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Table 1. Binder contents of the HMA and FAM mixtures according to some proposed methods in the literature.

		Binder Ccontent for HMA, %	BC for FAM, %			
			By Proposed Methods			
Sl.No	Mixture Types	HMA mix design	Branco et al. [4]	Coutinho and Feire et al. [19,69]	Sousa et al. [29]	Specific Surface Method [67,68]
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

Table 2. Studies on fatigue properties of FAM mixtures

Sl.No	Author Name	Year	Time Sweep Test/Cyclic Fatigue Test		Fatigue Failure Criteria
			Stress Controlled, kPa	Strain Controlled, %	
1	Smith et al. [3]	2000	-	0.2	50% reduction in the initial stiffness value
2	Kim et al. [1]	2003	-	0.2-0.56	No of loading cycles at maximum phase angle
3	Kim et al. [10]	2003	-	0.4-0.7	Maximum phase angle & different damage levels
4	Aragao et al. [14]	2010	-	0.3	No of loading cycles at maximum phase angle
5	Haghshenas et al. [27]	2016	-	0.15-0.25	No of loading cycles at maximum phase angle
6	Nabizadeh et al. [42]	2017	-	0.25	No of loading cycles at maximum phase angle
7	Zhu et al. [8]	2017	-	0.15	No of loading cycles at maximum phase angle
8	Sanchez et al. [36]	2017	-	0.09	40% reduction in the initial stiffness value
9	Freire et al. [19]	2017	418	0.065	No of loading cycles at maximum phase angle
10	Motamed et al. [45]	2012	275	-	Up to 300,000 cycles/ No of loading cycles at maximum phase angle
11	Karki et al. [35]	2014	225 and 400	-	60% reduction in the initial stiffness value
12	Sadeq et al. [2]	2016	75 and 400	-	50% reduction in the initial stiffness value

Table 3. Complex shear modulus and dynamic modulus of FAM and full asphalt mixtures

		SST Sample Results				FAM Sample Results		
Sl.No			**G*, Pa**				**G*, Pa**	
		Freq, Hz	**Temp, °C**	**G***		**Freq, Hz**	**Temp, °C**	**G***
1	Harvey et al. [61]	10	20	2.28E+09	Aragao et al. [14]	10	25	8.00E+08
2	Azari et al. [62]	10	25	2.96E+09	Motamed et al. [45]	10	16	1.56E+09
3	Azari et al. [63]	10	25	8.25E+08	Caro et al. [6]	10	28	2.50E+08
4	Visintine et al. [66]	10	20	2.07E+09	Zhu et al. [8]	10	20	7.00E+08
5	Druta et al. [65]	10	25	6.00E+08	Sadeq et al. [2]	10	25	1.24E+09

