has also been adopted in this research work (Smith and Hesph 2000; Sadeq et al. 2016; Karki et al. 2016).

The fatigue life of three FAM mixtures (F1, F2, and F3) at different strain levels and aging protocols is shown in Figure 4.10(a), Figure 4.10(b), and Figure 4.10(c). The average fatigue life and corresponding Coefficient of Variation (COV) for various FAM combinations are also provided in the plot. The maximum COV was found to be 27.7% for specimen 'A' of F1 mixture which is well below an acceptable value of 30% (Caro et al. 2015). Similarly, the maximum COV was found to be 25.9% for specimen 'B2' and 12.3% for specimen 'C' of F2 and F3 mixtures respectively. It is clear that the fatigue life of FAM mixtures are varying with different strain levels and aging levels. Irrespective of the aging level of a particular FAM specimen, an increase in strain level decreased the fatigue life as expected. For example, an increase in strain level from 0.09% to 0.15% for A3 specimen of F1 mixture decreased the average fatigue life from 33050 to 7700, indicating a decrease in fatigue life by 76.70%. Further, A3 specimen of F2 mixtutre decreased the average fatigue life from 20483 to 3033, indicating a decrease in fatigue life by 85.20%. Likewise, A3 specimen of F3 mixtutre decreased the average fatigue life from 25817 to 9383, indicating a decrease in fatigue life by 63.66%. Similar results can be obtained for other FAM specimens at other strain levels. Furthermore, as the aging level to FAM specimen increased, except the case of increase in aging level from A to A1 (for which unexpectedly increased fatigue life is evident) similar findings were observed in these studies Kingery (2004) and Araving and Das (2007), decrease in fatigue life can be clearly seen. The comparison of different aging protocols based on fatigue life of FAM mixtures (F1, F2, and F3) is shown in Figure 4.10(a), Figure 4.10(b), and Figure 4.10(c). The trend of different aging level protocols showed that the fatigue life of FAM specimens aged at 5 days for 95°C have more fatigue life than

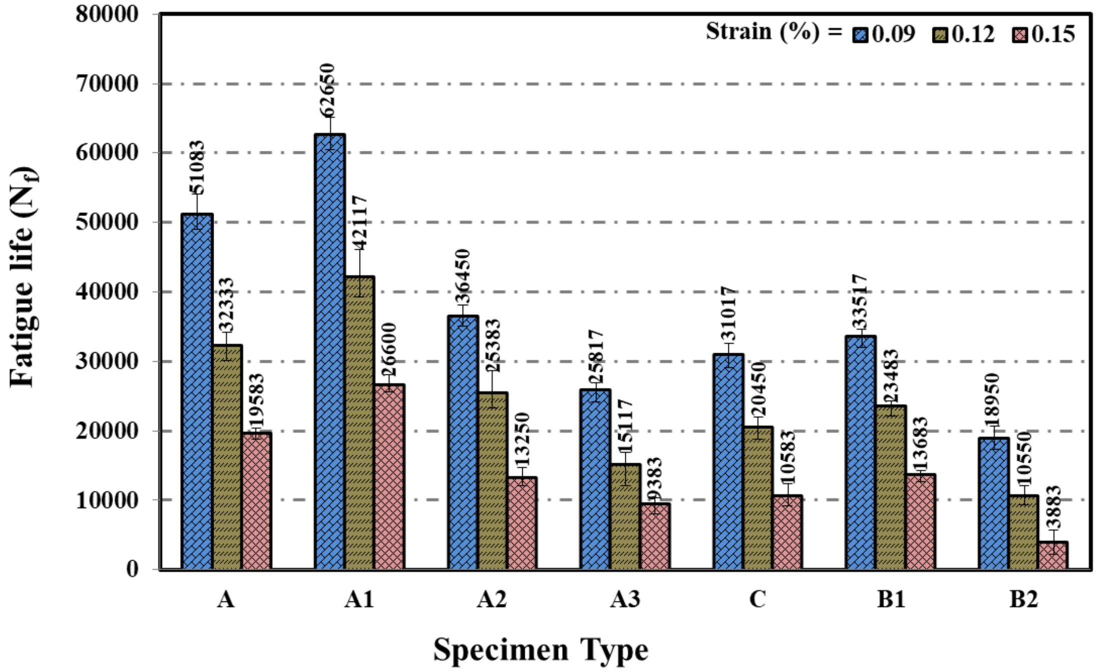
FAM specimen aged for 12 days at 95°C, and 24 hrs at 135°C in all the FAM mixtures. The FAM specimens aged for 24 hrs at 135°C showed better fatigue life than specimen aged for 12 days aged at 95°C. The potential reason for such response might be due to the presence of relatively higher amount of already aged and oxidized asphalt binder present in these FAM mixtures.



(a) Mixture type=F1



(b) Mixture type=F2



(C) Mixture type=F3

Figure 4.10 Strain controlled fatigue test results at 25°C and the frequency of 10 Hz. (a) F1 (b) F2 (c) F3

Further, the fatigue life of each STA and LTA specimens of three FAM mixtures was predicted by using regression analysis. The model coefficients obtained from regression analysis is presented in Table 4.9.

The fatigue model regression coefficients 'a' and 'b' are derived on the basis of measurable material parameters (Kim et al. 2003). It is clear that the fatigue life of FAM mixtures are varying with different strain and aging levels. It is to be noted that the fatigue model coefficients (a and b) value decreased with increase in aging level in general except to the case of increase in aging level from A to A1 specimens in all the FAM mixtures which may be attributed to unexpectedly higher fatigue life for A1 compared to A. For example, the 'a' value for A1 specimens of F2 mixture is 390.150 which decreased to 82.913 and 3.463 with an increase in aging duration from 6 hrs to 12 and 24 hrs respectively. Likewise, A1 specimen of F3 mixture is 1171.000 which decreased to 356.380 and 224.020. Further, an improper trend of regression coefficients can be seen with respect to different aging protocols at 95°C and 135°C.

Table 4.9 Fatigue model regression coefficients of FAM mixtures

Specimen type	Fatigue model regression coefficients								
	F1			F2			F3		
	a	b	R^2	a	b	R^2	a	b	R^2
A	143.00	-2.47	0.99	305.25	-2.05	0.98	588.89	-1.86	0.99
A1	111.20	-2.71	0.97	390.15	-2.02	0.97	1171.00	-1.66	0.98
A2	14.46	-3.39	0.99	82.91	-2.43	0.98	356.38	-1.95	0.95
A3	34.26	-2.85	0.99	3.46	-3.66	0.93	224.02	-1.98	0.99
C	326.23	-2.05	0.97	458.11	-1.67	0.96	222.11	-2.07	0.96
B1	321.20	-2.07	0.97	1274.10	-1.26	0.99	543.86	-1.73	0.96
B2	20.69	-2.97	0.99	4.17	-3.41	0.93	13.30	-3.05	0.95

This indicates the combined effect of regression coefficients ‘a’ and ‘b’ on overall fatigue life of FAM mixtures.

CHAPTER 5

5.0 LABORATORY EVALUATIONS AND RHEOLOGICAL MODELING OF CREEP-RECOVERY BEHAVIOR OF FAM MIXTURES

5.1 GENERAL

The main aim of this chapter is to assess and analyse the creep and recovery performance of different Fine Aggregate Matrix (FAM) mixtures. To investigate the creep recovery behavior, percent recovery (%R) and non-recoverable creep compliance (J_{nr}) were determined by conducting the Multiple Stress Creep Recovery (MSCR) test on FAM mixtures F1, F2, and F3 prepared with three different asphalt binders VG-30, VG-40, and PMB(S) respectively. The MSCR test involves a creep and recovery curve that could directly measure the permanent strain occurring in the FAM mixtures via J_{nr} parameter. In this study, the analysis of test results was focused on two stress levels (15 kPa, and 55 kPa) and three different test temperatures 30°C, 40°C, and 50°C respectively. Test conducted at different temperatures to understand the temperature susceptibility of FAM mixtures. Also, to examine the stress sensitivity of different FAM mixtures, the $\%R_{diff}$ and J_{nr_diff} values were calculated. In addition to the evaluation of %R and J_{nr} values for different combination of FAM mixtures, an attempt was made to conduct Burgers modeling of the strain response obtained from the MSCR test.

5.2 EXPERIMENTAL PLAN FOR RUT STUDIES ON FAM MIXTURES

The MSCR test was initially conducted to understand the response of FAM mixtures under repeated loading and unloading conditions. Subsequently, visco-elastic modelling of creep-recovery response was further carried out using Burgers four element model. The experimental plan for rut studies on FAM mixtures is shown in Figure 5.1. The average of three replicate FAM specimens was considered to report the different findings for various rheological studies. Further, the test matrixes adopted for the MSCR test in which 1-sec as loading and 9-sec as recovery period was considered for total 10 cycles are presented in Table 5.1. The details on the materials, gradations, methodology adopted, and the preparation of FAM specimens were as explained in Chapter 3.

Table 5.1 Details on different matrix for the MSCR study

Mixture type	Stress levels	Creep duration	Recovery duration	Testing temperature	Number of Specimens
F1	15 kPa, and 55 kPa	1 sec	9 sec	30°C, 40°C, and 50°C	1x2x3x3
F2				30°C, 40°C, and 50°C	1x2x3x3
F3				30°C, 40°C, and 50°C	1x2x3x3
				Total	**54**

Note: F1 and F2= FAM mixtures prepared with base binders VG-30 and VG-40 respectively, F3= FAM mixture prepared with polymer modified binder

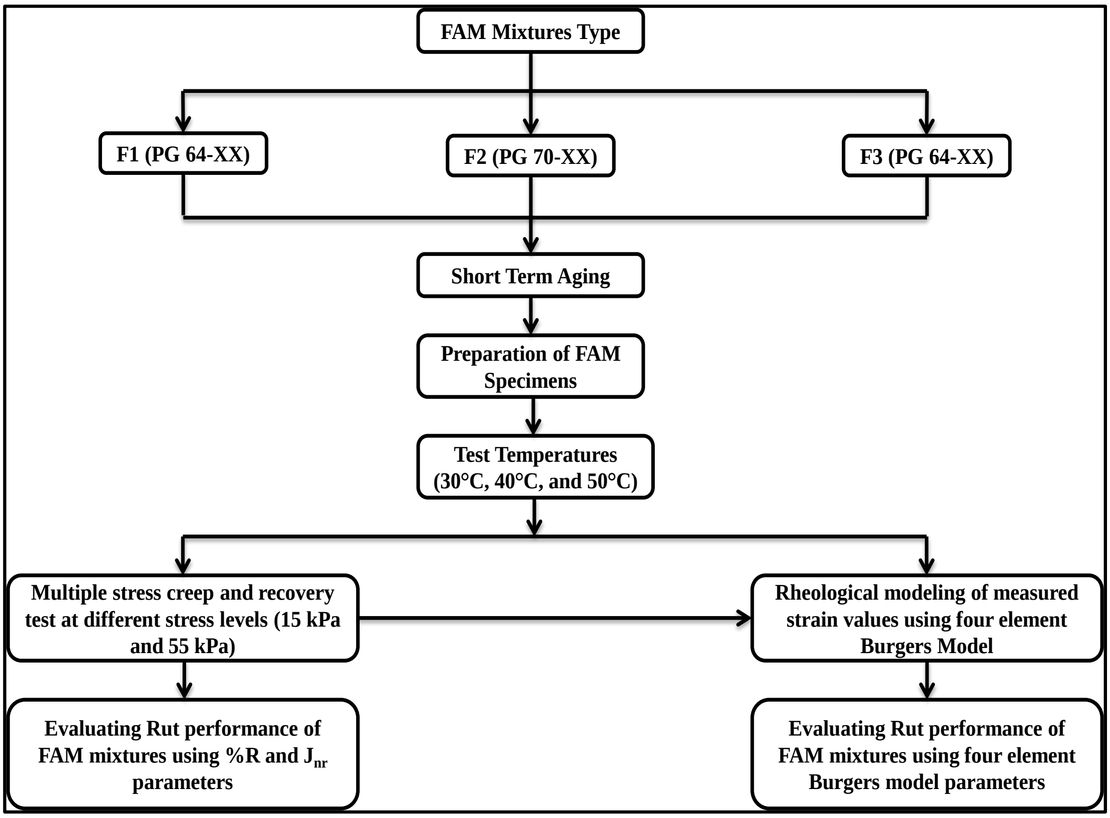


Figure 5.1 Flowchart for experimental plan of rutting studies on FAM mixtures

5.3 RESULTS AND DISCUSSION

The results and discussions of the present investigations are discussed in the following sections.

