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Laboratory Evaluation of Long-Term Aging Effect on Linear Viscoelastic and Fatigue Properties of FAM Mixtures

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ABSTRACT

Aging is considered as one of the major factor which causes an increase in stiffness and brittleness to asphaltic mixture. This study aimed at evaluating the effect of different aging protocol on viscoelastic and fatigue properties of Fine Aggregate Matrix (FAM) 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 FAM mixtures, 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. Irrespective of the aging level applied to the FAM specimen, the LVE limit was found almost constant 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 mixtures showed similar results from the master curve plots. The fatigue properties of FAM mixtures decreased as the aging level changed 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. 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.

Key Words: FAM, loose mix aging, viscoelastic, fatigue, strain sweep, time sweep.

HIGHLIGHTS

- The LVE limit for STA and LTA aged FAM mixtures was found to be almost constant.
- Complex shear modulus (|G*|) increased with a higher level of aging under lower and intermediate reduced frequency.
- 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.
- The fatigue properties 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.

1. Introduction

Fatigue cracking is considered as one of the major distress types to the flexible pavement. Fatigue failure occurs due to repeated application of load and it becomes especially critical for asphaltic pavements laid in intermediate to low temperature regions. Along with climatic temperature, the aging characteristics of asphaltic mixture also play an important role in controlling such cracks. An asphaltic mixture with a higher degree of susceptibility to aging is expected to have lower design life and vice versa. Though aging phenomena is directly related to the asphalt binder, various volumetric properties of asphaltic mixture play a critical role in the overall aging process. For example, an asphaltic mixture with a higher amount of air void is expected to have a higher degree of susceptibility to aging. Therefore, along with study purely at asphalt binder level, it is equally important to understand the impact of aging at asphaltic mixture level. Many research works have been reported which discusses the effect of aging on various rheological performance parameters of asphalt binder [1–4]. Further, number of studies have been reported recently for the corresponding phenomena at asphaltic mixture level too [5–10]. 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 mixture. To simulate the Short Term Aging (STA), it is recommended to condition the asphaltic mixture at 135°C for 4 hrs before compaction. Similarly, conditioning at 85°C for 5 days on compacted specimens has been recommended for simulating Long Term Aging (LTA) of the asphaltic mixture (AASHTO R30). Additionally, NCHRP 09-54 recommended laboratory aging of the loose mixture at 95°C and 135°C for different aging durations has been reported by various researchers to study the aging effect on viscoelastic and fatigue properties of asphalt concrete mixtures [11–18].

It is important to note that evaluating different viscoelastic properties, especially 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. This has led the researchers in this area to look into developing other methods which can address the limitations in evaluating the corresponding viscoelastic properties at asphaltic mixture level to reduce the amount of material and required time. The first attempt in this direction was made by Kim et al. [19] through examining viscoelastic properties of Fine Aggregate Matrix (FAM) and this approach reported to be cheaper, relatively simple, repeatable and less time consuming. It is important to note that the FAM phase of the overall asphaltic mixture is critical as the crack formation and propagation is largely governed by the viscoelastic properties of different materials within this phase [20–22]. FAM is defined as the combination of fine aggregates, mineral filler, and asphalt and have relatively more uniform structure compared to full asphalt concrete mixture [23,24].

Till date, many studies have been conducted to investigate the role of FAM in characterizing linear viscoelastic properties, time dependent behavior and fatigue properties in an overall asphaltic mixture [25–28]. Karki et al. [25] used the micromechanical modeling approach to predict the dynamic modulus of asphalt concrete mixtures and concluded that the FAM phase can anticipate the viscoelastic properties of asphalt concrete mixtures. Underwood et al. [29] studied the dynamic modulus and phase angle of FAM and full asphaltic 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 [30,31]. Overall, it may be concluded that FAM mixture can be effectively used for characterizing the full asphaltic mixtures in a qualitative way [20].

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 to the authors, only a single research work till date has been reported which aimed at understanding the effect of LTA on FAM mixture [32]. 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 [10,33,34]. 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.

Therefore, 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. 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.

2. Materials and FAM specimen preparation

2.1 Materials

The FAM mixture is a combination of asphalt binder, fine aggregates and filler having size less than 0.075 mm [21]. Following section briefly provides the information on basic properties of different materials, specimen preparation and experimental methodology.

2.1.1 Asphalt binder

Table 1. Basic properties of asphalt binder

Property	Test Results	Limiting value IS 73:2013
Penetration at 25°C, 0.1 mm	64.5	Min. 45
Softening point (R&B) (°C)	52.7	45-55
Ductility at 25°C (cm)	85.4	Min. 70
Absolute viscosity at 60°C (poise)	2700	2400-3600
Kinematic viscosity at 135°C (cSt)	438	Min. 350
Flash Point (°C)	≥220	Min. 220

Viscosity grade asphalt binder (VG-30) provided by M/s Mangalore Refinery and Petrochemicals Ltd. (Mangalore, India) was used as base binder. Basic properties of base binder are listed out in Table 1. It is clear that the base binder satisfied the various requirements set by IS: 73-2013. Moreover, the kinematic viscosity value of base binder at 135°C also satisfied the workability criteria set by Superpave (should be less than 3000 cSt).

2.1.2 Aggregates

To prepare FAM specimens throughout this study, single source granite aggregates obtained from Kinnigoli Quarry, Dakshin Kannada District, Mangalore, India was used. The fine aggregates smaller than 2.36 mm sieve size found to have specific gravity of 2.67. Similarly, water absorption value was found to be 0.54%, satisfying the criteria (≤ 2%) set by the Ministry of Road Transportation and Highways (MoRTH 2013).

2.1.3 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 [29,32,35]. 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 [32,35]. Also, FAM specimens prepared using larger size aggregates passing 4.75 mm may cause variability in test results [32,35]. 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 [24,36–38] are shown in Fig. 1. The optimum binder content for the FAM mixtures was determined with the help of surface area method [39–41]. Considering homogeneously coated aggregates with asphalt binder having film thickness of 10 µ [19,24,42] the optimum binder content for FAM mixture was found to be 7.3%. The target air void for various FAM specimens was 4% (±1%) [24,25,43]. It is to be noted that the proportioning of fine aggregate 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.1).

$$\text{\% passing sieve “x” in FAM} = \frac{\text{Mass of aggregate passing sieve "x" in full mixture}}{\text{Mass of aggregate passing sieve 2.36 in full mixture}} X 100 \qquad (1)$$

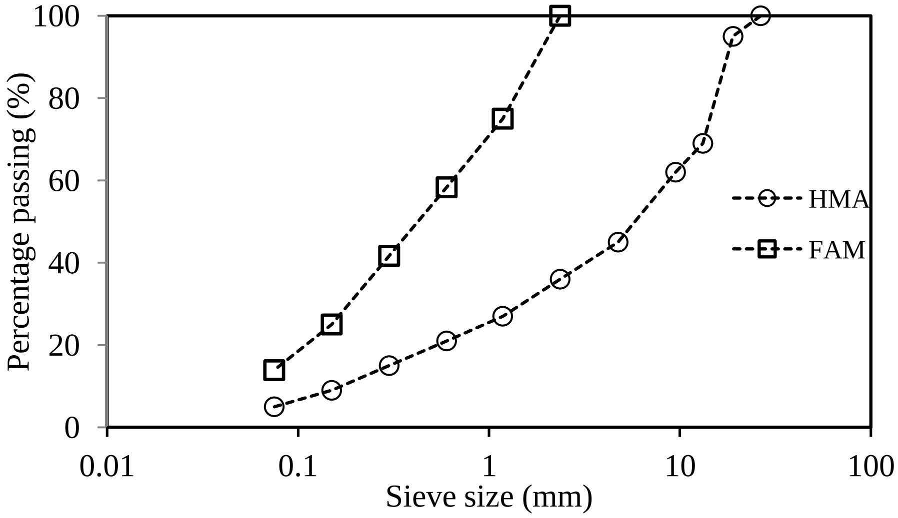

Fig. 1. Aggregate gradation for HMA and FAM mix design

2.1.4 FAM specimen preparation

Based upon the availability of resources and other laboratory constraints, either cylindrical or rectangular FAM specimens have been used by different researchers [35,44,45]. 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 [20,44]. 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. [46] and Nabizadeh et al. [47].

The mixing and compaction temperature were initially determined with the help of rotational viscometer as per ASTM D4402. Accordingly, the mixing and compaction temperature were found to be 153°C and 143°C respectively, satisfying the criteria for mixing temperature range (150-165°C) and compaction temperature should be minimum 140°C set by the

Ministry of Road Transportation and Highways (MoRTH 2013). The optimum asphalt binder content was initially mixed with the heated fine aggregate (see Fig. 2. for gradation) at the corresponding mixing temperature. Subsequently, STA of the loose mix was carried out for different FAM combinations at 135°C for 4 hrs as per AASHTO R30 recommendations. Further, theoretical maximum specific gravity (G_{mm}) of loose FAM mixtures was determined as per ASTM D2041. The G_{mm} of FAM specimen was found to be 2.21 g/cc at targeted air void. The FAM specimens were finally prepared by compacting (using static pressure) the required amount of loose mixture in the fabricated mould. A similar approach has been used by other researchers for the preparation of rectangular FAM specimens [44,46,47]. The details of method to fabricate FAM specimens in this study adopted are shown in Table. 2.

Table. 2. Details of method to fabricate FAM specimens

Steps	STA/LTA	Temperature	Time
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

Fig. 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 (Fig. 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.