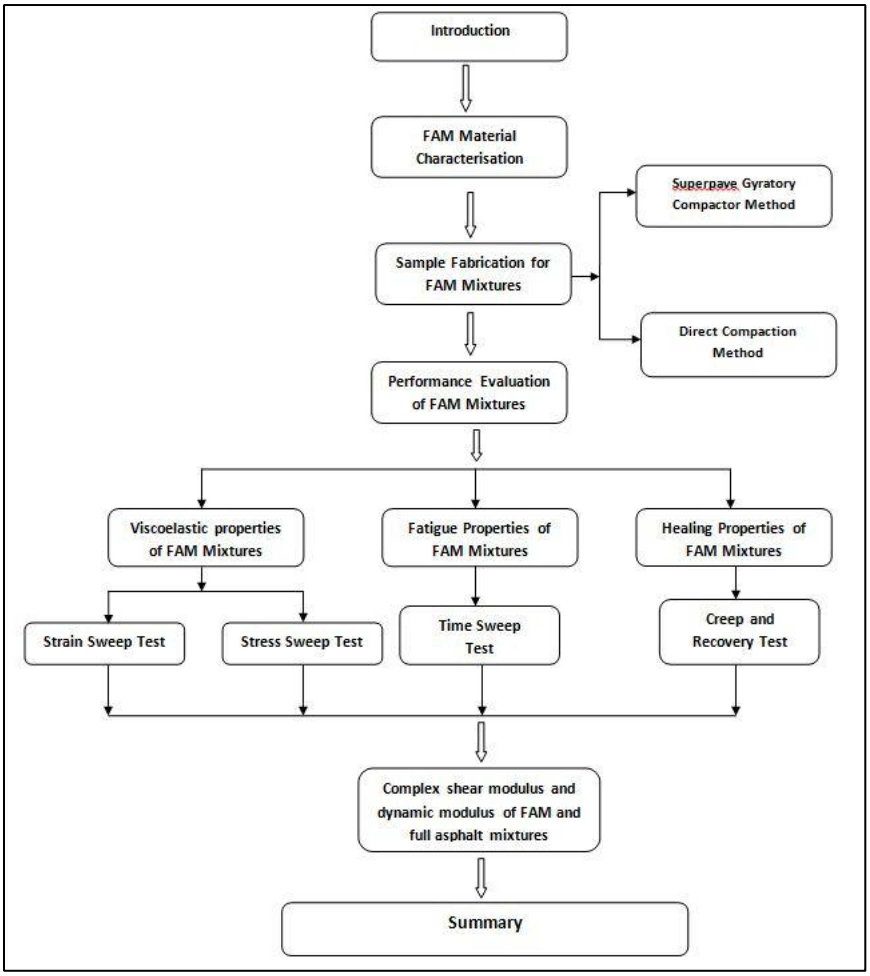
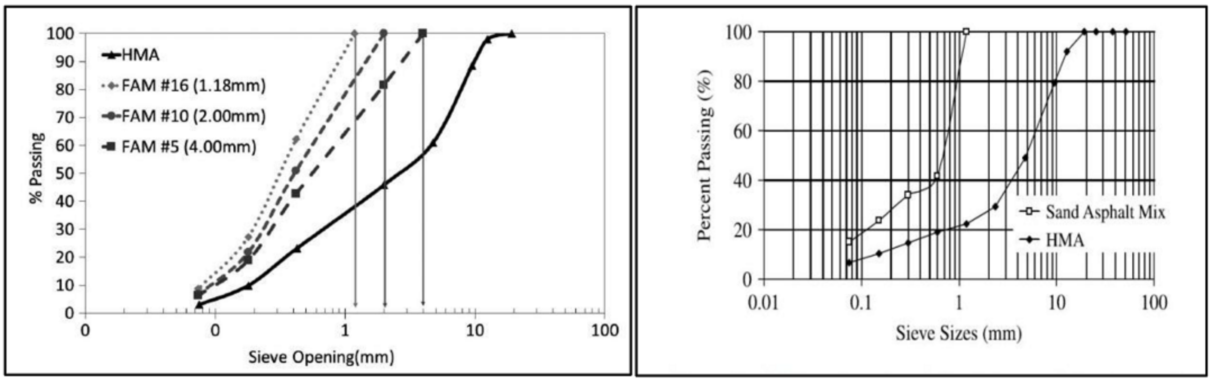


Fig. 1 Review outline



(a) (b)

Fig. 2 Details of different aggregate gradations adopted in FAM samples
(a) Freire et al. [19] (b) Masad et al. [23]