5.3.1 Percent recoveries

Figure 5.2(a) and 5.2(b) shows the percent recovery of FAM mixtures prepared with different binders i.e, VG-30 (F1), VG-40 (F2) and SBS modified softer binder (F3) at 15 kPa, and 55 kPa stress levels. It can be clearly seen that as the testing temperature increased from 30°C to 50°C, the %R reduced at both the stress levels for all FAM mixtures considered as expected. For example, the %R value for mixtures F1, F2, and F3 reduced by 9.28%, 11.30% and 15.20%, respectively at the stress level of 15 kPa. It is interesting to note that the degree of decrease in recovery value with increase in temperature is relatively higher for F3 mix. Such a response indicates that F3 mixture is relatively more susceptible to temperature compared to other two FAM mixtures which could be due to the relatively lower degree of delayed elastic response associated with F3 mixture. Therefore, given a choice for selecting among F1, F2, and F3 mix for regions where higher degree of temperature variability is experienced, selection of F3 mix may be avoided. While comparing the recovery value of different FAM mixtures at different temperatures, F2 mixture has the highest recovery followed by F1 and lowest for F3 mix at both the stress levels. Such a response could be due to the presence of relatively higher delayed elastic response to F2 mix compared to the other two mixes. This indicates that the F2 mix should be chosen among F1, F2 and F3 mix from recovery perspective for improved rutting performance. Furthermore, as the stress level increases from 15 kPa to 55 kPa, the %R value for all FAM mixtures decreased as expected for all the tested temperatures considered for this research, however, only by a marginal degree. For example, when stress level increased from 15 kPa to 55 kPa, %R values of F1, F2 and F3 mixtures at 30°C decreased by 3.17%, 2.22% and 4.11% respectively. The recovery results of FAM mixtures at different temperatures and stress levels are presented in Table 5.2.

The recovery response obtained in this research work is in agreement with findings reported by Montanez et al. (2020) where the %R value of RAP containing FAM at stress level of 50 kPa was found to be equal to 93.34% at 40°C. Also, when the stress level increased from 50 kPa to 75 kPa, the recovery response was marginal decreased by about 5%. Similarly, the study carried out by Sadeq et al. (2020) has shown almost similar trend in %R results for FAM mixtures with Warm Mix Asphalt

(WMA) additives. For example, considering the stress level of 75 kPa, the %R value observed for different FAM mixtures was found to be in the range of 73% to 93%. Overall, the %R and J_{nr} values of all the FAM mixtures considered in this research are in-line with the results observed from the earlier studies. Although stress levels and temperature for this research work was selected based on the referred literature, only marginal change in %R value with change in stress level and temperature indicates the inability of selected testing conditions to distinguish the effect of modifier such as SBS used in F3 FAM mixture on recovery response. This indicates the need for further research aiming at selecting appropriate temperature and stress level so that the effect of some of the expected changes made to the FAM (for ex., modifier) could be truly captured.

Table 5.2 %R results of FAM mixtures at different temperatures

Temperature (°C)	Recovery values (%)					
	F1		F2		F3	
	15 kPa	55 kPa	15 kPa	55 kPa	15 kPa	55 kPa
30	91.96	89.05	95.17	93.06	85.61	82.09
40	86.99	83.82	87.06	84.67	78.05	76.05
50	83.44	81.35	84.42	82.65	72.67	71.69

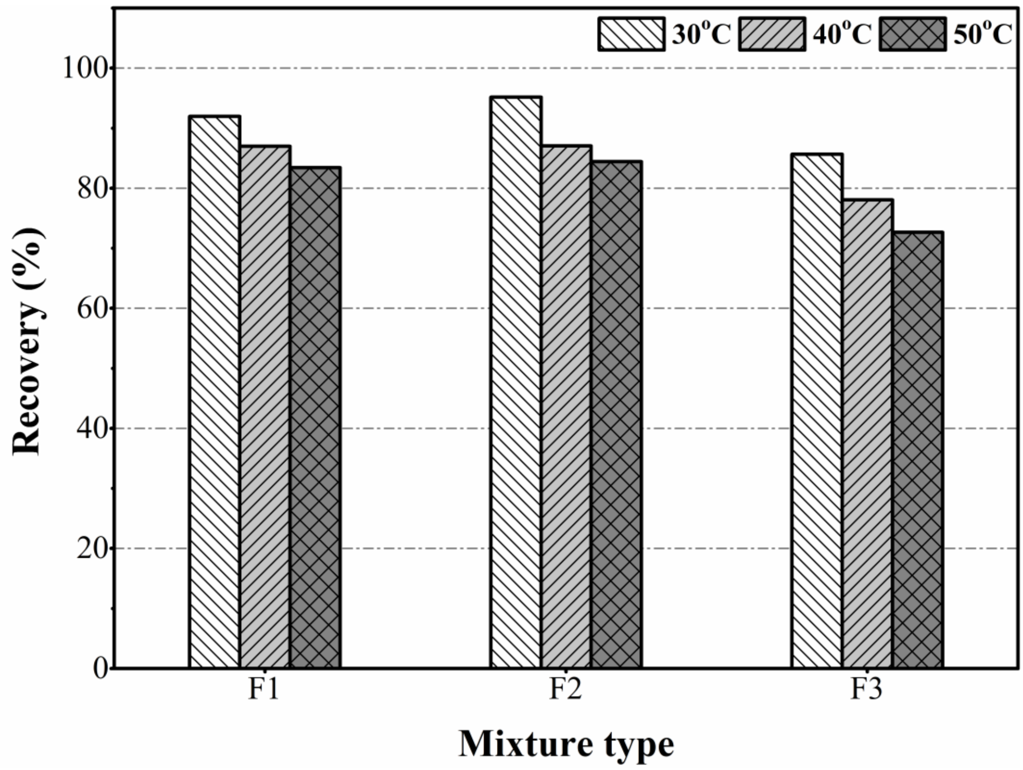
5.3.2 Non-recoverable creep compliance (J_{nr})

Figure 5.3(a) and 5.3(b) illustrates the variation of J_{nr} of FAM mixtures (F1, F2, and F3) prepared with different binder types. It is desirable to have lower value of J_{nr} for better performance under high temperature condition. Considering the stress level of 15 kPa at 30°C, the J_{nr} value observed for F2 mixture is 0.004 kPa^{-1} which is almost 2.75 and 22.75 times lesser compared to corresponding F1 and F3 mixtures respectively. Similarly, considering the stress level of 15 kPa at 50°C, the J_{nr} value of the F2 mixture is 1.4 and 5.95 times less than the F1 and F3 mixtures respectively. Such a response clearly indicated better performance for F2 among all combinations considered for this research and is in-line with findings from the recovery part as discussed earlier. Furthermore, the J_{nr} values for each FAM mixture increased when the stress level changes from 15 to 55 kPa, regardless of the test temperatures as expected. For example, J_{nr} values of FAM mixtures F1, F2 and F3 increased at 50°C by 4.97, 6.51, and 2.23 times, respectively, as stress level increased from 15 kPa to 55 kPa. Overall, the lower J_{nr} value for F2 mixture at both stress levels (15 kPa, and

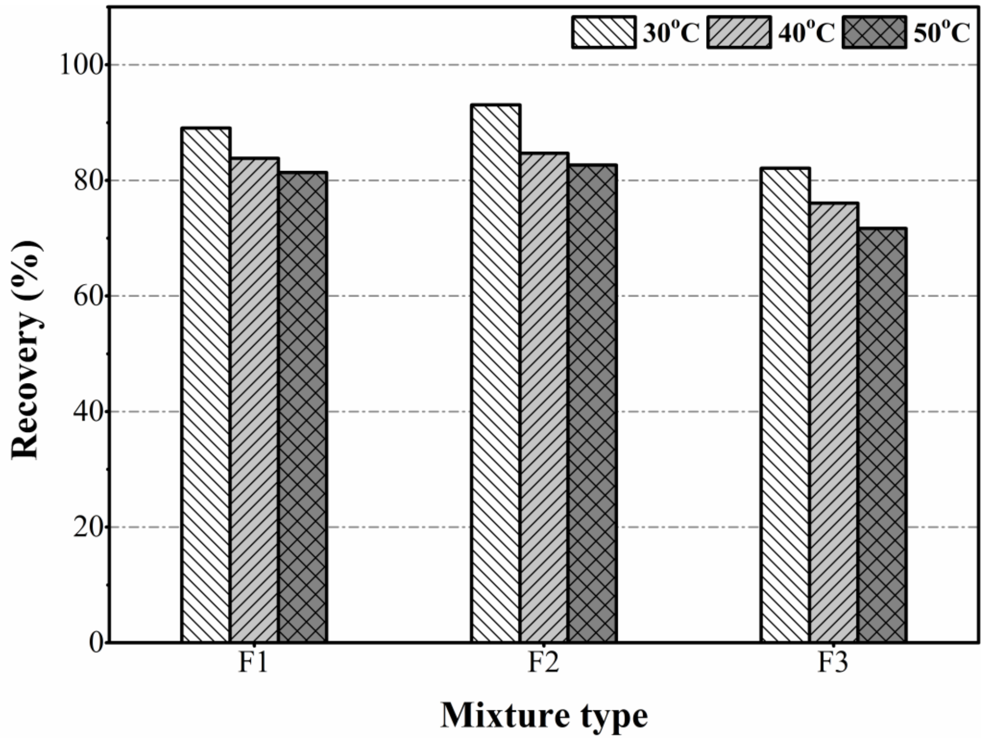
55kPa) for different temperatures indicates that the resistance to permanent deformation increased due to its relatively higher delayed elastic response. The non-recoverable creep compliance results of FAM mixtures at different temperatures and stress levels are presented in Table 5.3.