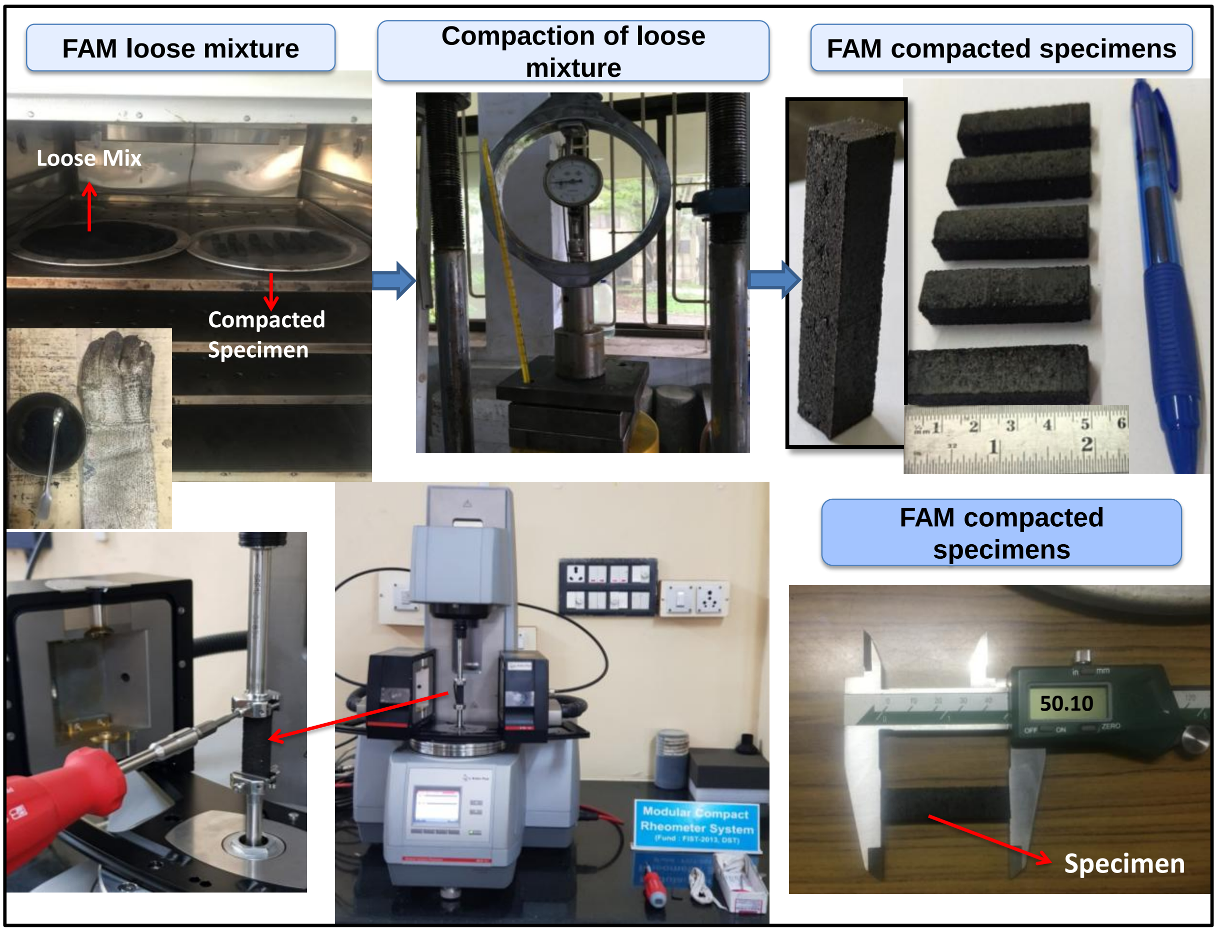

Fig. 2. Rectangular FAM Specimen Preparation

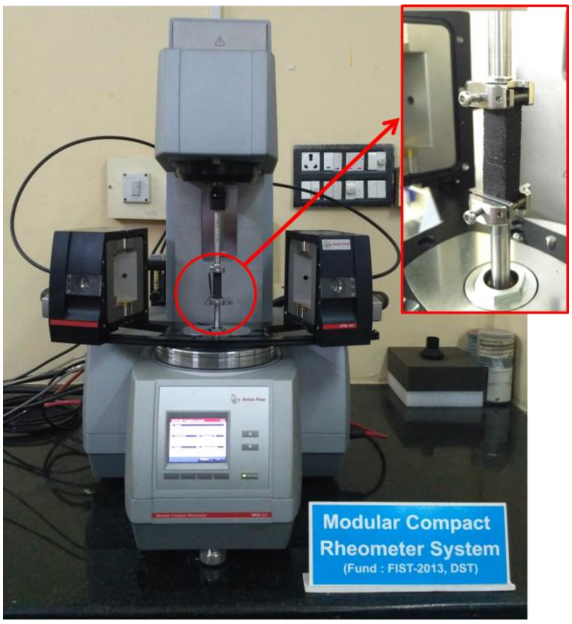

Fig. 3. Dynamic Shear Rheometer (MCR 502) Setup.

2.2. 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. 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, AASHTO R30's current protocol recommends to carry 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. 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. 3. A, A1, A2, A3, B1, B2 refers to loose mixture aging, whereas, C' refers to compacted specimen aging.

Table. 3. Details of Different FAM Combinations

Binder Type	Properties	Test Name	FAM Mixture Type							Number of Specimens
			Loose Mixture Aging						Compacted Specimen Aging	
			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
	Fatigue	Time sweep @ 4 strain levels	3x4	3x4	3x4	3x4	3x4	3x4	3x4	3x4x7=84

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

Flowchart for the overall experimental plan is presented in Fig. 4. 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 [20]. 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.

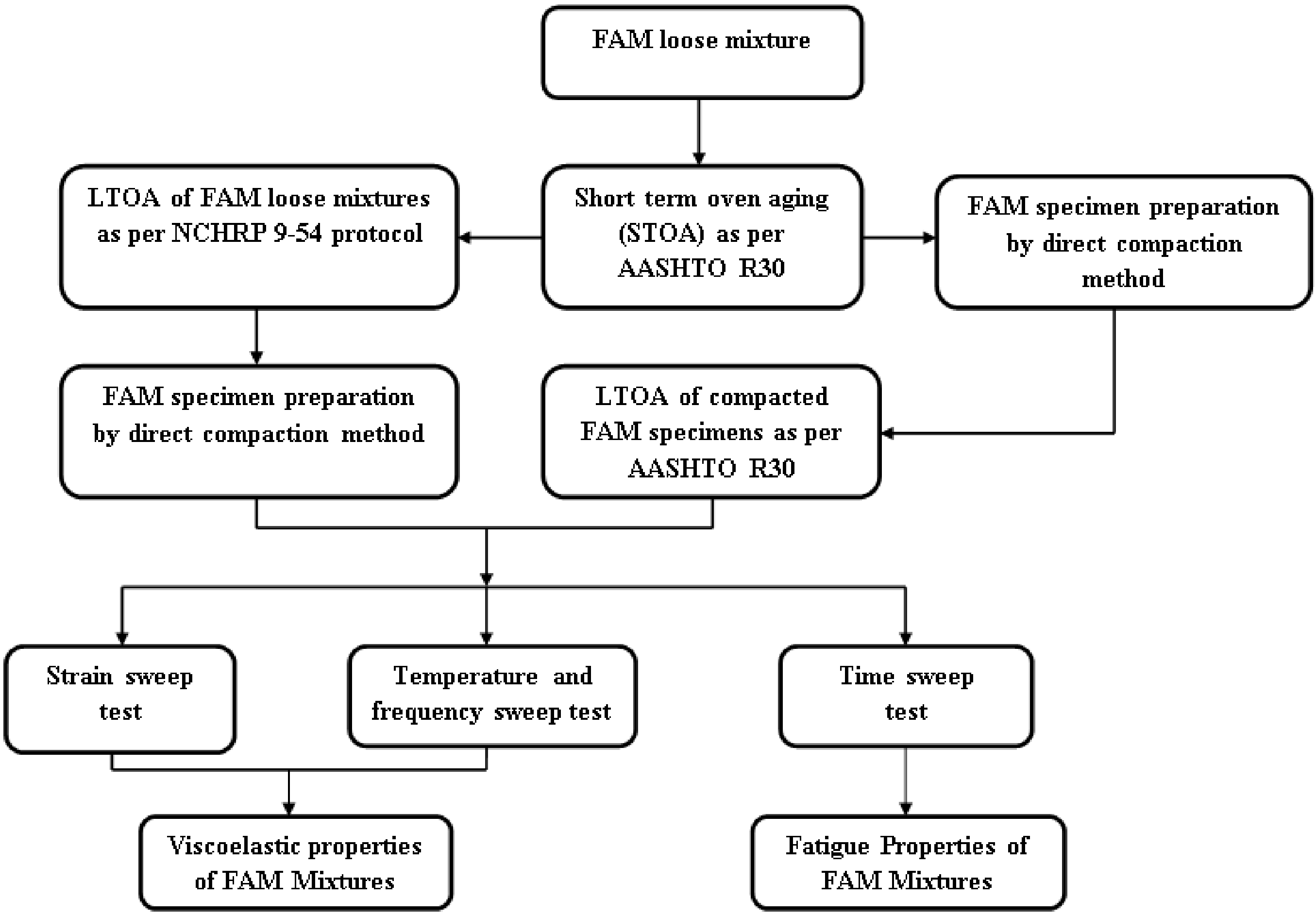

Fig. 4. Overall experimental plan

2.2.1 Linear viscoelastic region

Strain sweep test was carried out on both STA and LTA FAM specimens to determine the linear viscoelastic region of each FAM mixture [46–48]. 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.

2.2.2 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 well within LVE range was selected. 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 complex shear modulus |G*| and phase angle δ was subsequently drawn. Williams-Landel-Ferry (WLF) equation was used for finding out the reduced frequency at the reference temperature 25°C (Eq. 4) [29]. Logarithm sigmoidal model was further used for drawing the master curve for |G*| and δ at the reference temperature [15,16,29,49–51]. Eq. 2 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 shows the Lorentzian peak model equation for drawing the master curve for δ [17,52–54].

$$\log|G^*| = \alpha + \frac{\beta}{1+e^{\gamma+\kappa(\log\omega_r)}}, \qquad (2)$$

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.

$$\text{Phase angle } (\delta) = \frac{a * b^2}{[(\log \omega_r - c)^2 + b^2]}, \quad (3)$$

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, δ is phase angle and ω_r is the reduced frequency.

$$\log a_T = \frac{C1(T - T_R)}{C2 + T - T_R}, \quad (4)$$

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

2.2.3 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 [21,32,38,39,46,47,55,56]. This test was conducted at four different strain levels (0.06%, 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 [19,21,44,57]. Number of cycles at 50% reduction in the |G*| value was considered to be fatigue failure of FAM specimens [58–60]. Considering three replicate specimens, time sweep test was conducted on a total of 84 specimens to examining the fatigue potential of FAM mixture. Fatigue test results can be described by a phenomenological regression model as described by Eq. 8 [19].

$$N_f = a(\gamma)^b \quad (8)$$

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

3. Test Results and Analysis

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 various specimens in this research work. The results of the strain sweep test on various FAM specimens are presented in Fig. 5. The curves of |G*| versus strain from the strain sweep test has been plotted for FAM mixtures with different aging levels. It is clear from the plot that as the aging level increased, the stiffness value also increased. For example, the stiffness value within LVE range can be observed to be increased by approximately two times 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 2 for specimen nomenclature). 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. 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. 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. Irrespective of the aging level applied to the specimen, it is to be noted that the LVE range remained almost constant (≈0.006%). The results are in line with the findings reported by Aragão and Kim [27] and Li et al. [39] where LVE range was found to be insensitive to the induced aging level to the FAM specimens.