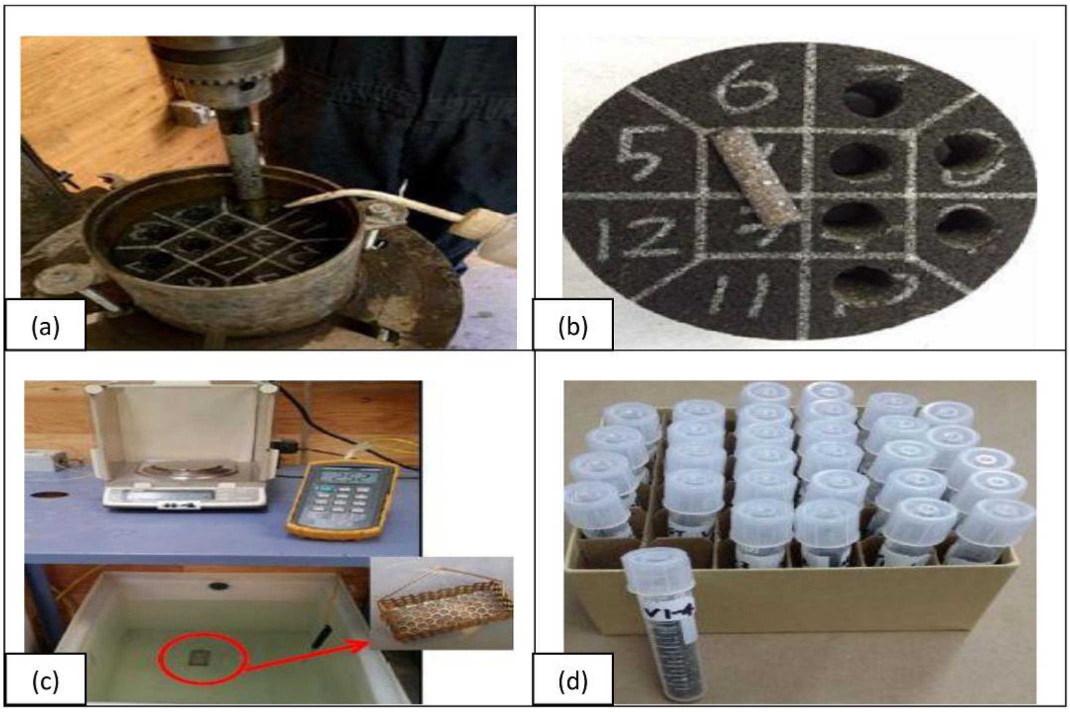


Fig.3. Procedure for preparation of cylindrical FAM samples
(a) Coring (b) FAM specimen (c) Weigh station to measure air voids (d) Storage of FAM samples [13]

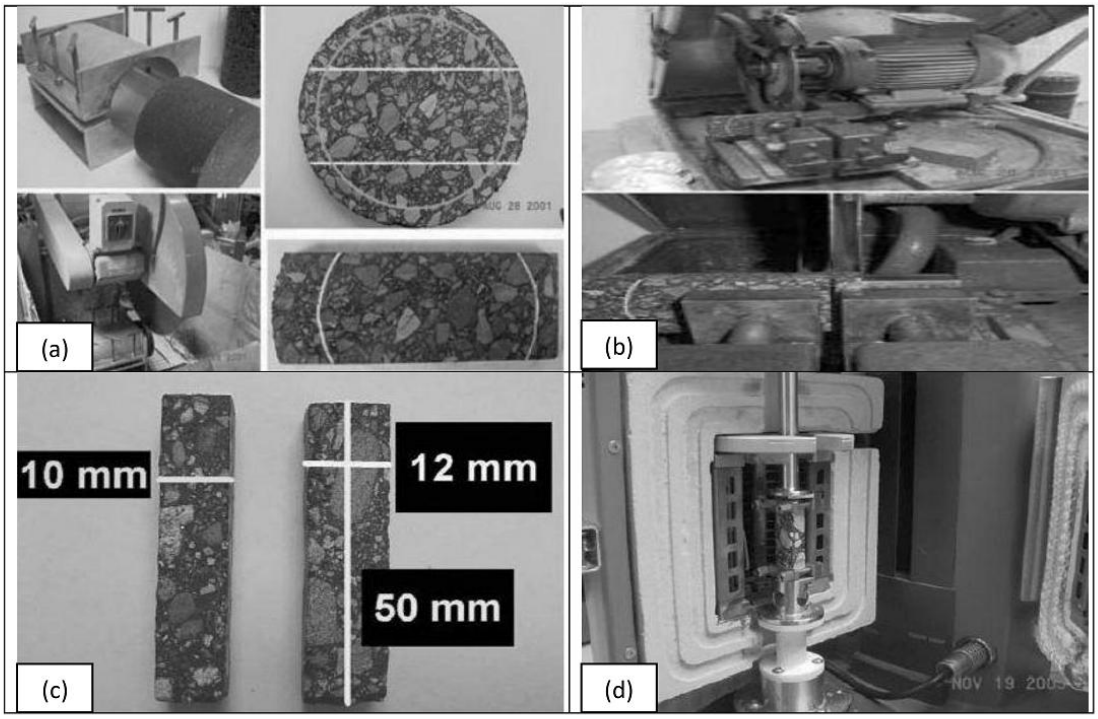


Fig.4. Procedure for preparation of rectangular FAM samples
(a) SGC specimen (b) Cutting of SGS specimen (c) FAM specimen (d) FAM specimen in DSR [40]