Table 5.3 J_{nr} results of FAM mixtures at different temperatures

Temperature (°C)	Non-recoverable creep compliance values (kPa^{-1})					
	F1		F2		F3	
	15 kPa	55 kPa	15 kPa	55 kPa	15 kPa	55 kPa
30	0.011	0.117	0.004	0.103	0.091	0.330
40	0.057	0.387	0.052	0.377	0.123	0.833
50	0.143	0.712	0.107	0.697	0.637	1.420

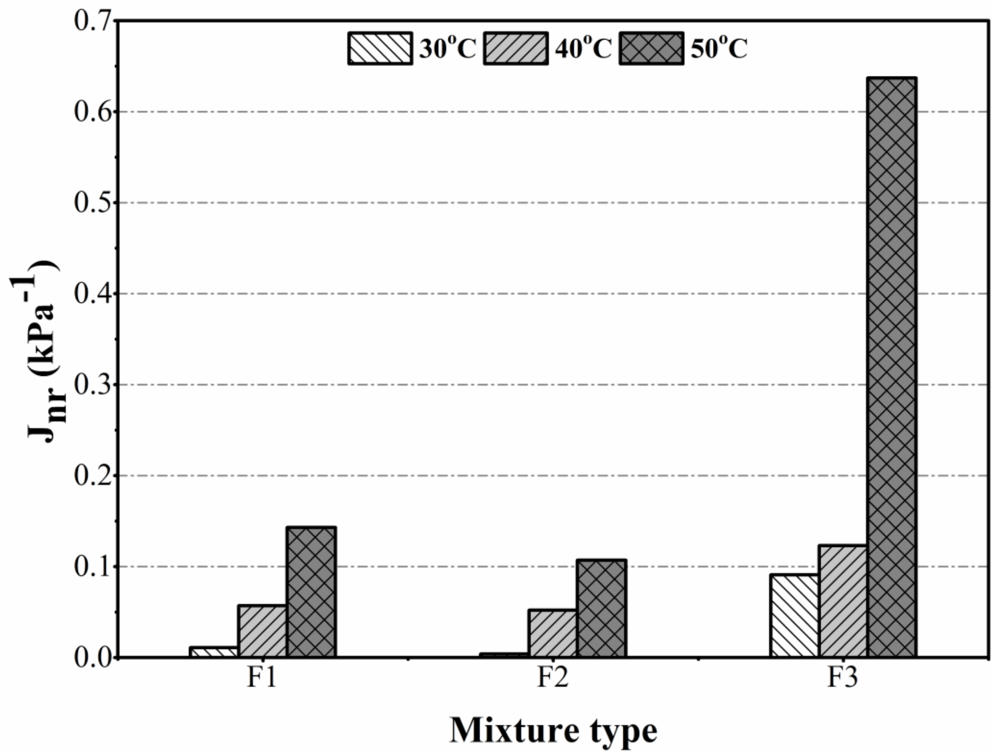


(a) Stress level=15 kPa

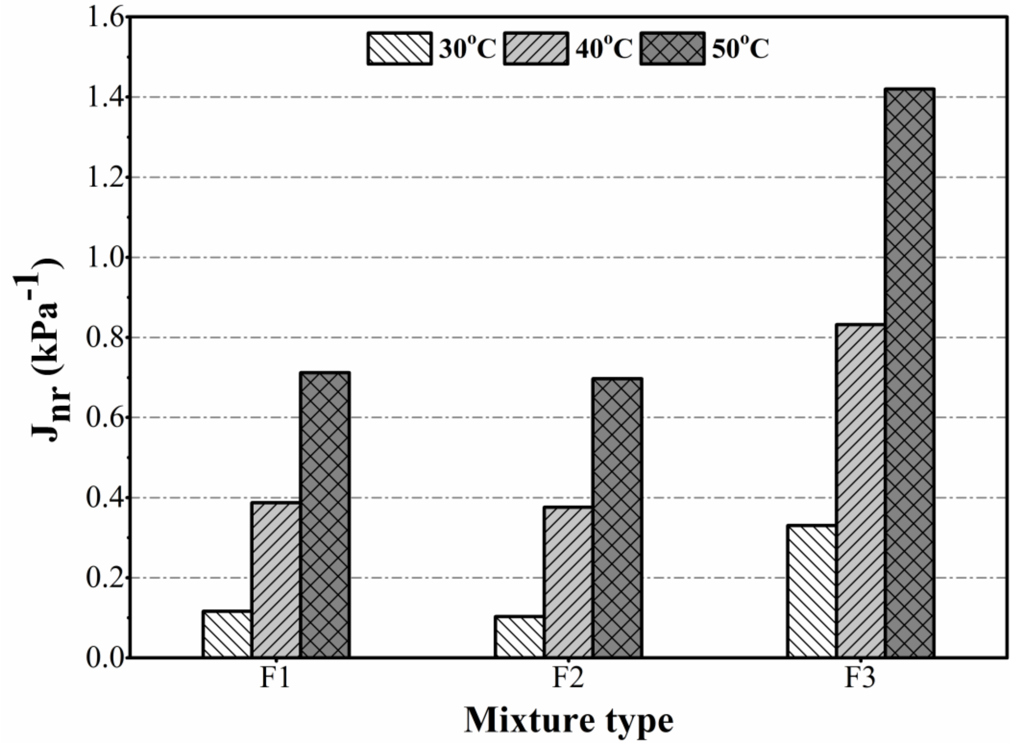


(b) Stress level=55 kPa

Figure 5.2 Percent recovery of FAM mixtures at (a) 15 kPa; and (b) 55 kPa stress levels for different temperatures



(a) Stress level=15 kPa



(b) Stress level=55 kPa

Figure 5.3 Non-recoverable creep compliance (J_{nr}) of FAM mixtures at (a) 15 kPa; and (b) 55 kPa stress levels for different temperatures.

To examine the stress sensitivity of different FAM mixtures, the $\%R_{diff}$ and J_{nr_diff} values were calculated using Eq. (3.8) and Eq. (3.9) and presented in Table. 5.4. FAM mixture with the lowest $\%R_{diff}$ and J_{nr_diff} values should be preferred considering their sensitivity to different loading and temperature conditions. The $\%R_{diff}$ and J_{nr_diff} values increased with an increase in stress level from 15 kPa to 55 kPa as expected, showing poor rut resistance of FAM mixtures under increased stress level. Considering the lower temperature of 30°C, the $\%R_{diff}$ value observed for F2 mixture is lesser when compared to the corresponding F1 and F3 mixtures. Similarly, considering the higher temperature of 50°C, the $\%R_{diff}$ value for F3 mixture is observed to be lesser than the corresponding values of F1 and F2 mixtures. Such a response clearly indicated that the F3 mixture is lesser sensitive when loading condition is changed from 15 kPa to 55 kPa among all the FAM combinations which could be possibly due to the use of polymer modifier in F3 mixture. Similarly, the F3 mixture showed a lower J_{nr_diff} value compared to the other two FAM mixtures at all the tested temperatures considered for this research.

Table 5.4 %R and J_{nr} difference values of FAM mixtures

Temperature (°C)	Stress level (kPa)	$\%R_{diff}$			J_{nr_diff}		
		F1	F2	F3	F1	F2	F3
30	15-55	-3.17	-2.22	-4.11	1006.96	2385.58	261.71
40	15-55	-3.66	-2.74	-2.56	583.10	619.86	578.85
50	15-55	-2.50	-2.10	-1.34	396.74	549.80	122.80

Based upon different $\%R_{diff}$ and J_{nr_diff} value of FAM mixtures at higher temperature of 50°C, the ranking was done from the stress sensitivity point of view. The ranking of different FAM mixture combinations based upon $\%R_{diff}$ value is as F3>F2>F1. Similarly, based upon the J_{nr_diff} value, the ranking is as F3>F1>F2. Overall, the F3 mixture shows the lowest J_{nr_diff} values at all the tested temperatures compared to the other two FAM mixtures, indicating a lower sensitivity to changes in loading conditions.

ANOVA (Analysis of variance) was performed for statistical analysis to determine the significance of the responses. To determine the impact of independent variables on the responses, statistical parameters are estimated. The low p-values ($p<0.05$) are significant for 95% confidence level and these terms are statistically significant for the responses. Significantly, higher 'F-value' indicates that the regression model is highly significant to predict the responses (Saboo et al. 2020; Nainegali et al. 2020).

Table 5.5 Two-way ANOVA results for MSCR test parameters

Mixture	Parameter	Source of variation	SS	df	MS	F value	p-value
F1	%R value	Temperature	65.772	1	65.772	111.241	0.002
		Stress level	11.125	1	11.125	18.816	0.023
		Error	1.774	3	0.591	-	-
		Total	78.671	5	-	-	-
	J_{nr}	Temperature	0.132	1	0.132	7.292	0.074
		Stress level	0.168	1	0.168	9.290	0.056
		Error	0.054	3	0.018	-	-
		Total	0.355	5	-	-	-
F2	%R value	Temperature	111.936	1	111.936	28.510	0.013
		Stress level	6.552	1	6.552	1.669	0.287
		Error	11.779	3	3.926	-	-
		Total	130.267	5	-	-	-
	J_{nr}	Temperature	0.121	1	0.121	6.009	0.092
		Stress level	0.171	1	0.171	8.479	0.062
		Error	0.061	3	0.020	-	-
		Total	0.353	5	-	-	-
F3	%R value	Temperature	136.189	1	136.189	142.092	0.001
		Stress level	7.042	1	7.042	7.347	0.073
		Error	2.875	3	0.958	-	-
		Total	146.106	5	-	-	-
	J_{nr}	Temperature	0.669	1	0.669	17.627	0.025
		Stress level	0.500	1	0.500	13.171	0.036
		Error	0.114	3	0.038	-	-
		Total	1.283	5	-	-	-

The above Table 5.5 presents the results of two-way ANOVA calculated corresponding to FAM mixtures (F1, F2, and F3) in consideration to test parameters of percent recovery (%R) and non-recoverable creep compliance (Jnr) at different temperature and stress levels. The results indicate that temperature has a significant effect on %R for all three types of mixtures. However, it is observed that there is a significant effect of temperature and stress levels on Jnr value in F3 mixture, but the influence is insignificant in the case of F1 and F2 mixtures. The effect of variation in temperature on %R behavior of F3 mixture is more compared to F1 and F2 mixture, as indicated by higher F value; and thus, validates the experimental findings. Hence, the FAM mixtures prepared with different types of asphalt binders such as VG-30 (F1), VG-40 (F2), and PMB (F3) studied at different temperatures and stress levels were more significant towards the creep and recovery behavior.

5.3.3 Rheological modeling of creep and recovery behavior through Burgers model

The review of literature indicated that the Burgers model has been successfully utilized to model the creep and recovery behavior of binders, mastics and full asphalt mixtures (Arabani and Kamboozia 2013; Ashish and Singh 2019; Celauro et al. 2012; Delgadillo and Bahia 2010; Domingos et al. 2019; Domingos and Faxina 2015, 2016; Goli et al. 2019; Hossain et al. 2016; Kumar et al. 2017; Notani et al. 2019; Saboo and Mudgal 2018). The same Burgers four element model was used in this study to fit the creep and recovery response of FAM mixtures. Different parameters for the Burgers model were obtained by minimizing the sum of the square of errors between the model and experimental values from the MSCR test using the solver function available with Microsoft Excel. The Burgers model strain fit variations for FAM mixtures (F1, F2, and F3) at different temperatures (30°C, 40°C and 50°C) for stress level of 15 kPa are shown in Figure 5.5. Similar plots were obtained at other combination of creep stress level of 55 kPa and temperatures, as shown in Figure 5.6. The strain values obtained from Burgers model equations Eq. 3.10 and Eq. 3.11 are represented by cross dash lines in the plot. The predicted strain values in recovery cycle can be seen to slightly deviating from the experimental values in almost every combinations of FAM mixture for all considered stress and temperature levels. The deviating region in the recovery response has been encircled for better visualization of the deviation. Moreover, the predicted strain values in the majority of the cases found to be higher than the corresponding observed strain values during the last period of the recovery phase. On the other hand in case of initial recovery period region, the predicted strain values were found higher than the corresponding observed value in some cases, while it was found to be opposite in some other cases as reflecting from the plot.

Further, the Burgers four element model parameters, numerical values SSE and AAE (as per Eq. 3.12 and Eq. 3.13 respectively) are presented in Table 5.6. As it can be inferred from the SSE and AAE values that the Burgers model fitted the FAM mixtures strain data reasonable well under both creep loading-unloading at different stress levels and temperatures. Among all Burgers four element model parameters

(η_m, E_m, η_k, and E_k), the η_m is considered as one of the most significant parameter for the characterisation of the rutting resistivity potential of asphalt binders and mastics (Ashish et al. 2020; Ashish and Singh 2019; Saboo and Mudgal 2018; Singh et al. 2017). The η_m is the dashpot component of Maxwell component of the Burgers model which represents the viscosity coefficient of steady flow. A lower value of η_m indicates a higher amount of unrecoverable strain for FAM mixtures. Therefore, a higher value of η_m is desirable from high temperature performance perspective. The Burgers model parameters for all FAM mixtures at considered stress levels and temperatures are encapsulated in Table 5.6.