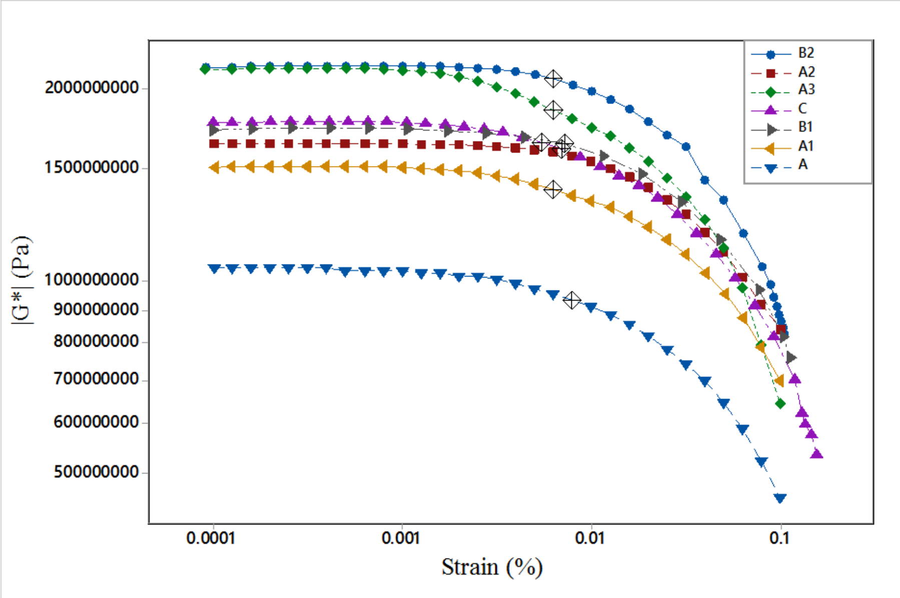

Fig. 5. Results of FAM strain sweep test

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 |G*| for seven different 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 different FAM specimens are presented in Table. 4. Each plot represents the average of three replicates specimens. γ value in the generalized sigmoidal model governs the horizontal positioning of turning point [50]. It is clear from the table that as the aging level increased, the γ value correspondingly decreased. For example, the γ value for A1 specimens 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. Such a response can be attributed to the stiffening effect to the FAM specimen 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/or corresponding aging duration [50]. 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 except to the case of β value when aging level at 135°C increased from 12 to 24 hrs.

Table. 4. Complex shear modulus |G*| master curve parameters of FAM mixtures

Mixture Type	α	β	γ	κ
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

Fig. 6 shows the master curve for different FAM mixtures. 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 [17,43,55]. 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, |G*| value of A3 mixture aged at 24 hrs at 135°C is about 8.8 times more than the STA FAM mixture 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 mixture at a frequency level of (0.00005 rad/s). 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) except at very low frequency level where the corresponding value for B1 can be seen as slightly higher than C. Similar findings has been reported by Rahbar-Rastegar et al. [17] for asphaltic mixture with different degree of aging. A higher value of |G*| for B1 in lower frequency range can be attributed to correspondingly higher conditioning temperature leading to a relatively higher 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 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 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. Fig.7 shows the variation of |G*| value at 0.001 Hz to demonstrate the effect of different aging level on corresponding parameter in lower frequency zone.

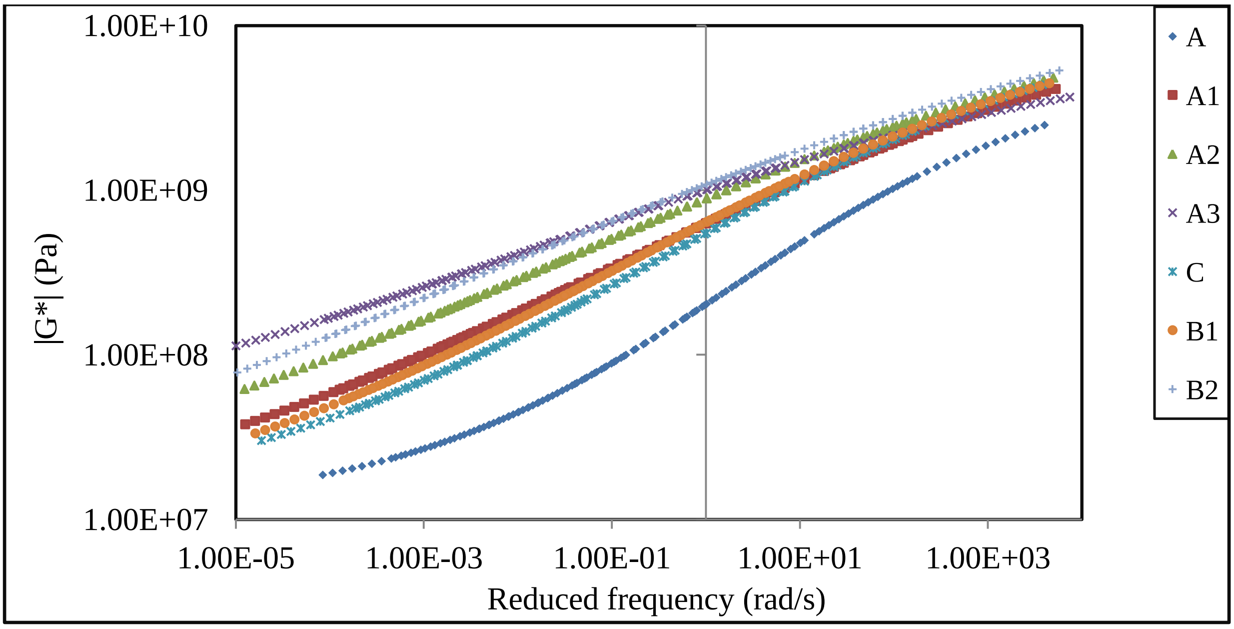

Fig. 6. Complex shear modulus |G*| of STOA and LTOA FAM mixtures at reference temperature 25°C.

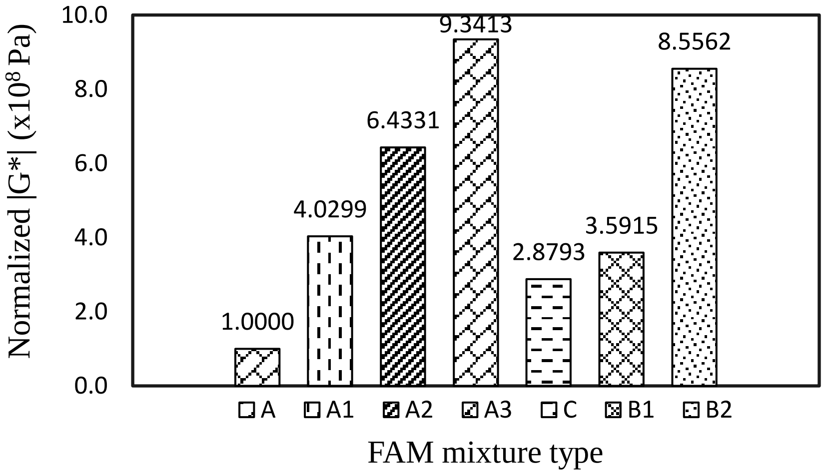

Fig. 7. Normalised |G*| of FAM mixtures at 0.001Hz and 25°C.

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) [61,62] was also are determined as shown in Table 5, m-values between each FAM mixtures at different frequency levels has been compared. The values in Table 4 clearly demonstrate the influence of aging on the m-values at higher temperature (or lower frequencies). The long-term aged FAM mixtures found to have distinctively different relaxation time compared with the STA FAM mixtures. Generally, the aged FAM mixtures take more stress relaxation time than the STA mixtures [47]. The increase in m-values may be attributed to increase in aging level to FAM specimen. For example, A3 mixture aged at 24 hrs at 135°C is having higher m-value compared to STA FAM mixture at a lower side of reduced frequency level.

Table. 5. Slope between each FAM mixtures at different frequency levels

Mixture 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)
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

Similarly, 5 days at 95°C (B1) loose mixture aged FAM specimen showed higher m-value compared to STA FAM mixture 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 mixtures 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. [49] for different FAM.

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 [63]. The (-γ/κ) parameter for STA FAM mixture (A) is almost equal to zero. Similarly, -γ/κ value of specimen aged for 5 days at 95°C (B1) loose mixture aged FAM specimen showed 3.97 times more compared to STA FAM mixture. 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). The corresponding value for B1 (-0.991) can be seen as slightly higher than C (-0.553). Similar findings have been reported by Rahbar-Rastegar et al.[17] 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 Fig. 8 that as the aging level increased, the -γ/κ value correspondingly increased. For example, the -γ/κ value for A1 specimens 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. 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 specimen with an increase in aging temperature and/or corresponding aging duration. These can also indicating that FAM mixtures with higher κ values are expected to be more susceptible to cracking [7,63].

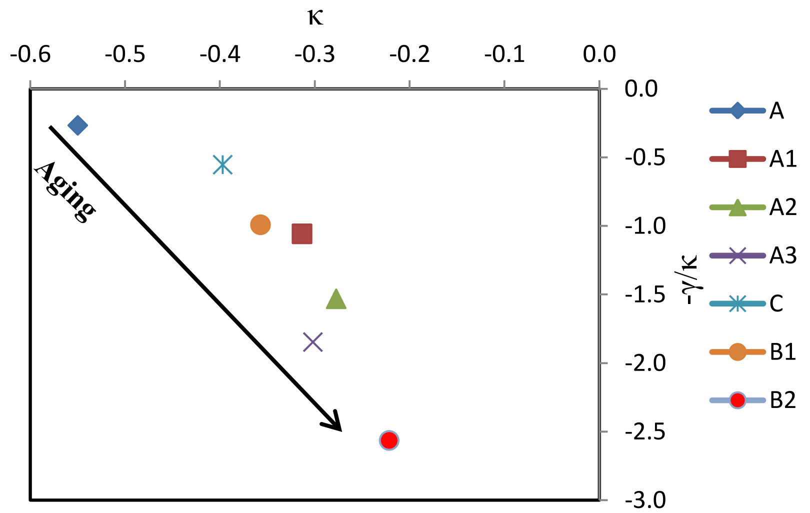

Fig. 8. Variations of |G*| master curve shape parameter with different aging levels at a reference temperature of 25°C.

The master curve of δ for each STA and LTA specimen was also drawn as shown in Fig. 9. Unlike the variation of |G*|, a distinct change in δ with a change in reduced frequency can be seen. It is clear from the plot that as the aging level increased to the FAM mixture, 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. Likewise, a similar decrease in δ value can be obtained with different aging level. 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 mixture. Such a response for the variation of δ over the wide range of frequency is in agreement with findings on FAM reported by Rastegar et al. [17] and Underwood and Kim [29]. 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. 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 mixture, 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 and shown in Table. 7.