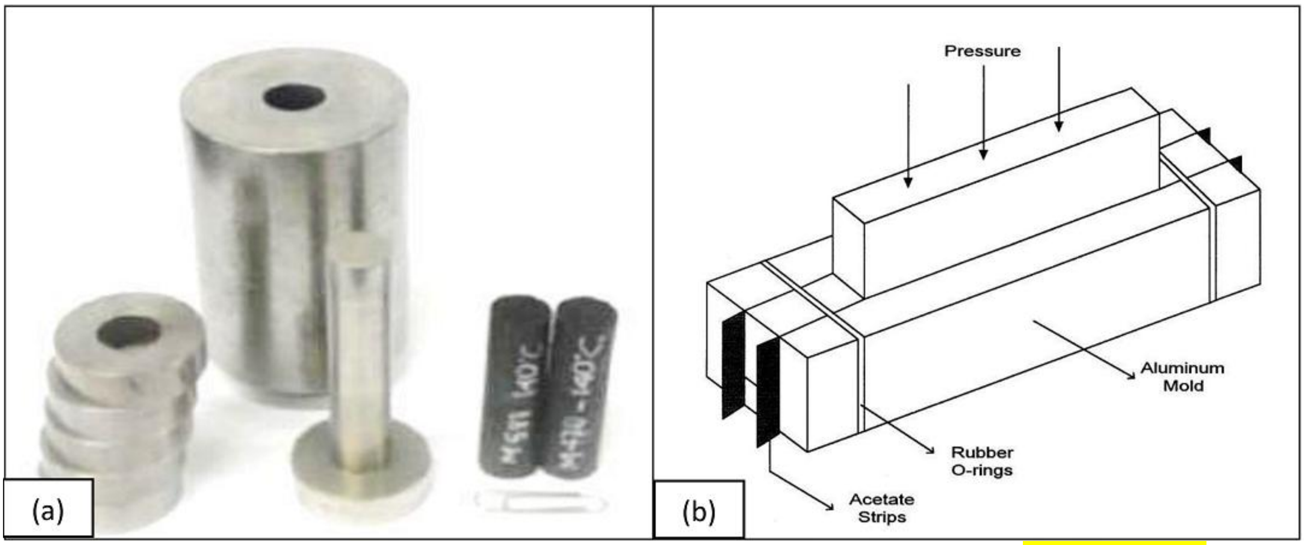


Fig. 5(a) Cylindrical FAM specimen mold [7], (b) Rectangular FAM specimen mould [41,44]

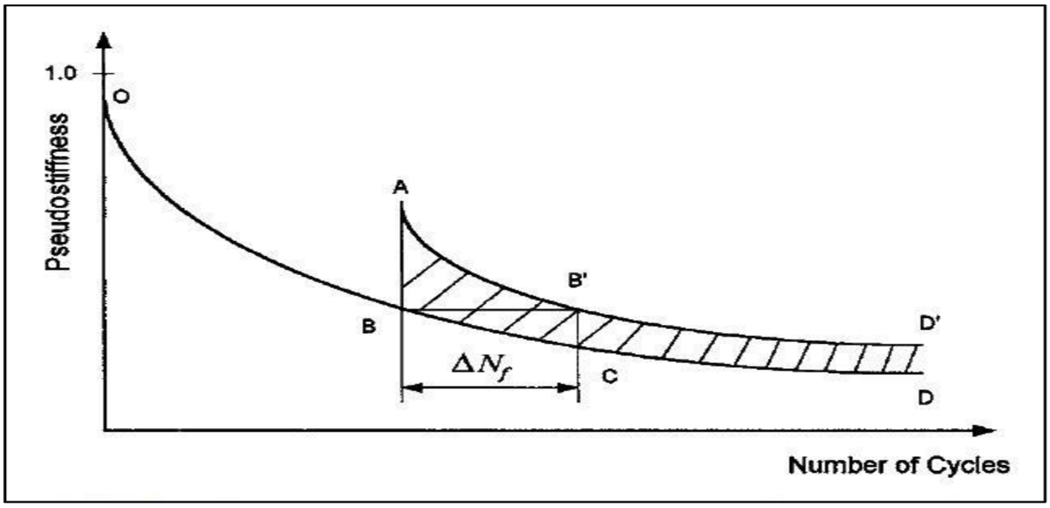


Fig.6. Ideal trend, which is conceptual not real, before and after rest period [41]