Table 5.6 Burger model parameters of FAM mixtures at 15 kPa and 55 kPa for different temperatures

Mixture Type	Temperature (°C)	Burger model parameters for stress level 15 kPa,					
		η_m (MPa.s)	E_m (MPa)	η_k (MPa.s)	E_k (MPa)	100SSE	AAE*
F1	30	3.430	3.410	0.561	1.780	0.0021	-0.0012
	40	0.693	1.030	0.261	0.515	0.0182	-0.0024
	50	0.363	0.480	0.163	0.237	0.0925	-0.0021
F2	30	5.420	3.220	1.100	1.750	0.0025	-0.0048
	40	0.813	0.987	0.303	0.504	0.0192	-0.0022
	50	0.380	0.480	0.149	0.221	0.0945	-0.0025
F3	30	0.815	1.300	0.163	0.738	0.0051	-0.0022
	40	0.310	0.410	0.150	0.152	0.1410	-0.0009
	50	0.161	0.213	0.053	0.078	0.9000	-0.0030
		Burger model parameters for stress level 55 kPa					
F1	30	2.850	6.140	0.975	1.360	0.0514	-0.0015
	40	0.628	1.670	0.355	0.303	0.5200	-0.0012
	50	0.265	0.695	0.210	0.166	2.1700	-0.0031
F2	30	4.140	4.120	1.090	1.180	0.0452	-0.0025
	40	0.789	1.540	0.367	0.297	0.4830	-0.0011
	50	0.331	0.682	0.210	0.160	2.1300	-0.0030
F3	30	0.447	5.310	0.436	0.335	0.3090	-0.0012
	40	0.298	0.554	0.187	0.124	3.0400	-0.0032
	50	0.050	0.235	0.125	0.075	11.120	-0.0048

*AAE (%) = average absolute error. This parameter shows the average percent difference between the predicted and observed data for all the creep recovery cycles.

The η_m value can be seen to be decreasing with increase in temperature. This is due to the fact that as the temperature will increase, the non-recoverable response is expected to increase. Further attempt was made to compare the η_m with the J_{nr}

response, as previously mentioned, which was considered an indicative parameter for non-recoverable creep strain value at the end of the recovery period. Figure 5.4 clearly shows that the increase in the value of J_{nr} of the corresponding FAM mixtures results in a decrease in the values of η_m. Also, it was found to be a fairly good correlation between parameter η_m and non-recoverable creep compliance J_{nr}. However, a study using more combinations of FAM mixtures and test data could give more confidence on establishing this correlation.

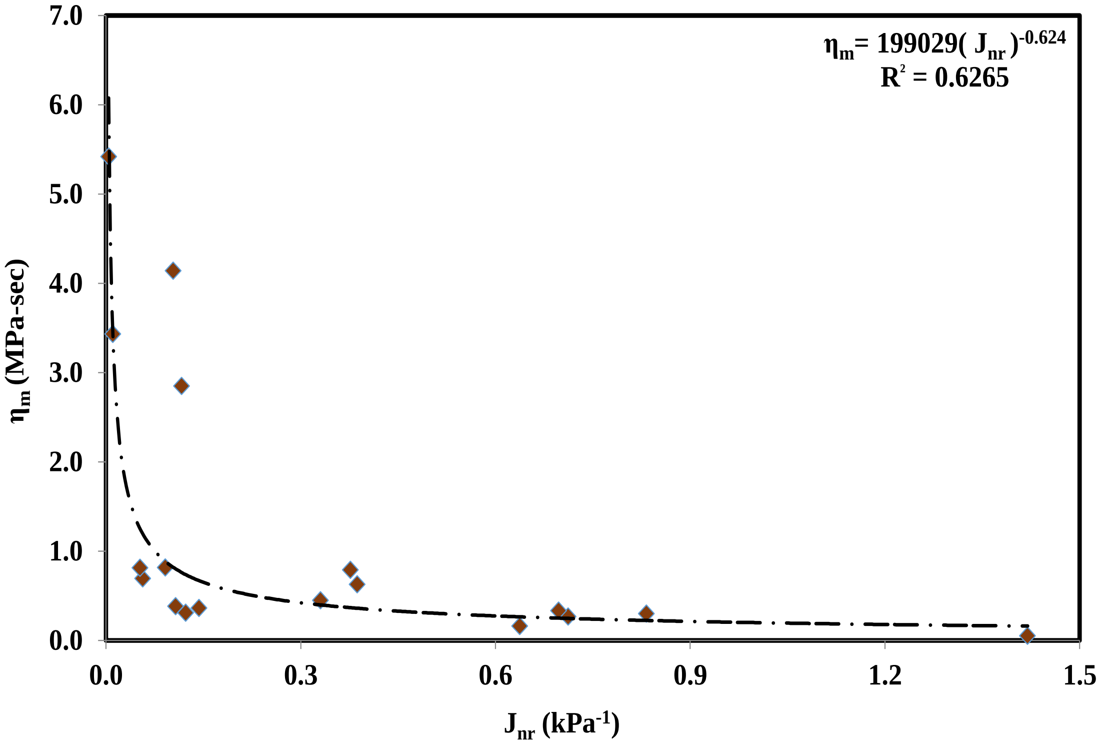


Figure 5.4 Correlation between J_{nr} and η_m parameter for FAM mixtures

The F2 mix combination showed highest η_m value among all FAM (F1, F2 and F3) mixtures at stress level of 15 kPa compared to F1 and F3 mixtures for all the temperatures (30°C, 40°C and 50°C). For example, at 40°C and stress level of 15 kPa, η_m value for F2 mixture is 8.13E+05 Pa-sec which decreased to 6.93E+05, and 3.10E+05 Pa-sec for F1 and F3 mixtures respectively. Such a response clearly indicates the relatively better high temperature performance for F2 compared to F1 and F3 mix. Also, the difference in the η_m value of FAM mixtures F2 and F1 was observed lesser compared to F3 mixtures. For example, at 50°C, The F2 mixture has η_m value 1.05 and 2.36 times more compared to F1 and F3 mixtures respectively. It can therefore be concluded that the presence of higher ηm value for F2 mixtures could be due to its higher elastic response compared to two other FAM mixtures. Similar observations can be made at higher stress level of 55 kPa and lower temperatures (30°C and 40°C). Such findings indicate that the F2 mixture is better in rut performance due to its delayed elastic response followed by F1 and F3 mixtures for higher temperatures and at both stress levels (15 kPa, and 55 kPa).

It is also to be noted that as the stress level changes from 15 kPa to 55 kPa, the η_m values of FAM mixtures decreased. For example, at 50°C, the η_m value for F1, F2, and F3 mixtures decreased about 26.70%, 12.89%, and 68.70% respectively. A similar decrease can be obtained for other temperatures. This decrease indicates that the FAM mixtures at different temperatures are sensitive to higher stress levels. However, such results are observed because of higher J_{nr} value (lower %R values) of FAM mixtures at higher stress level and temperatures.

The parameter E_m represents the modulus of Maxwell spring which is an indication for recoverable strain immediately after creep loading. As the stress level increases from 15 kPa to 55 kPa, the E_m value for all FAM mixtures increased as expected for all the tested temperatures considered for this research. For example, when stress level increased from 15 kPa to 55 kPa, E_m values of F1, F2 and F3 mixtures at 30°C increased by 1.80, 1.28 and 4.08 times respectively. Similarly, at a temperature of 50°C, the E_m values were found to be 1.45, 1.42, and 1.10 times higher for FAM mixtures F1, F2, and F3 respectively. The findings can be attributed to corresponding higher J_{nr} values (lower %R values) for the higher stress level of 55 kPa. Furthermore, a decrease in E_k values as well as a considerably higher increase of η_k values for each FAM mixture is observed when the stress level changes from 15 to 55 kPa, regardless of the test temperatures. For example, the E_k value of F2 mixture reduced from 2.21E+05 Pa-sec to 1.60E+05 Pa-sec and its η_k value increased from 1.49E+05 Pa-sec to 2.10E+05 Pa-sec at 50°C. The similar findings were observed for F1 and F3 mixtures at other two temperatures (30°C and 40°C). Such results may be attributed to the existence of higher J_{nr} values for each FAM mixtures at higher stress level of 55 kPa.

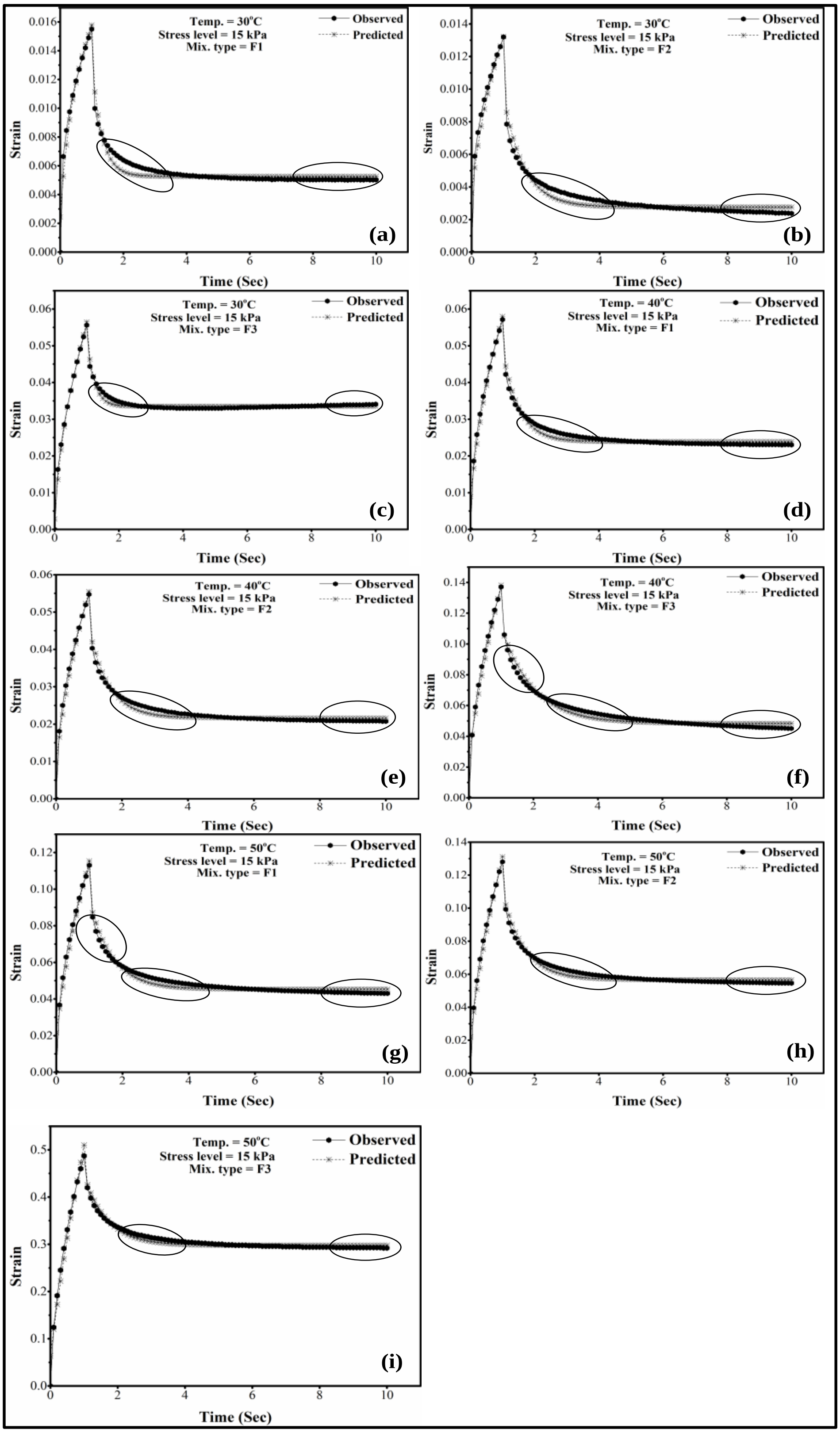


Figure 5.5 Variation of Burgers model strain for different FAM mixtures at different temperatures for the stress level of 15 kPa