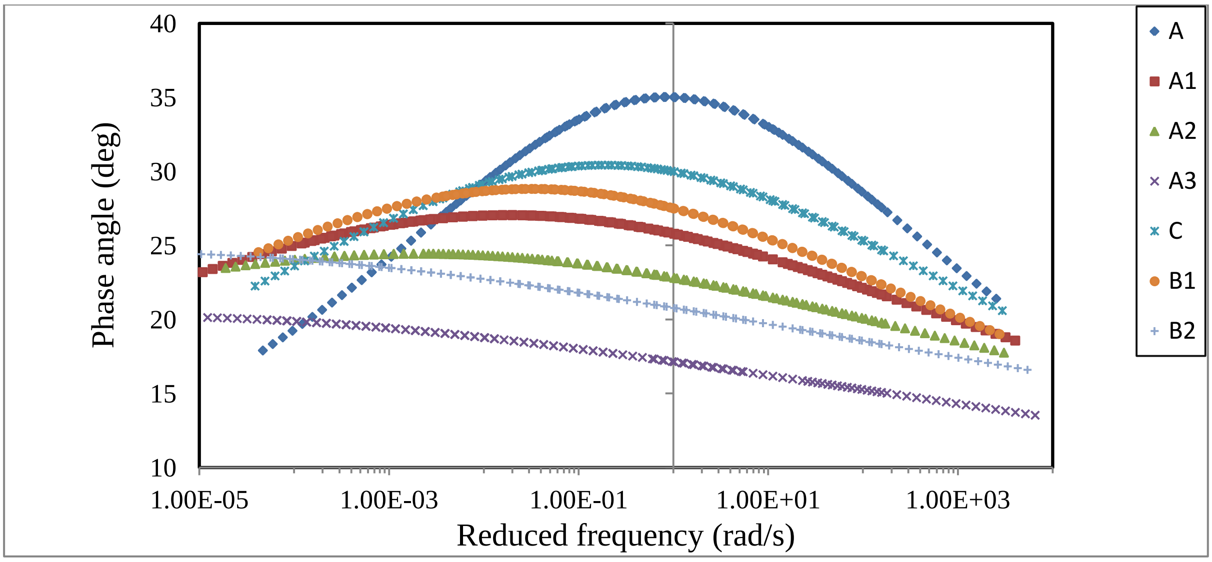

Fig. 9. Phase angle of STA and LTA FAM mixtures at a reference temperature of 25°C.

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. Fig. 9 can be an indicator for the relaxation potential of the FAM mixtures aged at different duration and temperature levels. Further, Fig. 10 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 mixtures 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, 'A' have higher relaxation capability and better fatigue behaviour compared to A3. The various model parameters obtained from the optimization technique for different FAM specimens are presented in Table. 6. Each plot represents the average of three replicates specimens.

Table. 6. Phase angle master curve parameters of FAM mixtures

Mixture Type	a	b	c
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

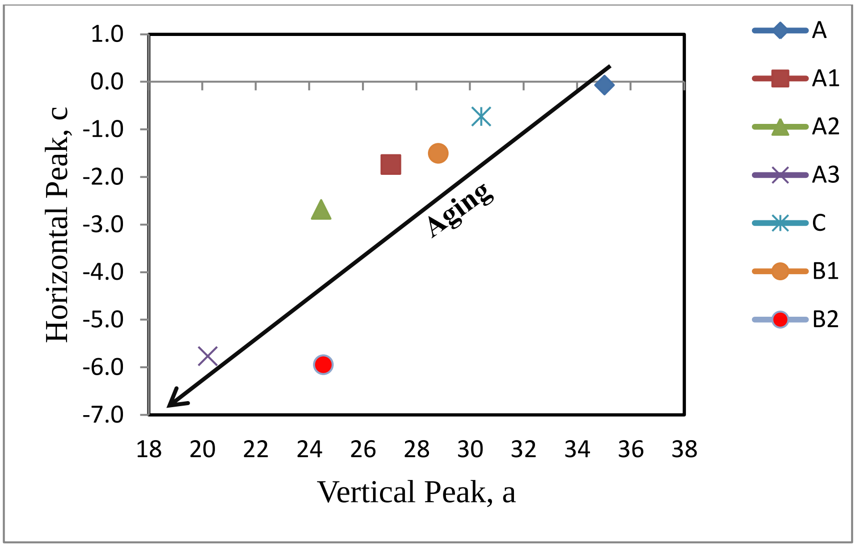

Fig. 10. Variations of δ master curve shape parameter with different aging levels at a reference temperature of 25°C.

Finally, the various values 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 analysis results are provided in Table. 7. It can be clearly seen that the goodness of fit parameters obtained for different specimens are well within the acceptable range.

Table. 7. Goodness-of-fit results of |G*| and δ from master curve analysis

Mixture Type	$\|G^*\|, R^2$	Acceptance criteria, [50,64]	δ, R^2	Acceptance criteria, [50,64]
	Coefficient of determination	Coefficient of determination	Coefficient of determination	Coefficient of determination
A	0.997	Excellent (≥0.90)	0.87	Good (0.70-0.89)
A1	0.990	Excellent (≥0.90)	0.71	Good (0.70-0.89)
A2	0.827	Good (0.70-0.89)	0.71	Good (0.70-0.89)
A3	0.900	Excellent (≥0.90)	0.93	Excellent (≥0.90)
C	0.975	Excellent (≥0.90)	0.73	Good (0.70-0.89)
B1	0.974	Excellent (≥0.90)	0.70	Good (0.70-0.89)
B2	0.990	Excellent (≥0.90)	0.84	Good (0.70-0.89)

3.3 Time sweep test results

To examine the effect of different aging protocols on fatigue life, time sweep test under strain controlled (0.06%, 0.09%, 0.12% and 0.15%) condition was carried out at 25°C using constant frequency level of 10Hz [19,20]. 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 [42,59,60].

The fatigue life of each FAM mixtures at different strain levels is shown in Fig. 11. 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' which is well below an acceptable value of 30% [45]. 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 0.06% to 0.15% for A3 specimen decreased the average fatigue life from 77300 to 7700, indicating a decrease in fatigue life by 90.03%. Similar results can be obtained for other FAM specimens at other strain levels. Further, as the aging level to FAM mixture 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 [65,66], decrease in fatigue life can be clearly seen. For example, an increase in aging level from A to A3 decreased the fatigue life from 54350 to 33050 at 0.09% strain level, indicating the decrease in corresponding value by 39.19%. Further, the comparison of different aging protocols based on fatigue life of FAM mixtures is shown in Fig. 11. The trend of different aging level protocols showed that the fatigue life of FAM specimen 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. The FAM specimen 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.

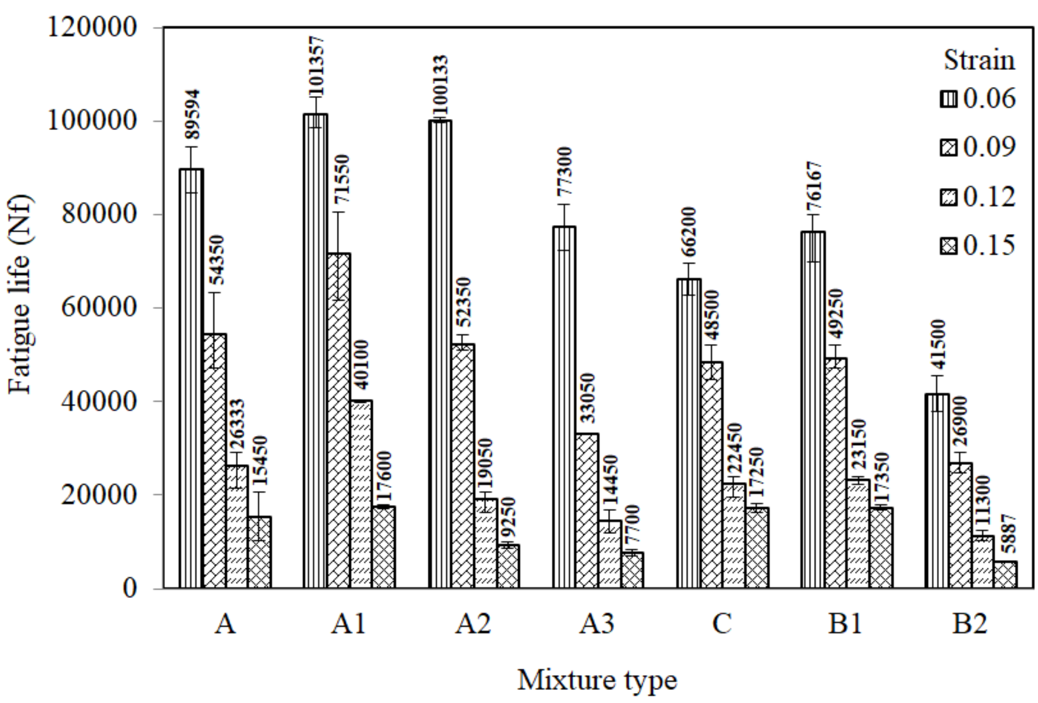

Fig. 11. Strain controlled fatigue test results at 25°C and the frequency of 10Hz

Further, the fatigue life of each STA and LTA FAM mixtures was predicted by using regression analysis. The model coefficients obtained from regression analysis is presented in Table. 8.

The fatigue model regression coefficients ‘a’ and ‘b’ are derived on the basis of measurable material parameters [21]. 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 which may be attributed to unexpectedly higher fatigue life for A1 compared to A. For example, the ‘a’ value for A1 specimens is 679.020 which decreased to 71.845 and 27.406 with an increase in aging duration from 6 hrs to 12 and 24 hrs respectively. Further, an improper trend of regression coefficients can be seen with respect to different aging protocols at 95°C and 135°C. This indicates the combined effect of regression coefficients ‘a’ and ‘b’ on overall fatigue life of FAM mixtures.

Table. 8. Fatigue model regression coefficients

Mixture type	Fatigue model regression coefficients	
	a	b
A	430.790	-1.934
A1	679.020	-1.840
A2	71.845	-2.627
A3	27.406	-2.861
C	924.390	-1.553
B1	708.080	-1.689
B2	283.650	-1.815

Summary of Findings.

The aging of FAM mixtures 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 of this study 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 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 properties 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.

These findings are based on the effect of different aging levels on FAM mixture prepared with only one binder type. However, the plan of this study is to expand the work to evaluate the effect of different aging levels on viscoelastic and fatigue properties of FAM mixtures prepared with different binder type, aggregates and mineral fillers. Further, permanent deformation and moisture damage study can also be carried out on different FAM mixtures.

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REFERENCES

[1] M.W. Mirza, M.W. Witczak, Development of a Global Aging System for Short and Long Term Aging of Asphalt Cements, Journal of the Association of Asphalt Paving Technologists. 64: (1995), 393–430.

[2] Y. Ruan, R.R. Davison, C.J. Glover, The effect of long-term oxidation on the rheological properties of polymer modified asphalts, Fuel. (2003). doi:10.1016/S0016-2361(03)00144-3.

[3] M. Ling, X. Luo, F. Gu, R.L. Lytton, Time-temperature-aging-depth shift functions for dynamic modulus master curves of asphalt mixtures, Constr. Build. Mater. (2017). doi:10.1016/j.conbuildmat.2017.09.156.

[4] P.K. Ashish, D. Singh, S. Bohm, Investigation on influence of nanoclay addition on rheological performance of asphalt binder, Road Mater. Pavement Des. 0629 (2016) 1–20. doi:10.1080/14680629.2016.1201522.