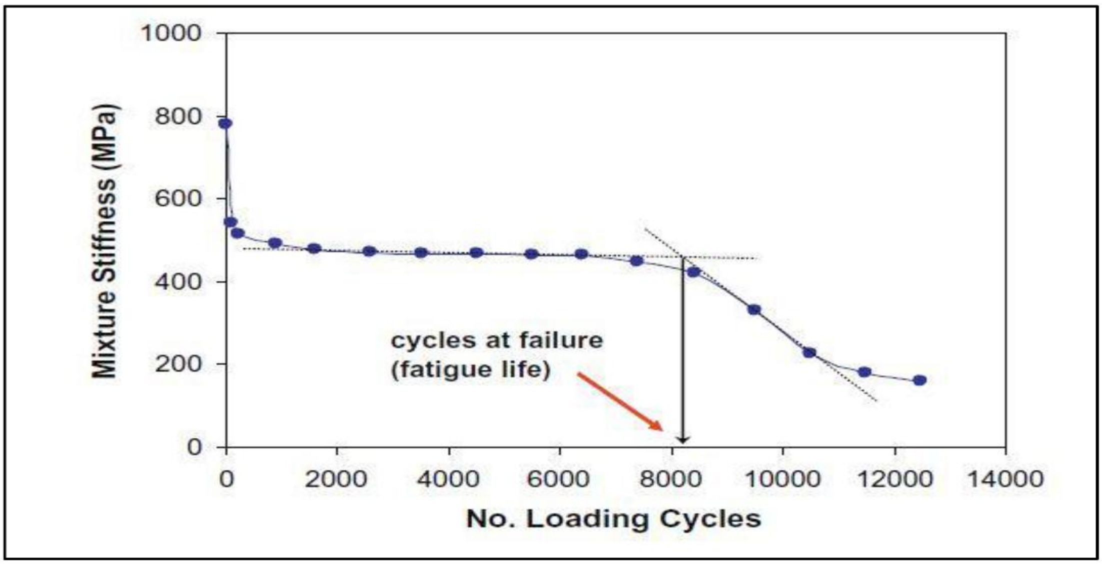


Fig. 7. The strain controlled time sweep test for determining fatigue failure [14]

Fig. 8(a) SST [64],

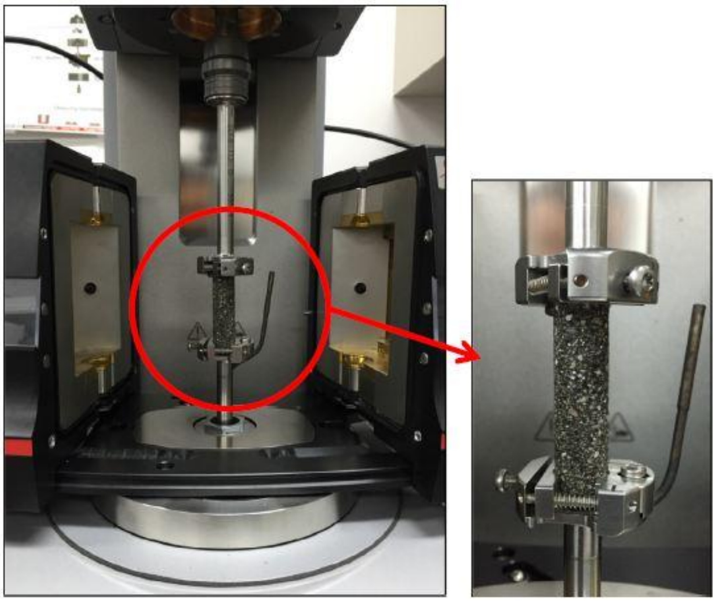


Fig. 8(b) DSR torsion bar fixture [13].