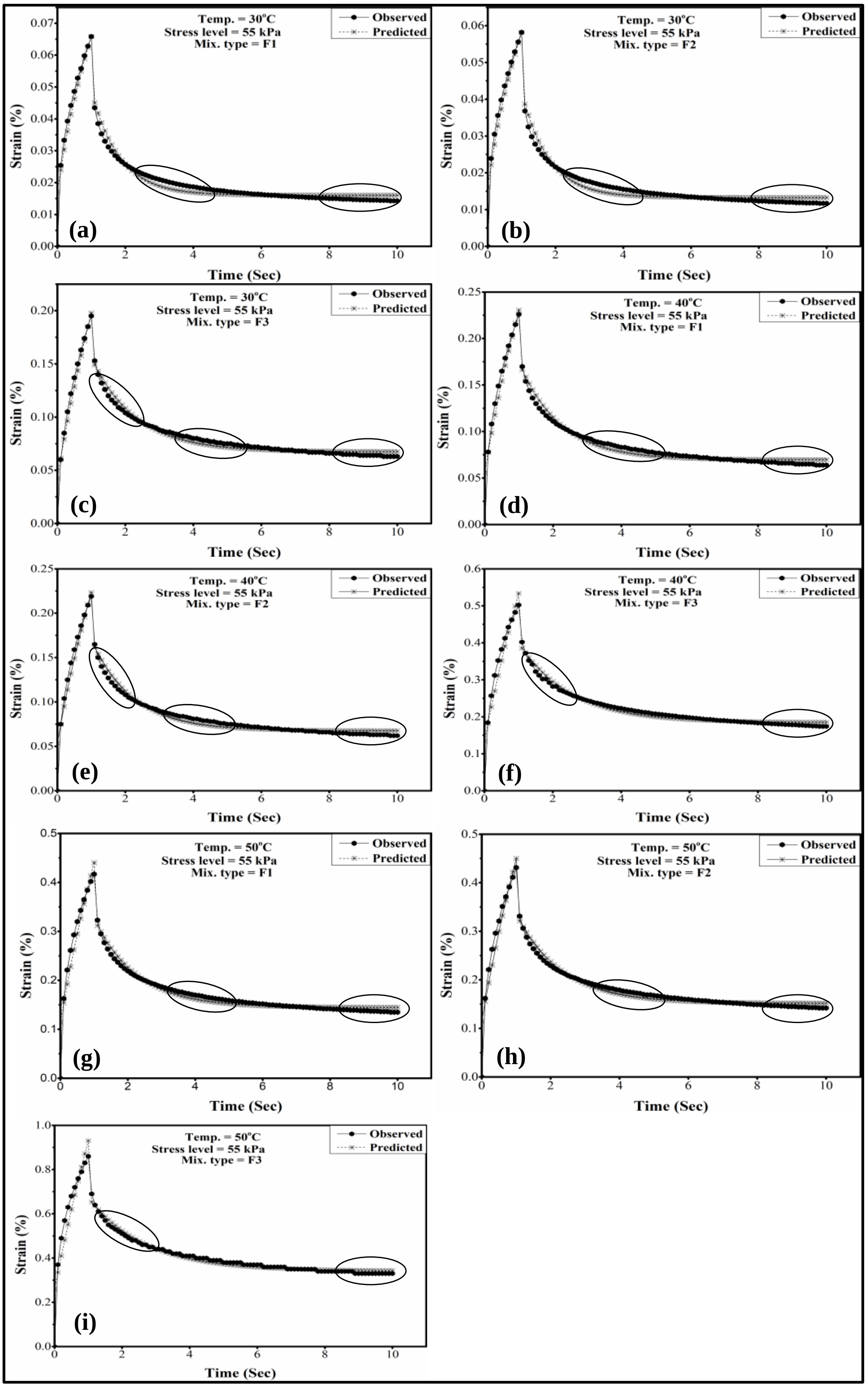


Figure 5.6 Variation of Burgers model strain for different FAM mixtures at different temperatures for the stress level of 55 kPa

CHAPTER 6

6.0 EVALUATION OF MOISTURE DAMAGE POTENTIAL OF FAM MIXTURES

6.1 GENERAL

The main aim of this chapter is to study and analyse the creep and recovery performance of FAM mixtures (F1, F2, and F3) in dry and wet conditions at four different stress levels (15 kPa, 35 kPa, 55 kPa, and 75 kPa) and temperature of 40°C by conducting the static creep recovery test. Percent recovery (%R) and non-recoverable creep compliance (J_{nr}) results of FAM mixtures in dry and wet conditions are then compared. Furthermore, ratios of %R and J_{nr} were determined for dry and wet conditioned FAM mixtures and presented to evaluate the moisture susceptibility of FAM mixtures.

6.2 EXPERIMENTAL PLAN FOR STUDIES ON MOISTURE DAMAGE PROPERTY OF FAM MIXTURES

The static creep recovery test was initially conducted to understand the response of dry and wet FAM mixtures under repeated loading and unloading conditions. The experimental plan for moisture damage property of FAM mixtures is shown in Figure 6.1. The average of three replicate FAM specimens was considered to report the different findings of moisture damage potential of FAM mixtures. Further, the test matrixes adopted for the static creep recovery test in which 30-sec as loading and 300-sec as recovery period was considered are presented in Table 6.1. The details on the materials, gradations, methodology adopted, and the preparation of FAM specimens were as explained in Chapter 3.

Table 6.1 Details on different matrix for the static creep and recovery study

Mixture type	Stress levels	Creep duration	Recovery duration	Dry conditioned	Wet conditioned	Number of Specimens
F1	15 kPa, 35 kPa, 55 kPa, and 75 kPa	30 sec	300 sec	3x4	3x4	24
F2				3x4	3x4	24
F3				3x4	3x4	24
				Total		**72**

Note: F1 and F2= FAM mixtures prepared with base binders VG-30 and VG-40 respectively, F3= FAM mixture prepared with polymer modified binder

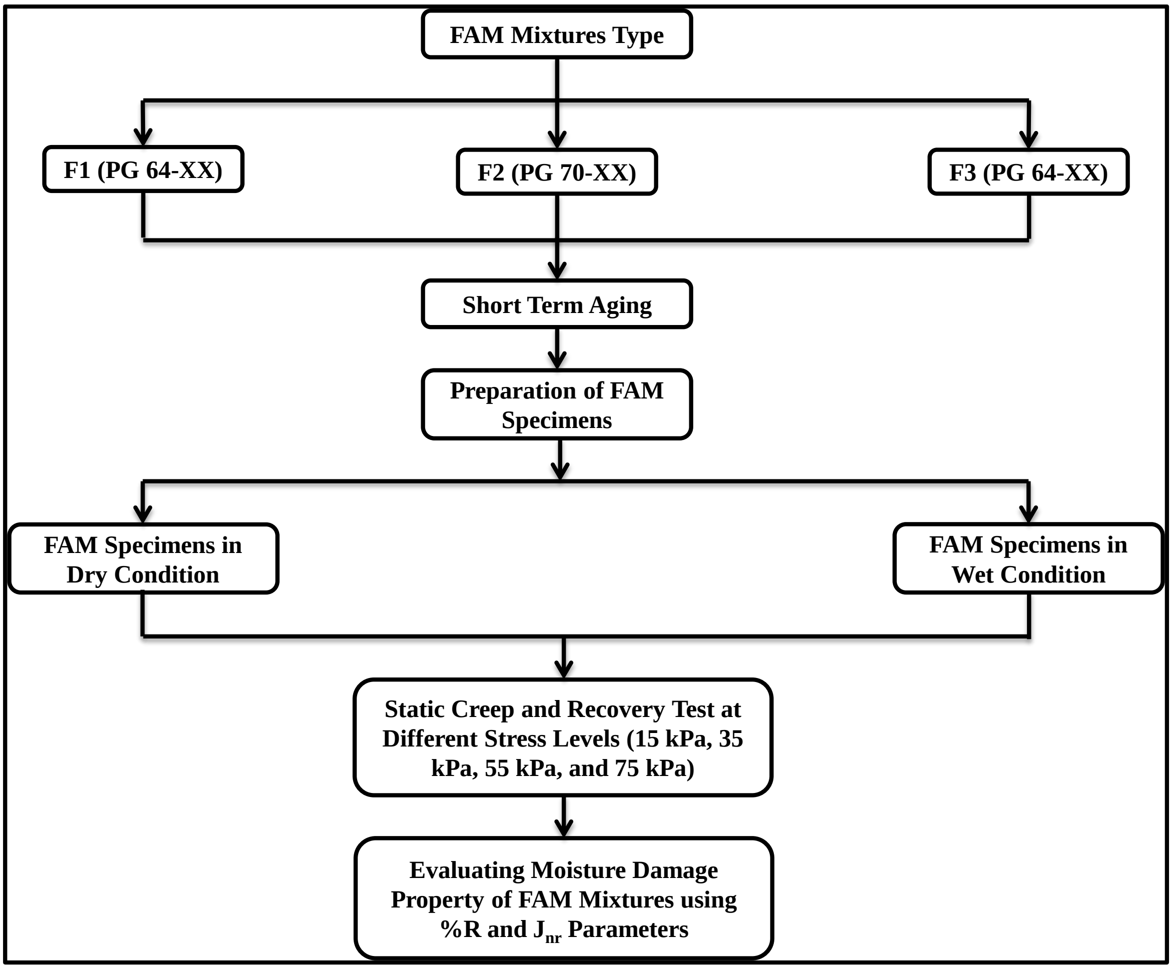


Figure 6.1 Flowchart for experimental plan of moisture damage property of FAM mixtures

6.3 RESULTS AND DISCUSSION

The results and discussions of the present investigations are discussed in the following sections.

6.3.1 Effect of moisture on %R of FAM mixtures

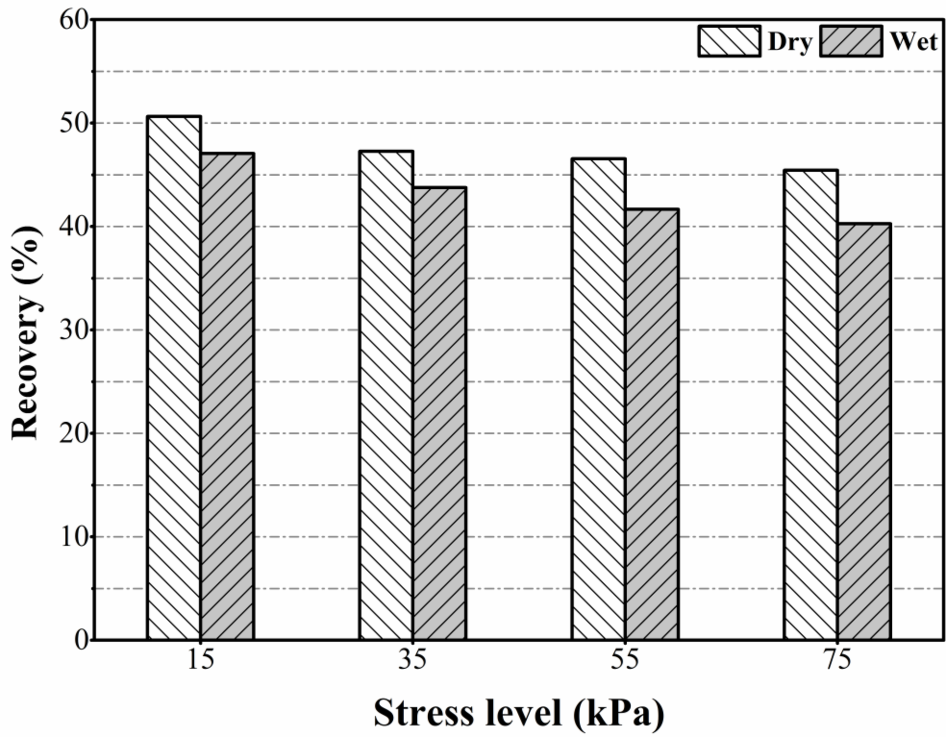
The attempt has made to illustrate the moisture effect on permanent deformation behavior of FAM mixtures, the amount of %R and J_{nr} (i.e., permanent strain) values of wet conditioned and dry FAM specimens at the end of testing (at 300 sec) were determined and presented in Table 6.2 and Table 6.3 respectively. The results indicated that the decrease in %R values and increase in J_{nr} values for all the corresponding FAM mixtures at all four different stress levels when the FAM specimens are tested in wet condition compared to dry specimens.