[5] R. Rahbar-Rastega, R. Zhang, J.E. Sias, E. V. Dave, Evaluation of laboratory ageing procedures on cracking performance of asphalt mixtures, Road Mater. Pavement Des. 0 (2019) 1–16. doi:10.1080/14680629.2019.1633782.

[6] Y. Zhang, T. Ma, X. Luo, X. Huang, R.L. Lytton, Prediction of Dynamic Shear Modulus of Fine Aggregate Matrix Using Discrete Element Method and Modified Hirsch Model, Elsevier Ltd, 2019. doi:10.1016/j.mechmat.2019.103148.

[7] Z. Zhou, X. Gu, Q. Dong, F. Ni, Y. Jiang, Low- and intermediate-temperature behaviour of polymer-modified asphalt binders, mastics, fine aggregate matrices, and mixtures with Reclaimed Asphalt Pavement material, Road Mater. Pavement Des. 0 (2019) 1–30. doi:10.1080/14680629.2019.1574233.

[8] X. Chen, M. Solaimanian, Simple Indexes to Identify Fatigue Performance of Asphalt Concrete, J. Test. Eval. 48 (2020) 20170722. doi:10.1520/JTE20170722.

[9] M. Elwardany, F.Y. Rad, C. Castorena, Climate- , Depth- , and Time-Based Laboratory Aging Procedure for Asphalt Mixtures, Journal of the Association of Asphalt Paving Technologists (AAPT), 87 (2018).

[10] M.D. Elwardany, F.Y. Rad, C. Castorena, Y.R. Kim, Evaluation of asphalt mixture laboratory long-term aging methods for performance testing and prediction, Asph. Paving Technol. Sess. 85 (2016) 35–75. doi:10.1080/14680629.2015.1266740.

[11] W.S. Mogawer, E.H. Fini, A.J. Austerman, Performance characteristics of high reclaimed asphalt pavement containing bio-modifier, Road Mater. Pavement Des. 0629 (2016) 753–767. doi:10.1080/14680629.2015.1096820.

[12] A. Hanz, E. Dukatz, G. Reinke, Use of performance based testing for high RAP mix design and production monitoring, Asph. Paving Technol. Sess. 85 (2016) 449–483. doi:10.1080/14680629.2015.1266766.

[13] F. Yin, F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, Characterising the long-term rejuvenating effectiveness of recycling agents on asphalt blends and mixtures with high RAP and RAS contents, Road Mater. Pavement Des. 18 (2017) 273–292. doi:10.1080/14680629.2017.1389074.

[14] C. Chen, F. Yin, P. Turner, R.C. West, N. Tran, Selecting a Laboratory Loose Mix Aging Protocol for the NCAT Top-Down Cracking Experiment, Transp. Res. Rec. (2018) 1–13. doi:10.1177/0361198118790639.

[15] M. Nobakht, M.S. Sakhaeifar, Dynamic modulus and phase angle prediction of laboratory aged asphalt mixtures, Constr. Build. Mater. 190 (2018) 740–751. doi:10.1016/j.conbuildmat.2018.09.160.

[16] H. Sahebzamani, M.Z. Alavi, O. Farzaneh, Evaluating effectiveness of polymerized pellets mix additives on improving asphalt mix properties, Constr. Build. Mater. 187 (2018) 160–167. doi:10.1016/j.conbuildmat.2018.07.143.

[17] R. Rahbar-Rastegar, J.S. Daniel, E. V. Dave, Evaluation of Viscoelastic and Fracture Properties of Asphalt Mixtures with Long-Term Laboratory Conditioning, Transp. Res. Rec. (2018). doi:10.1177/0361198118795012.

[18] C. Ogbo, F. Kaseer, M. Oshone, J.E. Sias, A.E. Martin, Mixture-based rheological evaluation tool for cracking in asphalt pavements, Road Mater. Pavement Des. 5 (2019) 1–16. doi:10.1080/14680629.2019.1592010.

[19] Y.-R. Kim, D. Little, I. Song, Effect of Mineral Fillers on Fatigue Resistance and

Fundamental Material Characteristics: Mechanistic Evaluation, Transp. Res. Rec. J. Transp. Res. Board. 1832 (2003) 1–8. doi:10.3141/1832-01.

[20] S.N. Suresha, A. Ningappa, Recent trends and laboratory performance studies on FAM mixtures : A state-of-the-art review, Constr. Build. Mater. 174 (2018) 496–506. doi:10.1016/j.conbuildmat.2018.04.144.

[21] Y.-R. Kim, D.N. Little, R.L. Lytton, Fatigue and Healing Characterization of Asphalt Mixtures, J. Mater. Civ. Eng. 15 (2003) 75–83. doi:10.1061/(ASCE)0899-1561(2003)15:1(75).

[22] E. Masad, V.T.F. Castelo Branco, D.N. Little, R. Lytton, A unified method for the analysis of controlled-strain and controlled-stress fatigue testing, Int. J. Pavement Eng. 9 (2008) 233–246. doi:10.1080/10298430701551219.

[23] S. Caro, E. Masad, G. Airey, A. Bhasin, D. Little, Probabilistic Analysis of Fracture in Asphalt Mixtures Caused by Moisture Damage, Transp. Res. Rec. J. Transp. Res. Board. 2057 (2008) 28–36. doi:10.3141/2057-04.

[24] V. Castelo Branco, E. Masad, A. Bhasin, D. Little, Fatigue Analysis of Asphalt Mixtures Independent of Mode of Loading, Transp. Res. Rec. J. Transp. Res. Board. 2057 (2008) 149–156. doi:10.3141/2057-18.

[25] P. Karki, R. Li, A. Bhasin, Quantifying overall damage and healing behaviour of asphalt materials using continuum damage approach, Int. J. Pavement Eng. 16 (2015) 350–362. doi:10.1080/10298436.2014.942993.

[26] S. Im, T. You, H. Ban, Y.R. Kim, Multiscale testing-analysis of asphaltic materials considering viscoelastic and viscoplastic deformation, Int. J. Pavement Eng. 18 (2017) 783–797. doi:10.1080/10298436.2015.1066002.

[27] F.T.S. Aragão, Y.R. Kim, Mode I Fracture Characterization of Bituminous Paving Mixtures at Intermediate Service Temperatures, Exp. Mech. 52 (2012) 1423–1434. doi:10.1007/s11340-012-9594-4.

[28] B.S. Underwood, Y.R. Kim, Effect of volumetric factors on the mechanical behavior of asphalt fine aggregate matrix and the relationship to asphalt mixture properties, Constr. Build. Mater. 49 (2013) 672–681. doi:10.1016/j.conbuildmat.2013.08.045.

[29] B.S. Underwood, Y.R. Kim, Experimental investigation into the multiscale behaviour of asphalt concrete, Int. J. Pavement Eng. 12 (2011) 357–370. doi:10.1080/10298436.2011.574136.

[30] K. Bemis, K. Bennett, Using numerical models and volume rendering to interpret acoustic imaging of hydrothermal flow, EOS Trans. Am. Geophys. Union. 25 (2009) 1209–1219. doi:10.1061/(ASCE)MT.1943-5533.0000673.

[31] T. Report, D. Page, P. Covered, Fracture Properties and Fatigue Cracking Resistance of Asphalt Binders March 2012 Arash Motamed , Amit Bhasin , and Anoosha Izadi Report 161122-1 Center for Transportation Research University of Texas at Austin 1616 Guadalupe Street , Suite 4 . 200 Southw, 7 (2012).

[32] J. Zhu, M.Z. Alavi, J. Harvey, L. Sun, Y. He, Evaluating fatigue performance of fine aggregate matrix of asphalt mix containing recycled asphalt shingles, Constr. Build. Mater. 139 (2017) 203–211. doi:10.1016/j.conbuildmat.2017.02.060.

[33] C. Chen, F. Yin, P. Turner, R.C. West, N. Tran, Selecting a Laboratory Loose Mix Aging Protocol for the NCAT Top-Down Cracking Experiment, Transp. Res. Rec. (2018). doi:10.1177/0361198118790639.

[34] Hanz, Andrew Dukatz, Ervin Reinke, Gerald Use of performance based testing for high RAP mix design and production monitoring, Road Mater. Pavement Des. 18(1), (2016), 284-310. DOI: 10.1080/14680629.2016.1266766.

[35] Y. He, M.Z. Alavi, D. Jones, J. Harvey, Proposing a solvent-free approach to evaluate the properties of blended binders in asphalt mixes containing high quantities of reclaimed asphalt pavement and recycled asphalt shingles, Constr. Build. Mater. 114 (2016) 172–180. doi:10.1016/j.conbuildmat.2016.03.074.

[36] V. Branco, A. Bhasin, E. Masad, D. Little, J. Soares, Separation of Nonlinear Viscoelastic Response From Fatigue Damage Using Dynamic Mechanical Analysis (Dma), (2008) 1–13.

[37] P. Sousa, E. Kassem, E. Masad, D. Little, New design method of fine aggregates mixtures and automated method for analysis of dynamic mechanical characterization data, Constr. Build. Mater. 41 (2013) 216–223. doi:10.1016/j.conbuildmat.2012.11.038.

[38] R.A. Freire, L. F. A. L. Babadopulos, V. T. F. Castelo Branco, A. Bhasin, Aggregate Maximum Nominal Sizes' Influence on Fatigue Damage Performance Using Different Scales, J. Mater. Civ. Eng. 29 (2017) 04017067. doi:10.1061/(ASCE)MT.1943-5533.0001912.

[39] Q. Li, Fatigue resistance investigation of warm mix recycled asphalt binder, mastic, and fine aggregate matrix, Wiley. 31 (2017) 233–248. doi:10.1111/ffe.12692.

[40] A.K.Y. Ng, A.C. Vale, A.C. Gigante, A.L. Faxina, D. Ph, Determination of the Binder Content of Fine Aggregate Matrices Prepared with Modified Binders, J. Mater. Civ. Eng. ASCE. 30 (2018) 1–12. doi:10.1061/(ASCE)MT.1943-5533.0002160.

[41] ANDRISE BUCHWEITZ KLUG ABK, Evaluation of the fatigue performance of fine aggregate matrices prepared with reclaimed asphalt pavements and shale oil residue, 2017. doi:10.11606/D.18.2018.tde-19022018-112755.

[42] M. Sadeq, H. Al-Khalid, E. Masad, O. Sirin, Comparative evaluation of fatigue resistance of warm fine aggregate asphalt mixtures, Constr. Build. Mater. 109 (2016) 8–16. doi:10.1016/j.conbuildmat.2016.01.045.

[43] Q. Li, G. Li, X. Ma, S. Zhang, Linear viscoelastic properties of warm-mix recycled asphalt binder, mastic, and fine aggregate matrix under different aging levels, Constr. Build. Mater. 192 (2018) 99–109. doi:10.1016/j.conbuildmat.2018.10.085.

[44] Y.-R. Kim, D.N. Little, R.L. Lytton, Evaluation of microdamage, healing, and heat dissipation of asphalt mixtures, using a dynamic mechanical analyzer, Transp. Res. Rec. (2001) 60–66. doi:10.3141/1767-08.