Recent Trends and Laboratory Performance Studies on FAM Mixtures: A state-of-the-art review

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ABSTRACT

In recent years, the testing and evaluation of Fine Aggregate Matrix (FAM) mixtures using Dynamic Shear Rheometer (DSR) which has drawn a growing interest because of its simplicity, reproducibility, and flexibility. However, several research studies have employed various sets of test methods for performance evaluation of FAM mixtures that calls for a critical review of the procedures that have been followed to date. This state-of-the-art review article presents the current work regarding material selection, sample fabrication methods and test methods to evaluate viscoelastic, fracture and healing properties of FAM mixtures.

Key Words: Fine Aggregate Matrix, Viscoelastic, Fatigue, Creep, Healing. SST, Complex Shear modulus

Highlights:

- Review focuses on characterisation of FAM mixtures.
- An overview of FAM sample fabrication methods is presented.
- Discussed fundamental assessment of viscoelastic, fatigue and healing properties.
- FAM sample test using DSR is an innovative technique for assessment of asphalt mixtures.
- Complex shear modulus and dynamic modulus of FAM and full asphalt mixtures.

1. Introduction

Fatigue damage is one of the major distresses in the flexible pavement during its service life due to repeated application of traffic loading. Laboratory tests have revealed that the pavement not only experience the fatigue damage during traffic loading but also have the capacity to recover from this damage during no traffic loads [1]. Fatigue life is defined as number of loading cycles to failure. Researchers have evaluated the fatigue life at 50% loss in initial stiffness [2,3]. Many studies have been carried out to characterise the fatigue damage distresses in order to know the factors that influences the fatigue resistance of HMA (full asphalt mixture). In addition, there are many different methods to measure and quantify fatigue cracking resistance of full asphalt mixtures [4,5,6,7,8]. Typically these mixtures are made up of binder, coarse aggregates, fine aggregates, fillers and air voids. Further, these mixtures compose of four different phases such as asphalt binder, mastic (binder and filler), FAM mixtures excluding coarse aggregates and HMA mixtures including coarse aggregates [9]. Fracture and healing performance of asphalt mixtures have been evaluated in laboratory by considering field conditions. Currently, fracture and healing performance of asphalt mixtures are being evaluated in the laboratory using, triaxial test, Semi-Circular Bend test(SCB) [50]. The characterisation of these asphalt mixtures is difficult and complex as these mixtures consumes lot of materials, expensive and time consuming. To overcome this, researchers proposed a new test method to characterise the FAM mixtures. This is only because of researchers found that fatigue cracks grow within the mortar or Fine Aggregate Matrix (FAM) of the asphalt mixture.

FAM mixtures composes of asphalt binder, fine aggregates lesser than the 4.75mm sieve sizes, filler less than 0.075mm sieve size and air voids excluding coarse aggregates. This term was initially coined by Kim et al. [10] in his studies with sand asphalt mixtures. FAM mixture represents the fine portion of full asphalt mixture is suited to evaluate the different material factors as an indicator for the fatigue resistance of asphalt mixtures. The advantage of using FAM mixtures is that it provides a very convenient technique to examine the influence of material related aspects i.e., binder type, additives and ageing on the fatigue, healing and moisture damage properties. The significance of characterising the FAM mixture is that most of the damage due to fatigue cracking is believed to be concentrated in this phase of the HMA. Recently the researchers used FAM samples to characterise the fatigue damage and healing properties of FAM mixtures [11,12]. FAM test has several benefits such as consistency, repeatability, reproducibility and simplicity in terms of sample preparation, testing and evaluation of fracture and healing properties of FAM mixtures using DSR.

HMA and FAM mixtures have different geometry, gradation, material type and requirement and testing procedures. However, FAM test has gained more attention by summary on the various test specifications used in conducting FAM test and its application is needed worldwide to characterise the fracture and healing properties of asphalt mixtures. Thus, this review will help researchers and practitioners in road construction industry to understand the importance of the test technique to assess both fracture and healing behaviour of FAM mixtures.