Table 6.2 %R results of FAM mixtures in dry and wet condition

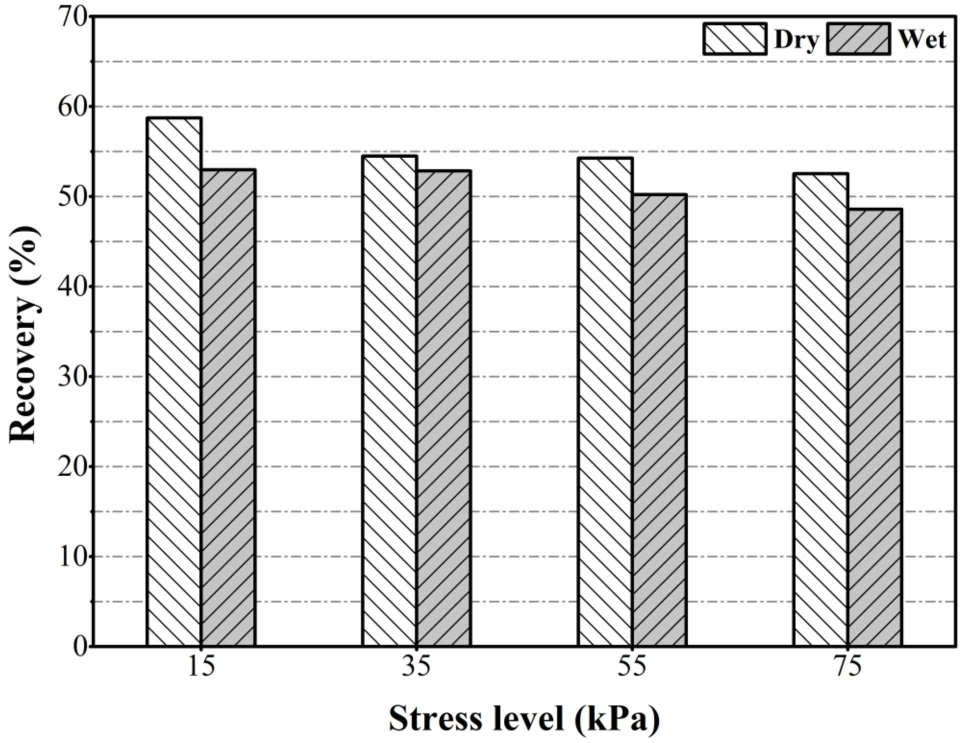
Stress level (kPa)	%R					
	F1		F2		F3	
	Dry	Wet	Dry	Wet	Dry	Wet
15	50.64	47.05	58.73	54.97	40.91	39.62
35	47.26	43.76	54.49	50.84	38.22	36.46
55	46.55	41.66	54.26	50.16	35.68	33.88
75	45.43	40.26	52.54	48.17	34.22	32.27

Figure 6.2(a), Figure 6.2(b), and Figure 6.2(c) shows the percent recovery of FAM mixtures prepared with different binders i.e, VG-30 (F1), VG-40 (F2) and SBS modified softer binder (F3) at 15 kPa, 35 kPa, 55 kPa, and 75 kPa stress levels. The wet conditioned FAM specimens showed the reduction in %R values at all the four stress levels for all FAM mixtures considered as expected. For example, the %R value for mixtures F1, F2, and F3 reduced by 7.63%, 6.84% and 3.25%, respectively, at the stress level of 15 kPa. Similar results were observed for higher stress levels too. It is interesting to note that the decrease in recovery value is relatively lower for wet conditioned F3 mixture. Such a response indicates that F3 mixture is relatively lesser susceptible to moisture damage compared to other two FAM mixtures which could be due to the relatively higher degree of elastic property associated with F3 mixture even after wet condition. Therefore, given a choice for selecting among F1, F2, and F3 mixtures for regions where highest rainfall variability is experienced, selection of F3 mixture may be suitable. Furthermore, as the stress level increases from 15 kPa to 75 kPa, the %R value for all FAM mixtures in both wet and dry condition decreased as expected. For example, when stress level increased from 15 kPa to 75 kPa, %R values of dry specimens of F1, F2 and F3 mixtures at 40°C decreased by 11.47%, 11.78%

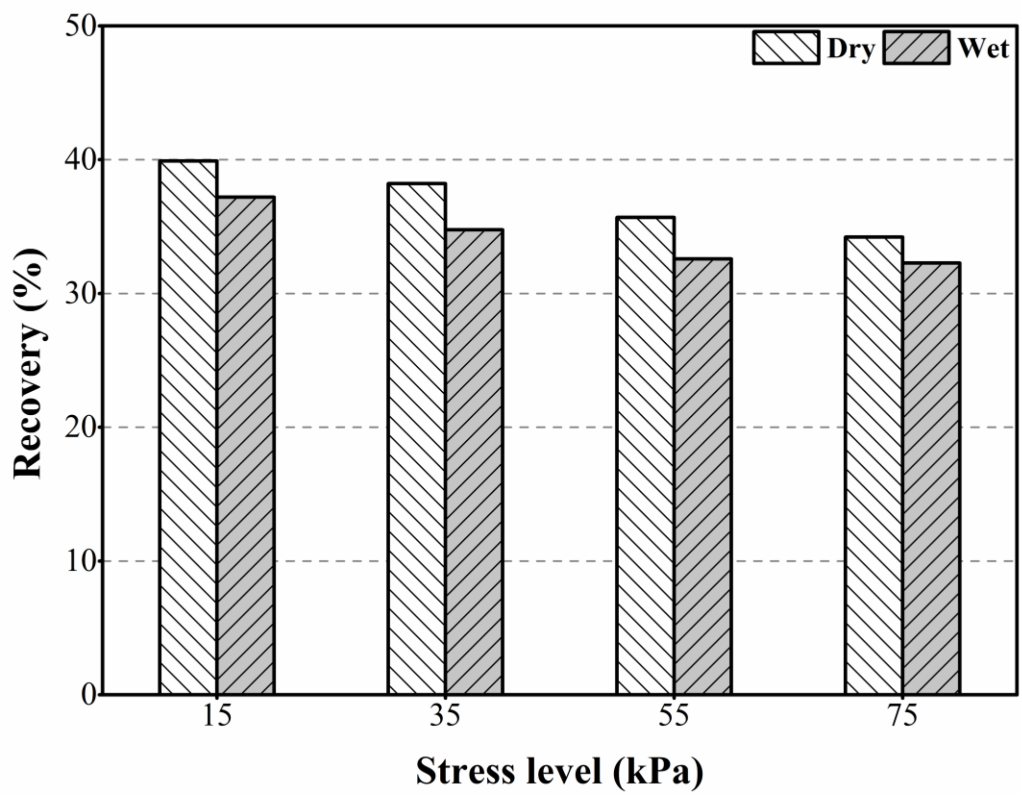
and 19.55% respectively. Similarly, wet conditioned specimens are also showed a same decreasing trend in %R values.



(a) Mixture type=F1



(b) Mixture type=F2



(C) Mixture type=F3

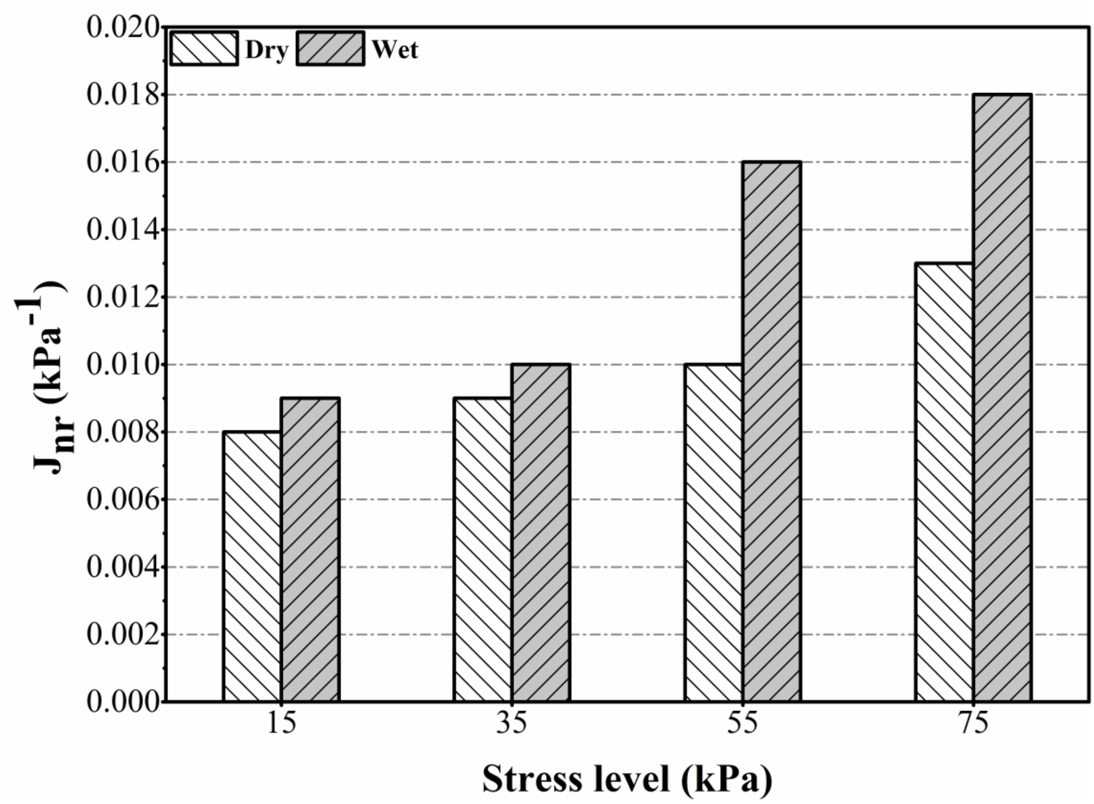
Figure 6.2 Percent recovery of FAM mixtures in dry and wet condition (a) F1 (b) F2 (c) F3