[45] S. Caro, D.B. Sánchez, B. Caicedo, Methodology to characterise non-standard asphalt materials using DMA testing: Application to natural asphalt mixtures, Int. J. Pavement Eng. 16 (2015) 1–10. doi:10.1080/10298436.2014.893328.

[46] F.T.S. Aragão, J. Lee, Y.R. Kim, P. Karki, Material-specific effects of hydrated lime on the properties and performance behavior of asphalt mixtures and asphaltic pavements, Constr. Build. Mater. 24 (2010) 538–544. doi:10.1016/j.conbuildmat.2009.10.005.

[47] H. Nabizadeh, H.F. Haghshenas, Y.R. Kim, F.T.S. Aragão, Effects of rejuvenators on

high-RAP mixtures based on laboratory tests of asphalt concrete (AC) mixtures and fine aggregate matrix (FAM) mixtures, Constr. Build. Mater. 152 (2017) 65–73. doi:10.1016/j.conbuildmat.2017.06.101.

[48] M.O. Marasteanu, D.A. Anderson, Establishing Linear Viscoelastic Conditions for Asphalt Binders, Transp. Res. Rec. J. Transp. Res. Board. (2007). doi:10.3141/1728-01.

[49] D.B. Sánchez, G. Airey, S. Caro, J. Grenfell, Effect of foaming technique and mixing temperature on the rheological characteristics of fine RAP-foamed bitumen mixtures, Road Mater. Pavement Des. 0 (2019) 1–17. doi:10.1080/14680629.2019.1593228.

[50] N.I.M. Yusoff, F.M. Jakarni, V.H. Nguyen, M.R. Hainin, G.D. Airey, Modelling the rheological properties of bituminous binders using mathematical equations, Constr. Build. Mater. 40 (2013) 174–188. doi:10.1016/j.conbuildmat.2012.09.105.

[51] S. Yang, A. Braham, S. Underwood, A. Hanz, G. Reinke, Correlating field performance to laboratory dynamic modulus from indirect tension and torsion bar, Asph. Paving Technol. Assoc. Asph. Paving Technol. Tech. Sess. 85 (2016) 131–162. doi:10.1080/14680629.2015.1267438.

[52] R. Nemati, E. V Dave, Nominal property based predictive models for asphalt mixture complex modulus (dynamic modulus and phase angle), 158 (2018) 308–319. doi:10.1016/j.conbuildmat.2017.09.144.

[53] R. Rahbar-rastegar, CRACKING IN ASPHALT PAVEMENTS : IMPACT OF COMPONENT PROPERTIES AND AGING ON FATIGUE AND THERMAL CRACKING, (2017). Doctoral Dissertations. 2284. https://scholars.unh.edu/dissertation/2284

[54] R. Nemati, Evaluation of Structural Contribution of Asphalt Mixtures Through Improved Performance Indices, (2019). Doctoral Dissertations. 2460. https://scholars.unh.edu/dissertation/2460

[55] D.B. Sánchez, J. Grenfell, G. Airey, S. Caro, Evaluation of the degradation of fine asphalt-aggregate mixtures containing high reclaimed asphalt pavement contents, Road Mater. Pavement Des. 18 (2017) 91–107. doi:10.1080/14680629.2017.1304250.

[56] H.F. Haghshenas, H. Nabizadeh, Y.-R. Kim, The Effect of Rejuvenators on RAP Mixtures: A Study Based on Multiple Scale Laboratory Test Results, Geo-Chicago 2016. (2016) 697–707. doi:10.1061/9780784480137.066.

[57] Y. Kim, H. Lee, Evaluation of the effect of aging on mechanical and fatigue properties of sand asphalt mixtures, KSCE J. Civ. Eng. 7 (2003) 389–398. doi:10.1007/BF02895837.

[58] M.E. Kutay, N. Gibson, J. Youtcheff, Conventional and Viscoelastic Continuum Damage (VECD) - Based Fatigue Analysis of Polymer Modified Asphalt Pavements, J. Assoc. Asph. Paving Technol. (2008).

[59] B.J. Smith, S.A.. Hesp, Crack pinning in asphalt mastic and concrete, Transp. Res. Rec. J. Transp. Res. Board. 1728 (2000) 75–81.

[60] P. Karki, A. Bhasin, B.S. Underwood, Fatigue Performance Prediction of Asphalt Composites Subjected to Cyclic Loading with Intermittent Rest Periods, Transp. Res. Rec. J. Transp. Res. Board. 2576 (2016) 72–82. doi:10.3141/2576-08.

[61] H. Nabizadeh, Viscoelastic, Fatigue Damage, and Permanent Deformation Characterization of High Rap Bituminous Mixtures Using Fine Aggregate Matrix (Fam), (2015) 88. http://digitalcommons.unl.edu/civilengdiss%5Cnhttp://digitalcommons.unl.edu/civilengdiss.

[62] Sanchez, Meso-scale Rheological Characteristics of Foamed Bitumen Mixtures with High RAP Content (2018). http://eprints.nottingham.ac.uk/50503/1/Final%20PhD%20Thesis%20Diana%20March%202018%20after%20viva.pdf

[63] D.J. Mensching, A. Andriescu, C. Decarlo, X. Li, J.S. Youtcheff, Effect of Extended Aging on Asphalt Materials Containing Rerefined Engine Oil Bottoms, Transp. Res. Board TRB 2017 Annu. Meet. (2017) 1–18.

[64] D. Singh, M. Zaman, S. Commuri, Evaluation of predictive models for estimating dynamic modulus of hot-mix asphalt in Oklahoma, Transp. Res. Rec. (2011) 57–72. doi:10.3141/2210-07.

[65] W.R. Kingery, Laboratory Study of Fatigue Characteristics of HMA Surface Mixtures Containing Recycled Asphalt Pavement (RAP), (2004).

[66] K. Aravind, A. Das, Pavement design with central plant hot-mix recycled asphalt mixes, Constr. Build. Mater. 21 (2007) 928–936. doi:10.1016/j.conbuildmat.2006.05.004.

Table. 1. Basic properties of asphalt binder

Property	Test Results	Limiting value IS 73:2013
Penetration at 25°C, 0.1 mm	64.5	Min. 45
Softening point (R&B) (°C)	52.7	45-55
Ductility at 25°C (cm)	85.4	Min. 70
Absolute viscosity at 60°C (poise)	2700	2400-3600
Kinematic viscosity at 135°C (cSt)	438	Min. 350
Flash Point (°C)	≥220	Min. 220

Table. 2. Details of method to fabricate FAM specimens

Steps	STA/LTA	Temperature	Time
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

Table. 3. Details of Different FAM Combinations

Binder Type	Properties	Test Name	FAM Mixture Type							Number of Specimens
			Loose Mixture Aging						Compacted Specimen Aging	
			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
	Fatigue	Time sweep @ 4 strain levels	3x4	3x4	3x4	3x4	3x4	3x4	3x4	3x4x7=84

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

Table. 4. Complex shear modulus |G*| master curve parameters of FAM mixtures

Mixture Type	α	β	γ	κ
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

Table. 5. Slope between each FAM mixtures at different frequency levels

Mixture 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)
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

Table. 6. Phase angle master curve parameters of FAM mixtures

Mixture Type	**a**	**b**	**c**
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

Table. 7. Goodness-of-fit results of \|G*\| and δ from master curve analysis

Mixture Type	|G*|, R^2	Acceptance criteria, [50,64]	δ, R^2	Acceptance criteria, [50,64]
	Coefficient of determination	Coefficient of determination	Coefficient of determination	Coefficient of determination
A	0.997	Excellent (≥0.90)	0.87	Good (0.70-0.89)
A1	0.990	Excellent (≥0.90)	0.71	Good (0.70-0.89)
A2	0.827	Good (0.70-0.89)	0.71	Good (0.70-0.89)
A3	0.900	Excellent (≥0.90)	0.93	Excellent (≥0.90)
C	0.975	Excellent (≥0.90)	0.73	Good (0.70-0.89)
B1	0.974	Excellent (≥0.90)	0.70	Good (0.70-0.89)
B2	0.990	Excellent (≥0.90)	0.84	Good (0.70-0.89)

Table. 8. Fatigue model regression coefficients

Mixture type	Fatigue model regression coefficients	
	a	b
A	430.790	-1.934
A1	679.020	-1.840
A2	71.845	-2.627
A3	27.406	-2.861
C	924.390	-1.553
B1	708.080	-1.689
B2	283.650	-1.815

Figure
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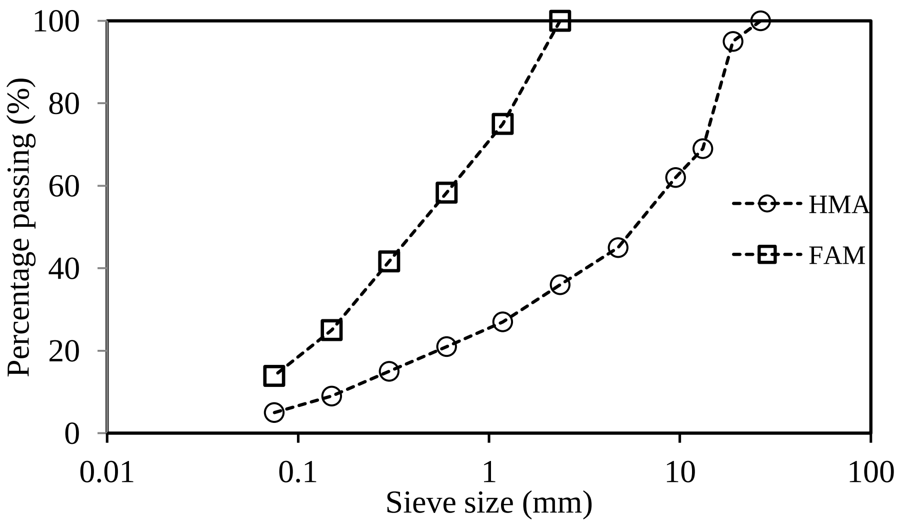