The main purpose of this review article was to present the current knowledge about the various test procedures adopted by different researchers to evaluate the fracture and healing 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 samples testing using DSR methodology turn out to be promising test method. This review article is divided into three major heads as shown in Fig. 1, which includes i) FAM Material Characterisation; ii) Sample Fabrication for FAM Mixtures; 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. FAM Material Characterisation

2.1 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. The studies also have been evaluated the FAM mixtures containing recycled asphalt pavement/shingles (RAP/RAS) [8,13,36]. 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 fracture properties [2,5]. There are different methods adopted by researchers to select and finalise the quantity of materials required to prepare FAM mixtures. The details of materials (aggregates and asphalt binders), aggregate gradation and air voids studied are explained in the following sections.

2.2 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 [14,15,16,17,18]. Freire et al. [19] 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) [1]. There are different gradations for 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 [4,5,20-27,51]. Dai and You and Aragao et al. [28,14] 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 shown in Figs. 2(a) and 2(b).

2.3 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. [10] by adopting a fixed value of 8 % of asphalt content, which represents an asphalt film thickness of 10 microns. Branco et al. [4,51] 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 et al. [55] adopted the same assumption presented by Kim et al. [10] and proposed calculations based on a film thickness of 12 microns. Later, Coutinho et al. [69] and Sousa et al. [29] 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 et al. [19,53] proposed a correction in the calculations presented by Coutinho et al. [69], 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 et al. [67,68] 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 1., the results of asphalt content for FAM mixtures using different methods are shown.

2.4 Air Void Content

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 [21] 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. [17] 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% [8,13]. 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 [4,19,37,51]. Karki et al. [31] 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. [31] 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 [9] 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.

3. Sample Fabrication for FAM Mixtures

FAM sample 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 samples, i) Superpave Gyratory Compaction (SGC) and cutting samples out of a larger cylindrical sample, ii) sample preparation using direct compaction method.

3.1 Superpave Gyratory Compactor Method

FAM samples have been fabricated using Superpave Gyratory Compactor (SGC) [21]. 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 [2,19,25,29,31] and 150mm [6-9,26,30-33], 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. [15] used the MAS 0.6mm for his FAM study. There are many authors used 1.18mm as MAS for preparing the FAM samples [2,5-7,19,23,25,26,29,30,31,32,34, 35,36,37,52]. Few authors have used the 2.36mm as MAS for the preparation of FAM samples Zhu et al. [8], Underwood et al. [9,33] and only one author used MAS 4mm and 2mm for preparation of FAM samples [19]. 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. Fig 3 [13] represents the procedure for preparation of 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. [38] and ii) 50x10x10mm Li et al. [39] and from mould of diameter 150mm, the rectangular sample of size 50x12x10mm Reinke et al. [40] 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. Fig 4 [40] represents the procedure for preparation of rectangular FAM samples.

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.

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 has been 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 [41]. There are two different methods of FAM sample preparation.

FAM samples are prepared by using direct compaction method is used by many researchers. Researchers 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 Fig 5(a) [7]. Authors selected the maximum aggregate size of aggregates from 0.6mm [16] to 1.18mm [14,27,42,43,60] 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 Fig 5(b) [41,44].

4.0 Viscoelastic Properties of FAM Mixtures

4.1 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 [14,20,27,42]. Motamed et al. [45] 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 [46]. Kim et al. [41] 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. [8] 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% [5,6] by conducting the strain sweep test. Caro et al. [7] 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. [36] 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. [47] 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. [23] 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 [39] 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. [9,59] 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 [44] was 0.01%

strain. This strain level was recommended by ASTM D 7552 [48], they consider directly this strain level as LVE limit for further tests.

4.2 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 [23]. 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 [42]. 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 [10]. 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 [37]. Masad et al. [23] 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 [2]. 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.

5. Performance Evaluation of FAM Mixtures.

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 characterised 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 different damage levels in the FAM samples as final damage generated within the FAM mixtures at the end of the cyclic loading test.

5.1.1 Time Sweep Test

In order to evaluate fatigue cracking potential of FAM mixture, time sweep test is 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) [1,41]. 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 [42,57]. 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. [45] 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 they have given to find the fatigue failure of FAM samples. To understand the fatigue damage in the FAM mixture, [10] 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 [3] 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. [1] 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 [10], 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 5minutes) rest periods introduced intermittently at decreasing order of stiffness levels [32]. Karki et al. [35] 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. [8] and Caro et al. [5-7] 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 [36]. They conducted the time sweep test with 0.09% as strain value about 4 hours to induce the fatigue failure in the FAM mixtures samples. The time sweep can be conducted in both stress controlled and strain controlled mode [19,53]. 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. [47] 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. [29] used the high strain level 0.35% to characterise the fatigue failure of FAM samples. Sadeq et al. [2] 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. [39] 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 [14]. 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 [27,54]. 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.