6.3.2 Effect of moisture on J_{nr} of FAM mixtures

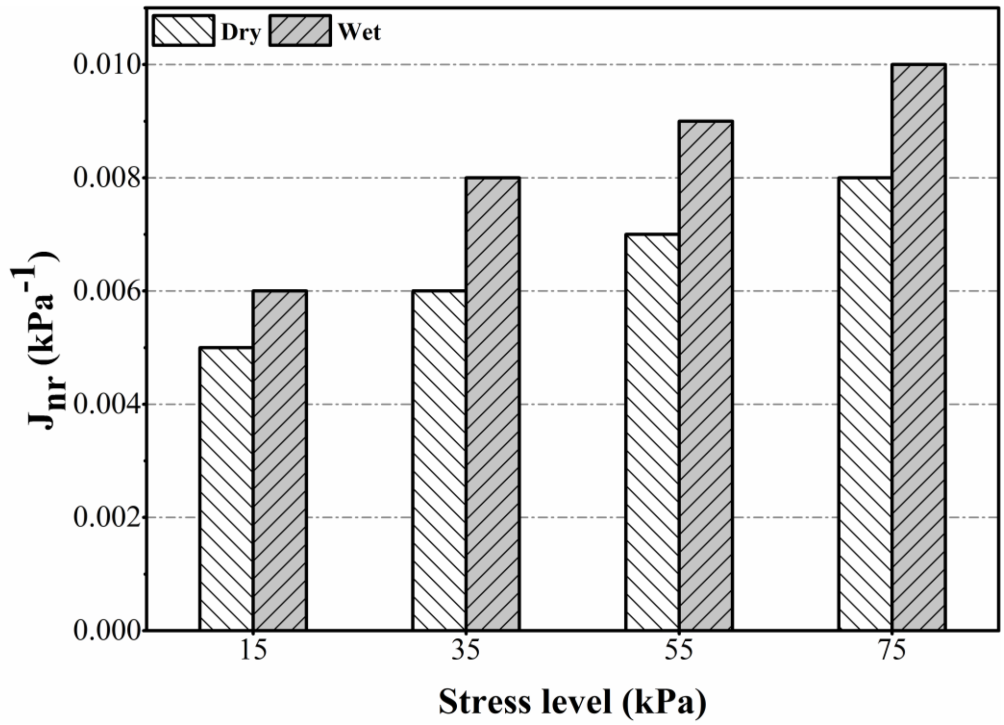
Figure 6.3(a), Figure 6.3(b), and Figure 6.3(c) illustrate the variation of J_{nr} of FAM mixtures (F1, F2, and F3) in dry and wet condition at different stress levels. Normally moisture increases the susceptibility to permanent deformation of the FAM mixtures. The results indicated that the increase in J_{nr} values for all the corresponding FAM mixtures when the specimens are tested in wet condition compared to dry specimens. It is desirable to have lesser increment in J_{nr} value for wet conditioned FAM specimens compared to dry specimens for better performance under moisture condition. The results of J_{nr} values for FAM mixtures are presented in Table 6.3. Considering the F3 mixture at stress level of 15 kPa, the increment in J_{nr} value observed for wet conditioned F3 specimen is 16.0% which is almost 1.56 and 1.25 times lesser compared to corresponding F1 and F2 mixtures respectively. The similar results were observed for other stress levels. Such a response clearly indicated that F3 mixture showed better performance against moisture susceptibility among all combinations considered for this research and is in-line with findings from the recovery part as discussed earlier. Overall, the lesser increment in J_{nr} value for F3 mixture at all the stress levels (15 kPa, 35 kPa, 55 kPa, and 75kPa) for tested temperature of 40°C indicates that the resistance to moisture damage increased due to retained higher delayed elastic response even after moisture conditioning.

Table 6.3 Results of J_{nr} values for FAM mixtures in dry and wet condition

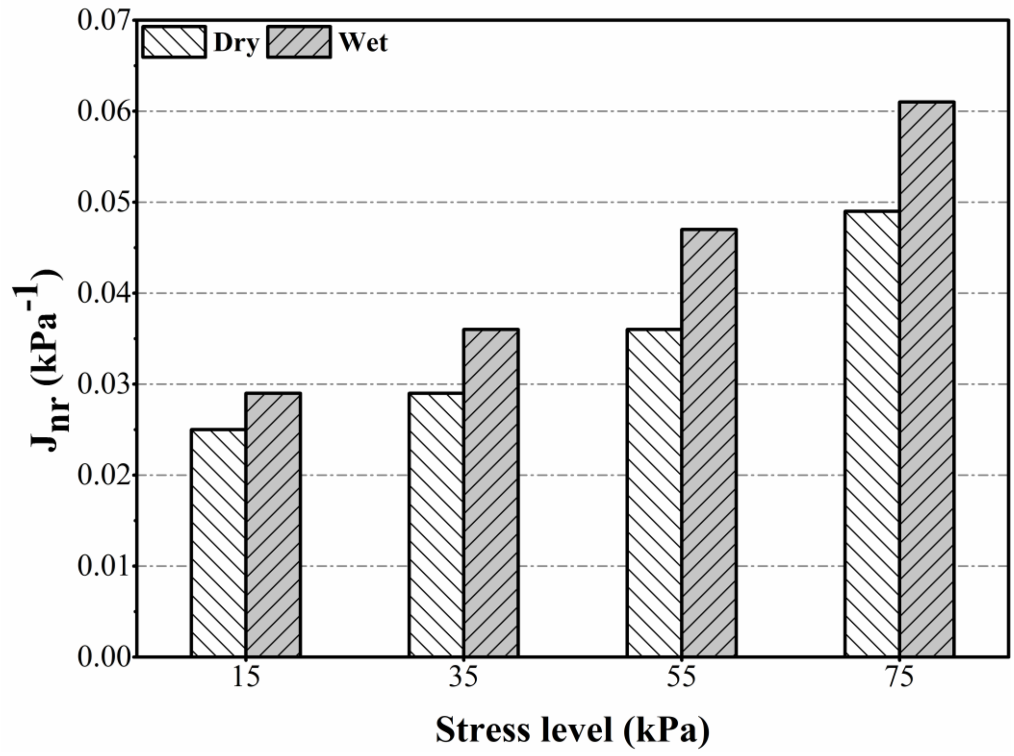
Stress level (kPa)	J_{nr} (kPa^{-1})					
	F1		F2		F3	
	Dry	Wet	Dry	Wet	Dry	Wet
15	0.008	0.010	0.005	0.006	0.025	0.029
35	0.009	0.012	0.006	0.008	0.029	0.036
55	0.011	0.016	0.007	0.009	0.036	0.046
75	0.013	0.018	0.008	0.01	0.049	0.061



(a) Mixture type=F1



(b) Mixture type=F2



(c) Mixture type=F3

Figure 6.3 J_{nr} values of FAM mixtures in dry and wet condition (a) F1 (b) F2 (c) F3

Table 6.4 presents the results of two-way ANOVA calculated corresponding to FAM mixtures (F1, F2, and F3) in consideration to test parameters of percent recovery (%R) and non-recoverable creep compliance (J_{nr}) with respect to wet and dry conditions and at different stress levels.

Table 6.4 Results of two-way ANOVA test for moisture-induced properties of FAM mixtures

Mixture	Parameter	Source of variation	SS	df	MS	F value	p-value
F1	%R value	Stress level	37.655	1	37.655	52.362	0.001
		Condition	36.765	1	36.765	51.124	0.001
		Error	3.596	5	0.719	-	-
		Total	78.016	7	-	-	-
	J_{nr}	Stress level	5.06E-005	1	5.06E-005	61.364	0.001
		Condition	2.81E-005	1	2.81E-005	34.091	0.002
		Error	4.13E-006	5	8.25E-007	-	-
		Total	8.29E-005	7	-	-	-
F2	%R value	Stress level	39.760	1	39.760	36.094	0.002
		Condition	31.522	1	31.522	28.615	0.003
		Error	5.508	5	1.102	-	-
		Total	76.790	7	-	-	-
	J_{nr}	Stress level	1.32E-005	1	1.32E-005	125.952	<.05
		Condition	6.13E-006	1	6.13E-006	58.333	0.001
		Error	5.25E-007	5	1.05E-007	-	-
		Total	1.99E-005	7	-	-	-
F3	%R value	Stress level	55.790	1	55.790	246.487	<.05
		Condition	5.780	1	5.780	25.537	0.004
		Error	1.132	5	0.226	-	-
		Total	62.702	7	-	-	-
	J_{nr}	Stress level	0.001	1	0.001	77.608	<.05
		Condition	1.36E-0004	1	1.36E-0004	12.347	0.017
		Error	5.51E-005	5	1.10E-005	-	-
		Total	0.001	7	-	-	-

Results indicate that not only the different stress levels and conditions significantly influence %R value, but also that of Jnr values of FAM mixtures. However, the effect of moisture condition on F3 mixture is insignificant to creep recovery behaviour, as indicated by lower F value. Hence, the FAM mixtures prepared with different types of FAM mixtures (F1, F2, and F3) studied in dry and wet conditions and at different stress levels were more significant towards the creep and recovery performance.

To examine the degree of effect of moisture on the rutting performance, the %R and J_{nr} ratios that is defined as the ratio of the %R and J_{nr} values of wet conditioned specimen FAM specimen to that of dry specimen. The ratios were determined from the measured data. The measured data for the F1, F2, and F3 mixtures at four different stress levels (15 kPa, 35 kPa, 55 kPa, and 75 kPa) and temperature of 40°C are shown in Table 6.5. The improvement of the rutting resistance characteristics of FAM mixtures would result in a lower J_{nr} and higher %R ratios. For example, the $\%R_{ratio}$ value observed for F3 mixture is higher (the $\%R_{ratio}$ is near to 1) when compared to the corresponding F1 and F2 mixtures at all the tested stress levels. Similarly, considering the J_{nr_ratio}, the value for F3 mixture is observed to be lesser than the corresponding values of F1 and F2 mixtures. Such a response clearly indicated that the F3 mixture is lesser sensitive to moisture when loading condition is changed from 15 kPa to 75 kPa among all the FAM combinations which could be possibly due to the use of polymer modifier in F3 mixture.

Table 6.5 Impact of moisture on ratios of %R and J_{nr} values of FAM mixtures

Stress level (kPa)	$\%R_{Ratio} = \%R_{Wet}/\%R_{Dry}$			$J_{nrRatio} = J_{nrWet}/J_{nrDry}$		
	F1	F2	F3	F1	F2	F3
15	0.93	0.94	0.97	1.25	1.20	1.16
35	0.93	0.93	0.95	1.33	1.33	1.24
55	0.89	0.92	0.95	1.45	1.29	1.28
75	0.89	0.92	0.94	1.38	1.25	1.24

Based upon different $\%R_{ratio}$ and J_{nr_ratio}value of FAM mixtures at temperature of 40°C, the ranking was done from the moisture sensitivity point of view. The ranking of different FAM mixture combinations based upon $\%R_{ratio}$ value is as F3>F2>F1. Further, the similar ranking order is observed when considering the J_{nr_ratio}

value, the ranking is as F3>F2>F1. Overall, the F3 mixture shows the highest $\%R_{ratio}$ and lowest J_{nr_ratio} values at all the tested stress levels compared to the other two FAM mixtures, indicating a lower sensitivity to moisture damage.

CHAPTER 7

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

7.1.1 Viscoelastic and fatigue properties of FAM mixtures .

The aging of FAM mixtures (F1, F2, and F3) was performed based on the AASHTO R30 and NCHRP 09-54 recommendations. Effect of aging on |G*| and δ at larger temperature range and frequencies were evaluated by conducting temperature and frequency sweep test. Results were compared through constructing master curves for each FAM mixtures at reference temperature 25°C. Further, fatigue performance of FAM mixtures at intermediate temperature 25°C and four different strain levels were evaluated using time sweep test. Results of fatigue cracking potential of each FAM mixtures at different aging levels and strains by considering 50% reduction in the initial stiffness |G*| values were compared. The findings from this study are based on the effect of different aging levels on FAM mixture prepared with three binder types and the same findings are summarized below:

- The LVE limit for STA and LTA aged FAM mixtures was found to be almost constant. This indicates that the LVE range was found to be insensitive to the induced aging level to the FAM specimens.
- The |G*| value of B2 (aged for 12 days at 95°C) specimen within the LVE range was observed to be double of the corresponding value for STA (aged for 4 hrs at 135°C) specimen. Also, |G*| plot for specimen B2 overlapped with the corresponding plot with specimen A3 within LVE range. This indicates the equivalency of aging level of FAM mixtures A3 and B2.
- The |G*| master curve plot showed that the A3 specimen had |G*| value 8.8 times more compared to STA specimen at a lower frequency zone. Such a response was attributed to the stiffening effect to FAM specimens due to increase in the relative proportion of asphaltene and a corresponding decrease in maltene in asphalt binder used in FAM with an increase in aging temperature and aging duration.