Fig. 1. Aggregate gradation for HMA and FAM mix design

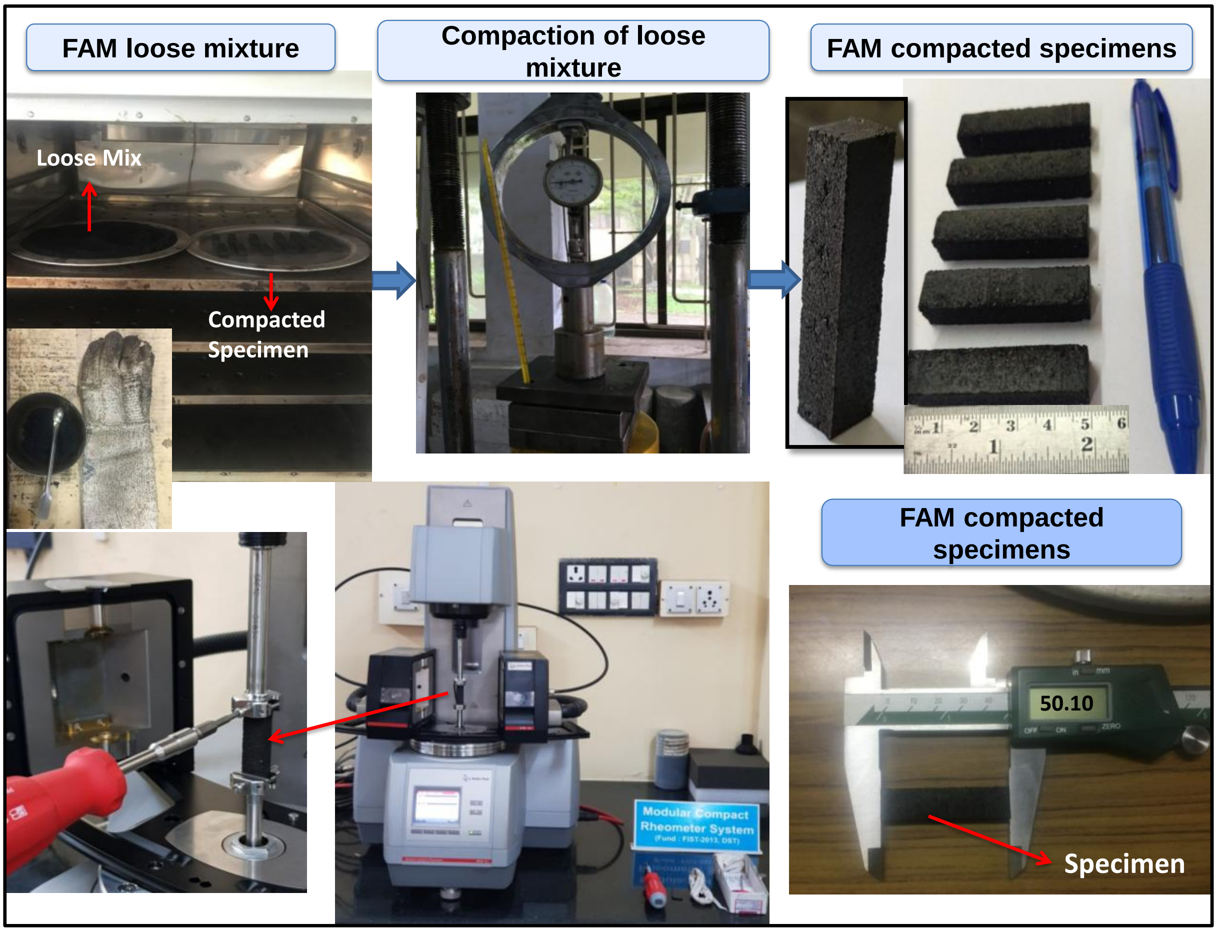

Fig. 2. Rectangular FAM Specimen Preparation

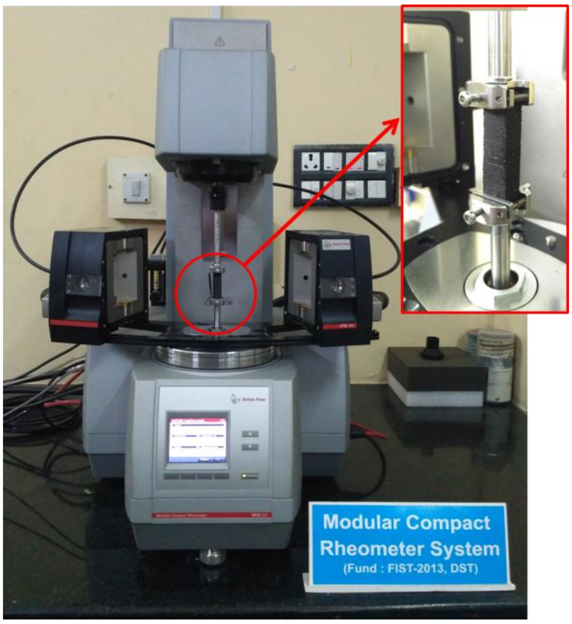

Fig. 3. Dynamic Shear Rheometer (MCR 502) Setup.

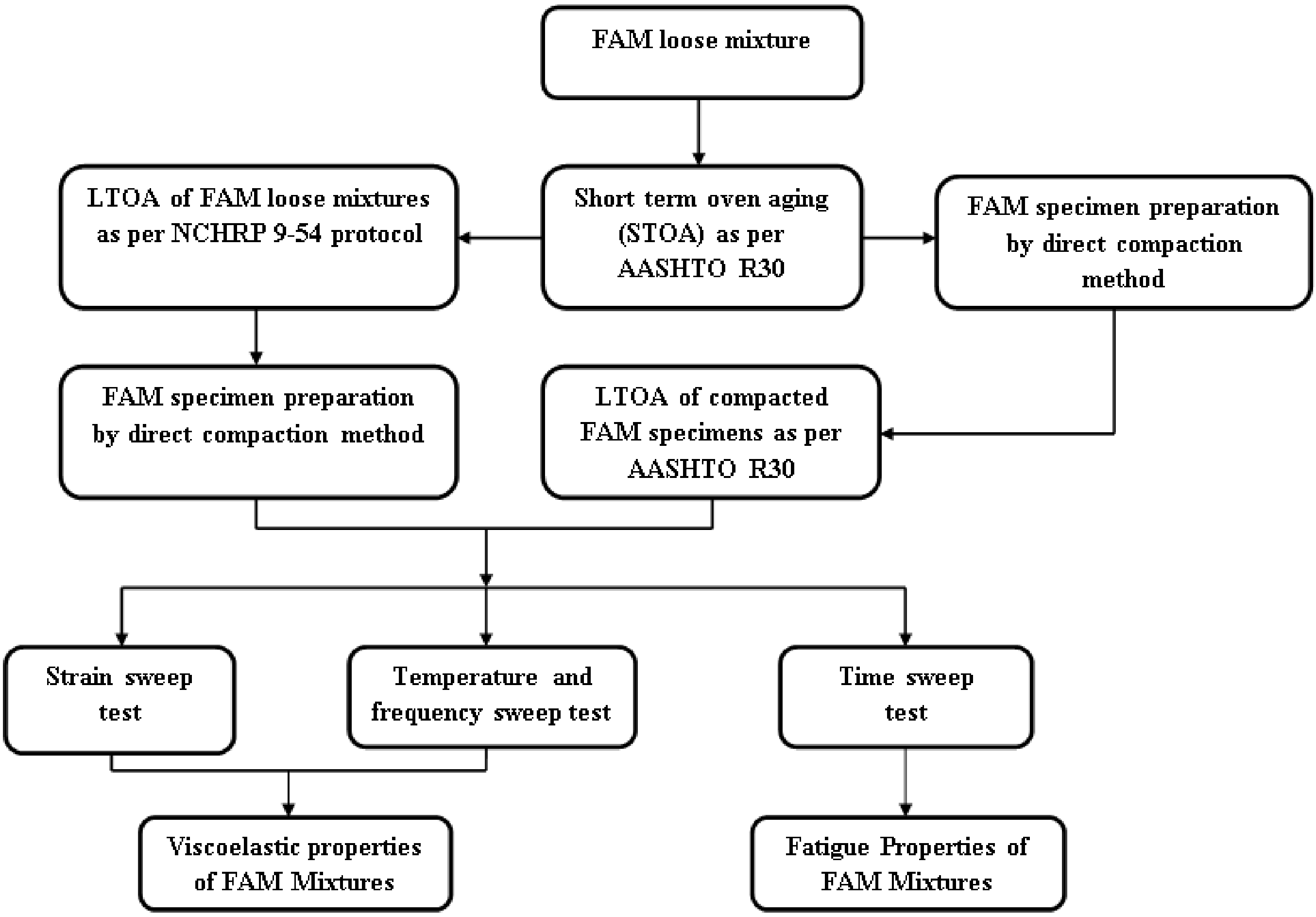

Fig. 4. Overall experimental plan

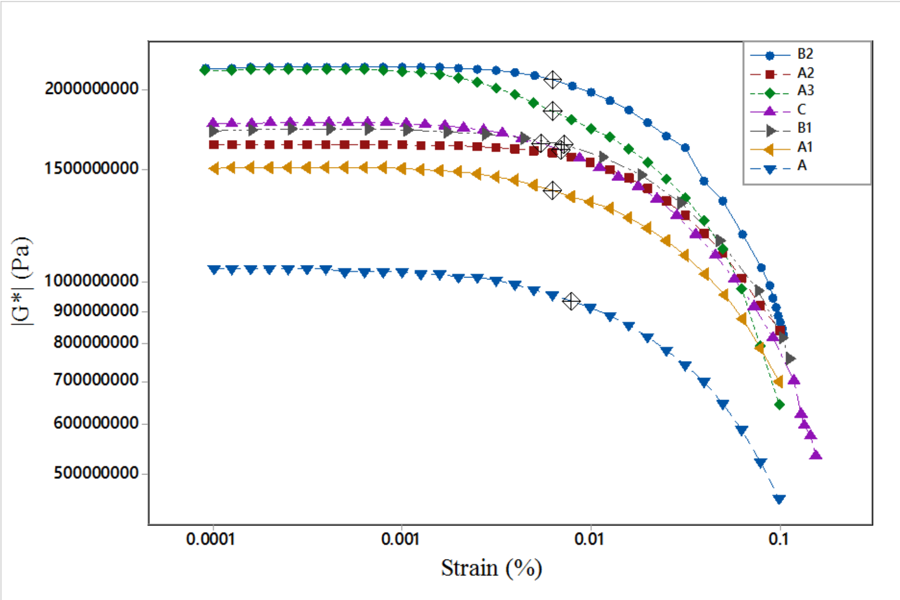

Fig. 5. Results of FAM strain sweep test

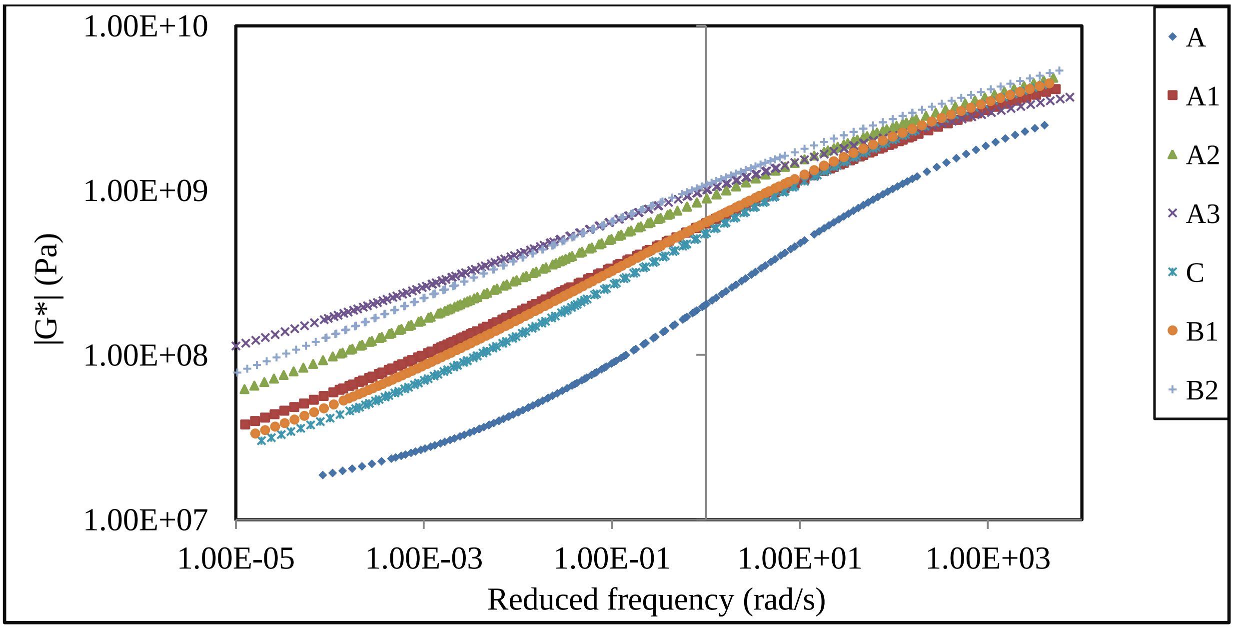

Fig. 6. Complex shear modulus |G*| of STOA and LTOA FAM mixtures at reference temperature 25°C.