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, Fig. 7 [14] presents the failure criterion determined by the transition point.

5.2 Healing Properties of FAM Mixtures

Healing properties 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 FAM materials. To investigate the healing 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 healing of FAM mixtures is more when rest periods introduce at lower level of damage than higher level of damage [18,32,35]. 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.

5.2.1 Creep and Recovery Test

Creep and 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 [42]. 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 30sec and recovery time of 300sec given for conducting the creep and recovery test at different stress levels 15 kPa, 25 kPa, 50 kPa and 75 kPa [42]. From this study, they found out the irrecoverable strain of the FAM mixtures at the end of 300sec. This test can also be carried out using different strain levels [3]. Bhasin et al. [34] used the 4minutes rest periods for nine times while conducting the fatigue test on the FAM samples. Each 4mins 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. [45,56] 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 3sec and recovery time of 300sec. Creep loading is limited only upto strain reaches 0.035%. This indicates the material's response most likely within the viscoelastic limit.

Smith and Hesp [3] 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 50mm long, 6mm thick and 10mm wide of FAM samples, then rest period of 18hrs provided for recovery in FAM mixture stiffness. From this test, they determined the percent recovery in fatigue life of FAM samples over 18 hours rest period. Controlled shear strain cyclic test conducted on rectangular bar FAM samples of size 60mm long, 6mm thick and 12mm wide. Rest periods are used in this study 1, 2, 1 and 4mins 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 microdamage healing. Palvadi et al. [25,58] and Karki et al. [35] 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. 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 30sec followed by 500sec recovery time applied on the FAM samples [37].

An ideal trend for pseudo stiffness versus the number of cycles before and after a rest period is shown in Fig 6 [41]. In Fig 6, 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.

5. 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 [61-66], the instrument Superpave Shear Tester (SST) (Fig. 8a) is used for finding the complex shear modulus of full asphalt mixture as per ASTM D 7312 [49]. While, complex shear modulus (G*) of FAM mixture is determined using DSR (Fig. 8b) in laboratory which is defined by the ratio of shear stress to shear strain. In recent years, researchers [2,6,8,14,45] are being used the DSR to find the complex shear modulus of FAM mixtures as per ASTM D 7552 [48]. 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 3, 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 $2.5\text{x}10^8$ Pa to $2.96\text{x}10^9$ Pa and are not similar. However, G* as determined by using DSR at a strain of 0.01 % as per ASTM D7552[48] produces results comparable to those obtained on the Superpave Shear Tester (SST) performing the Frequency Sweep at Constant Height with other similar test conditions. 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 [9]. This correspondence between the FAM and full asphalt mixture properties was also observed for the moisture characterization and fatigue cracking and permanent deformation characterisation [5,45,56,69,57,27,54,37]. Motamed et al. [45,56] 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.

6. Summary

The utilisation of smaller FAM samples rather than the HMA samples to assess fracture and healing performance of FAM mixtures in road construction industries is gaining more popularity worldwide due to its simplicity and rational approach. This review article presents utilization of test conducted on FAM mixtures to evaluate fracture and healing properties. However, several studies are available in the domain of fracture and healing characterisation of FAM 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 4.75mm, 2.36mm, 2mm, 1.18mm and 0.6mm was adopted. Further, selection of asphalt content was based on aggregate surface area method. In addition, varying air voids of 1.5% [18] to 15% [45] 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. The second part of this review focused on the sample fabrication methods for FAM mixtures. In this section, review has concentrated on studies carried out using different methods in preparing the FAM samples. The characterisation of fracture and healing properties of FAM mixtures was done usually using DSR by adopting rectangular and cylindrical samples with different dimensions.

The major part of the review focused on the tests carried out in characterisation of fracture and healing 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 fracture 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 and maximum phase angle of the FAM mixtures. Then the healing 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. 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 fracture and healing properties.

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