- The |G*| value of A3 from master curve was found to be higher than B2 at lower frequency zone. Whereas, |G*| value of B2 was observed more than A3 at higher frequency level. This indicates that specimen A3 may perform better than B2 specimen in higher temperature condition and specimen B2 may perform better in low to intermediate temperature conditions.
- FAM mixtures aged at 95°C for 12 days and 135°C for 24 hrs showed similar response for |G*| variation in lower and intermediate frequency zone, indicating the equivalencies of their respective aging protocol.
- Increase in aging level decreased the degree of dependency of δ value on loading frequency. Among A, A1, A2, and A3 specimen, the flatness of δ plot over reduced frequency was observed to be highest for A3. Such a response may be attributed to the increased effect of elastic aggregate structure in overall material response.
- The master curve parameters, -γ/κ decreased and κ increased, as more aging happens, such a response can be attributed to the stiffening effect to the FAM specimen with an increase in aging temperature and/or corresponding aging duration. These can also indicate that FAM mixtures with higher κ values are expected to be more susceptible to cracking.
- The viscoelastic properties (|G*| and δ) of FAM mixtures (F1, F2, and F3) obtained from the modeling were statistically compared with the corresponding experimental values and the goodness of fit was evaluated for each FAM specimen. The statistical results showed that the goodness of fit parameters obtained for different specimens are well within the acceptable range.
- The fatigue life of 24 hrs at 135°C aged FAM mixtures showed better fatigue life than 12 days aged at 95°C FAM mixtures. The potential reason for such response might be due to the presence of relatively higher amount of already aged and oxidized asphalt binder present in these FAM mixtures.
- The fatigue life of FAM mixtures decreased as the aging level changes from 5 days at 95°C to higher level aging of 12 days at 95°C. Despite of the similar viscoelastic properties, the trend observed between FAM mixtures aged 12 days at 95°C and 24 hrs at 135°C were not found to have similar fatigue properties.

7.1.2 Creep and recovery behavior of FAM mixtures

The creep and recovery performance of three types of FAM mixtures (F1, F2, and F3) were evaluated at two different stress levels (15 kPa, and 55 kPa) and three temperatures (30°C, 40°C, and 50°C) by conducting the MSCR test. Percent recovery (%R) and non-recoverable creep compliance (J_{nr}) results of FAM mixtures were compared at different temperatures for different corresponding stress levels. Thereafter, Burgers four element model was used to fit the creep and recovery response of all the FAM mixtures during creep loading and unloading duration. The importance of model parameters which indicates the elastic and viscous behavior of different FAM mixtures and impacts on the characteristics of the permanent deformation was investigated. Based on the detailed rheological investigation of FAM mixtures in the laboratory, following conclusive remarks are summarized below:

- The higher %R value and lower J_{nr} value for F2 mixture at both stress levels for different temperatures indicates that the resistance to permanent deformation increased due to its higher elastic property. The F2 mix should be chosen among F1, F2, and F3 mix from a recovery perspective for improved rutting performance.
- The degree of decrease in recovery value with increase in temperature is relatively higher for F3 mixture. Such a response indicates that F3 mixture is relatively more susceptible to temperature compared to other two FAM mixtures which could be due to the relatively lower degree of delayed elastic response associated with F3 mixture.
- Among all the FAM mixtures, the presence of higher η_m value for F2 mixture was observed. Such findings indicate that the F2 mixture is better in rut performance due to its delayed elastic response followed by F1 and F3 mixtures for higher temperatures and at both stress levels (15 kPa, and 55 kPa).
- The Burgers model parameters can be utilised successfully to illustrate the rheological characteristics of FAM mixtures under creep and recovery phase at different temperatures and corresponding stress levels.
- From the SSE and AAE values, the Burgers model fitted the FAM mixtures strain response successively under both creep loading-unloading conditions at both stress levels and temperatures mentioned in this study. Also, shown very small

deviations in the predicted and observed values (average absolute errors lower that 0.48%).

- Due to marginal change in %R value with change in stress level and temperature indicates the inability of selected testing conditions to distinguish the effect of modifier such as SBS used in F3 mixture on recovery response. This indicates the need for further research aiming at selecting appropriate temperature and stress level so that the effect of some of the expected changes made to the FAM (for ex., modifier) could be truly captured.

7.1.3 Moisture-induced damage properties of FAM mixtures

The effect of moisture on creep and recovery performance of three types of FAM mixtures (F1, F2, and F3) was evaluated by conducting the static creep and recovery test. Further, the %R and J_{nr} ratios were calculated to examine the degree of effect of moisture on the rutting performance of FAM mixtures. The major conclusions drawn are as follows:

- The reduction in %R values and increase in J_{nr} values regardless of type of FAM mixtures at all four different stress levels. These results can be clearly attributed to loss of elastic property in FAM specimens due to presence of moisture.
- The decrease in recovery value is relatively lower for wet conditioned F3 mixture. Such a response indicates that F3 mixture is relatively lesser susceptible to moisture damage compared to other two FAM mixtures which could be due to the relatively higher degree of elastic property associated with F3 mixture even after wet condition.
- The lesser increment in J_{nr} values for F3 mixture at all the stress levels (15 kPa, 35 kPa, 55 kPa, and 75kPa) for tested temperature of 40°C. Such a response clearly indicated that the F3 mixture is lesser sensitive to moisture among all the FAM combinations which could be possibly due to the use of polymer modifier in F3 mixture.
- From the moisture sensitivity point of view, the ranking of different FAM mixture combinations were made based upon $\%R_{ratio}$ value is as F3>F2>F1. Further, the similar ranking order is observed when considering the J_{nr_ratio} value, the ranking order is as F3>F2>F1. Overall, the F3 mixture shows the highest

%R_{ratio} and lowest J_{nr_ratio} values compared to the other two FAM mixtures, indicating a lower sensitivity to moisture damage.

7.2 RECOMMENDATIONS

This section provides recommendations for the utilisation of smaller FAM specimens rather than the HMA specimens to assess rheological performance properties of FAM mixtures in road construction industries which is gaining more popularity worldwide due to its simplicity and rational approach. Following recommendations are made in the light of conclusions of rheological investigations on FAM performed.

It is important to note that evaluating different viscoelastic properties, especially moisture induced damage, rutting, and fatigue performance of asphaltic mixture in the laboratory demands larger amount of materials, expensive equipment and an appreciable amount of time for specimen preparation, aging simulation, and performance testing. Unlike the need for vast laboratory infrastructure for evaluation of full asphaltic mixture, the performance evaluation on FAM mixtures in the laboratory needs only Dynamic Shear Rheometer (DSR). Therefore, it not only saves the maximum space in the laboratory but also requires lesser time and consumes small amount of materials for the preparation of FAM specimens in the laboratory. Additionally, one can attain higher precision in test results from DSR by maintaining the uniformity in the prepared FAM specimens. Overall, characterization of FAM phase in place of full asphalt mixtures in the laboratory is faster which saves testing time, and reduces labour work to prepare FAM specimens.

- This dissertation on FAM mixtures makes a good contribution in asphalt industry to improve the evaluation and prediction approaches of performance properties in place of full asphalt mixtures.

Aging changes the physical property of asphalt mixtures by increasing stiffness, brittleness, and decreasing relaxation capability. Therefore, it is important to give due consideration to aging phenomena at the mixture design stage to provide a durable pavement structure. To achieve this problem, aging of asphaltic mixtures needs to be simulated in the laboratory.

Since the standard protocol recommends conditioning the specimen for 5 days at 85°C which is a significantly longer time period, however, it can be reduced by increasing the conditioning temperature. Such changes may significantly save the conditioning time. Though the increase in conditioning temperature can decrease the conditioning time, it is important to quantify the decrease in conditioning time with a corresponding increase in conditioning temperature considering its influence on performance parameter of asphaltic mixtures.

- From this study, loose FAM mixtures aged at 95°C for 12 days and 135°C for 24 hrs showed similar linear viscoelastic charcteristics ($|G^*|$ and δ), indicating the equivalencies of their respective aging protocol. From this finding, 135°C for 24 hrs LTA procedure mentioned above can be used while characterisation of viscoelastic properties of any asphaltic mixtures rather than current aging standard recommended by AASHTO R-30.
- To evaluate the aging equivalency for characterisation of long term performance, further studies may be required by considering the different viscoelastic parameters.

7.3 SUGGESTIONS FOR FUTURE RESEARCH

The conclusions and suggestions presented in the previous sections are based on the findings of extensive laboratory research carried out on FAM mixtures. The following suggestions are provided needs to be addressed in future studies:

- Further study need to evaluate the effect of different aging levls with respect to different climatic regions in India on performance properties of different FAM and asphalt mixtures.
- Further study can be conducted to link the present study findings with the full asphalt mixtures prepared in the laboratory and cores from the field. This will give more insight nad justification toward adoption of the current study test methods nad characterisation approach.
- The present research work can be extended to evaluate the effect of these aging levels on viscoelastic and fatigue properties of FAM mixtures prepared with different binder types, aggregates and mineral fillers.

- There is a need for evaluating equivalencies in different aging levels by conducting the performance studies on FAM mixtures prepared with different type of WMA modified and recycled binders.
- To evaluate the effect of different air voids and binder contents on the fatigue and rutting behaviour of FAM mixtures prepared with modified asphalt binders and different type of aggregates.
- There is a need for evaluating the fatigue properties of FAM mixtures at lower temperatures (<10°C). Because, some of the regions in India are expose to lower temperature for majority of the time. Due to this reason, non-load associated cracks will appear in the pavement.
- The fatigue property of FAM mixtures can be evaluated using different failure criterion (eg: calculating G-R value using viscoelastic parameters $|G^*|$ and δ).
- There is need for evaluation of multiple scales of asphaltic mixtures properties in order to verify correlation between different scales and full asphalt mixture properties.

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LIST OF PUBLICATIONS

Publications based on Ph.D. Research Work

Indian Patent

1. **Ningappa Akhandappagol,** Suresha Subbarao Nagabhushanrao, "Direct Compaction Mould for Preparation of Bitumen Bounded Fine Aggregate Matrix Specimen." ***Indian patent filed-Application Number: 20204100619,*** dated 13th February 2020.

Articles in SCI journals

1. Suresha, S. N., and **Ningappa, A.** (2018). "Recent trends and laboratory performance studies on FAM mixtures: A state-of-the-art review." ***Construction and Building Materials, CBM.***
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2. **Ningappa, A.,** and Suresha, S. N. (2020). "Laboratory Evaluation of Long-Term Aging Effect on Linear Viscoelastic and Fatigue Properties of FAM Mixtures." ***Construction and Building Materials, CBM.***
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3. **Ningappa, A.,** and Suresha, S. N. (2020). “Laboratory Evaluation and Rheological Modeling of Creep-Recovery Behavior of FAM Mixtures.” ***Advances in Civil Engineering Materials (ACEM),*** **(Communicated),** [Publisher: ASTM]
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Conferences/Seminars: International

1. **Ningappa, A.,** and Suresha, S.N. “Assessment of Different Long Term Aging Effect on FAM Mixtures” *Advances in Materials and Pavement Performance Prediction* ***(AM3P-2020),*** held on Aug 03-07 2020, **ONLINE**

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Conferences/Seminars: National

1. **Ningappa, A.,** and Amarnath, M. S. "Application of Self Compacting Concrete using Silica Fume for Rigid pavements." National Conference on Futuristic Technology in Civil Engineering for Sustainable Development” **(NCFTCES-14),** held at SJBIT, Bangalore 14th May, 2014.
2. **Ningappa, A.,** and Amarnath, M. S. "Evaluation of Strength Properties of Silica Fume Admixed Steel Fiber Reinforced Self Compacting Concrete." National Conference on Recent Advancements in Infrastructural Development” **(RAID-15),** held at JSS Academy of Technical Education, Bangalore. 25th March, 2015.
3. **Ningappa, A.,** and Amarnath, M. S. "Comparative Studies on Bituminous Concrete Mix Using Different Fillers and Zycotherm as Additive." National Conference on transportation Systems Engineering and management” **(CTSEM-15),** held at National Institute of Technology (NIT), Tiruchirapalli on May 1-2, 2015.
4. **Ningappa, A.,** and Amarnath, M. S. "Studies on Strength Characteristics of Polymer Modified Bituminous Concrete with Zycotherm Additive." National Conference on Transportation Young Researchers Symposium” **(TYRES-15),** held at National Institute of Technology (NIT), Warangal on May 10-15, 2015.