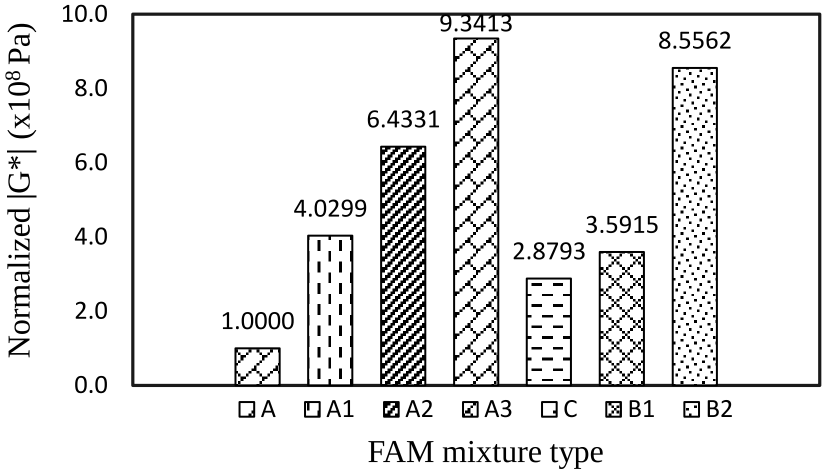

Fig. 7. Normalised |G*| of FAM mixtures at 0.001Hz and 25°C.

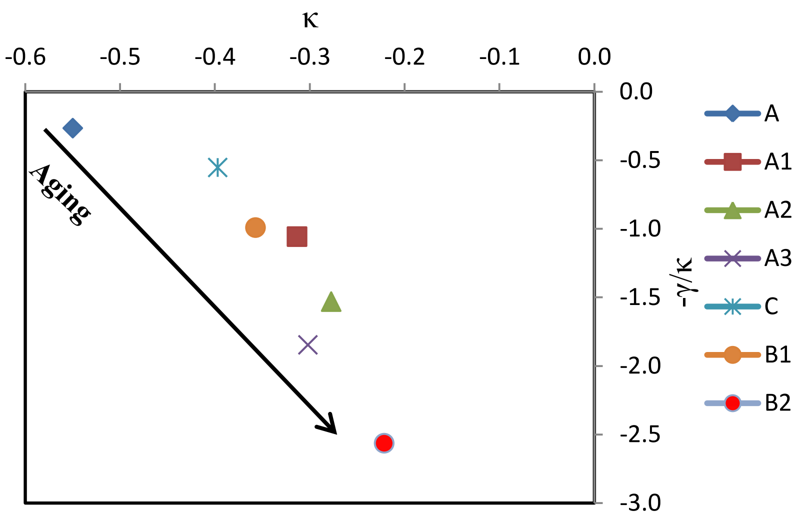

Fig. 8. Variations of |G*| master curve shape parameter with different aging levels at a reference temperature of 25°C.

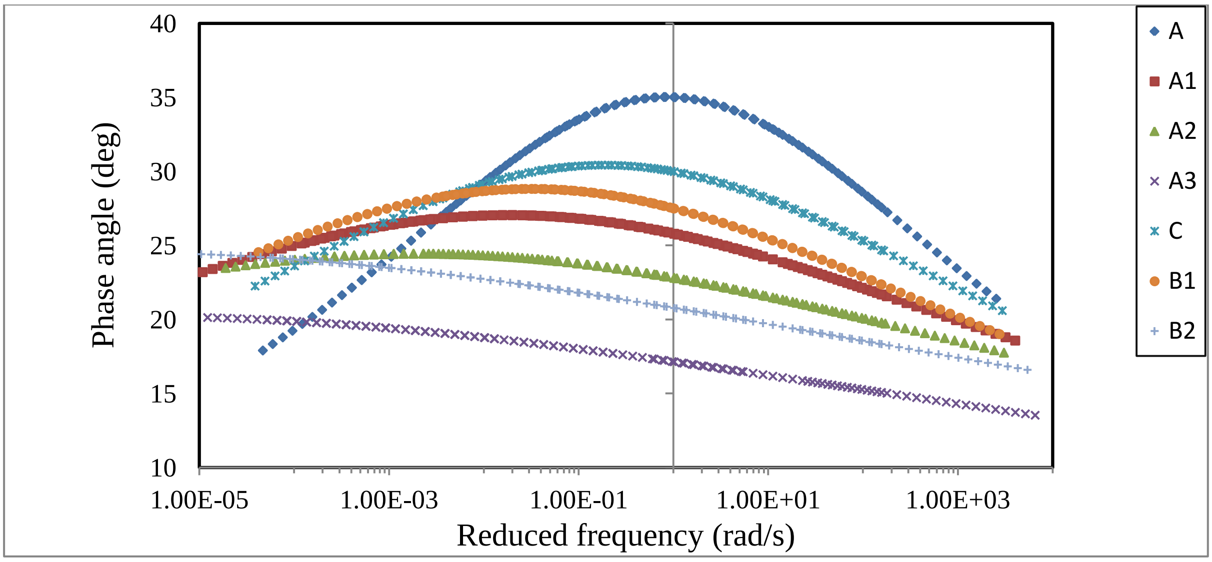

Fig. 9. Phase angle of STA and LTA FAM mixtures at a reference temperature of 25°C.

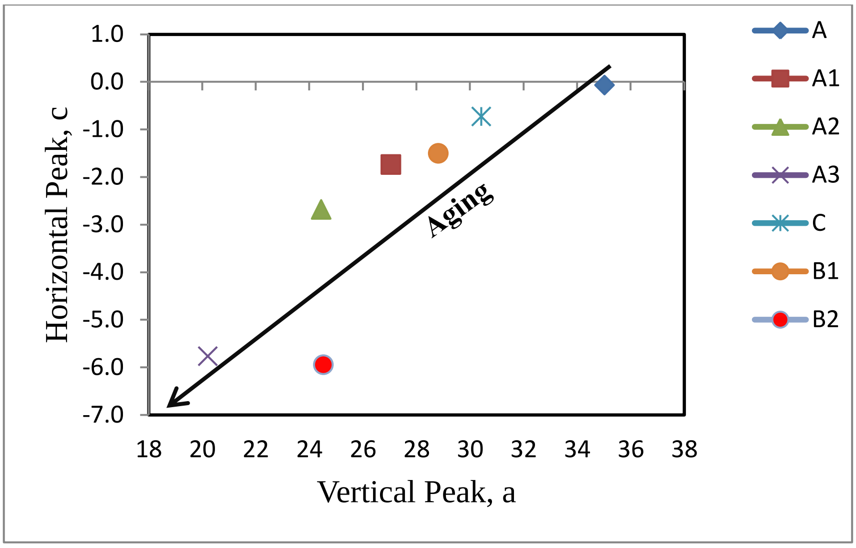

Fig. 10. Variations of δ master curve shape parameter with different aging levels at a reference temperature of 25°C.

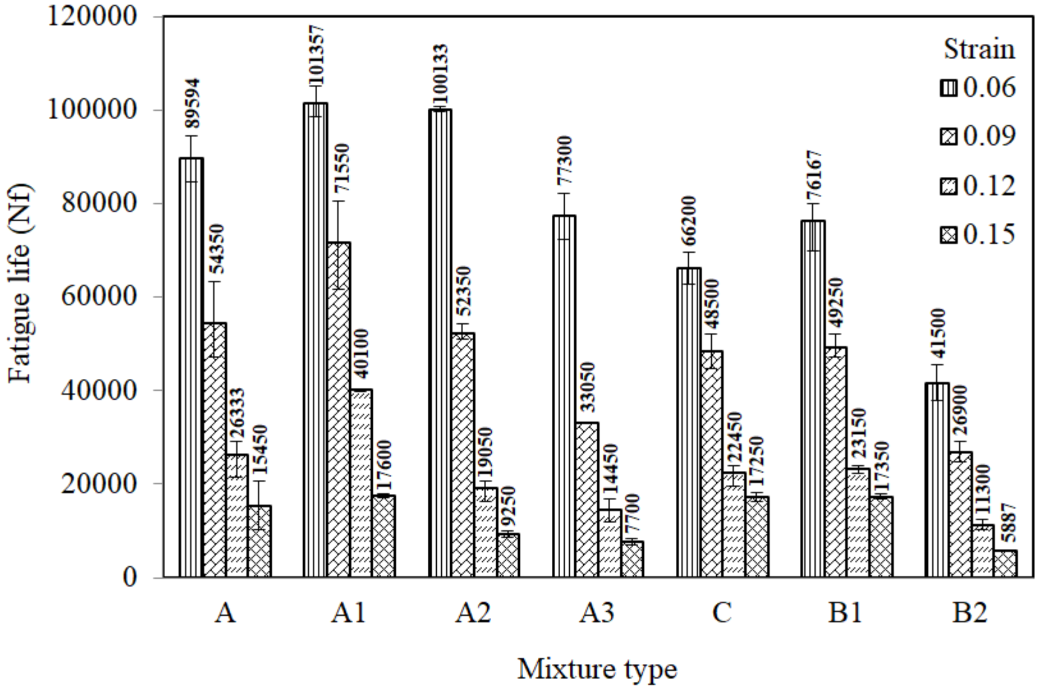

Fig. 11. Strain controlled fatigue test results at 25°C and the frequency of 10Hz

***Declaration of Interest Statement**

None.