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Synergistic influence of aging and moisture on performance of warm mix asphalt

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Abstract

In this study, the influence of aging and moisture on the two different mechanical behaviors of warm mix asphalt was studied. The cracking and permanent deformation resistance were assessed in terms of tensile strength and flow number computed using a three stage model respectively. The influence of temperature on the tensile strength and both stress and temperature levels on the permanent deformation response of aged and moisture conditioned warm mix asphalt were investigated. Results show that moisture and increase in temperature had a negative impact on the tensile strength of warm mix asphalt while aging had a positive impact. However, the variation in tensile strength of mixtures was strongly related to variation in percent air voids. Aging and interestingly moisture conditioning found to increase the resistance to permanent deformation of warm mix asphalt. Permanent deformation behavior of moisture conditioned samples was further studied to assess the impact of saturation. Results showed that the presence of moisture in samples increase the permanent deformation resistance. From the statistical analysis it was found that both the individual and interaction of aging and moisture had a significant effect on the tensile strength and flow numbers.

Keywords: Aging; Moisture damage; Tensile strength; Permanent deformation; Flow number

1. Introduction

Warm mix asphalt (WMA) technology was developed by the asphalt paving industry to address the issue of greenhouse gas emission from the manufacturing sector highlighted in the Kyoto Protocol [1–3]. The main objective of the technology is to produce asphalt mixture with a temperature reduction of at least 30 °C [4] when compared to hot mix asphalt (HMA). Among various benefits associated with warm mix asphalt, the key advantages over HMA include construction in cool weather, longer hauling distance, better compaction with stiffer mixtures and reduced thermal cracking along with cost and risk reduction [5,6]. Despite the benefits associated with temperature reduction, risk of moisture damage and decrease in resistance to permanent deformation due to reduced binder aging is a major concern [7–10].

The resistance to permanent deformation of the asphalt mixture is greatly influenced by moisture and aging [8,10–14]. The moisture damage in asphalt mixture results in an adhesive or cohesive failure or a combination of both [15]. The extent of moisture damage is influenced by the temperature, type of aggregate and binder used, viscosity and asphalt film thickness [16]. Studies have reported a reduction in strength of asphalt mixtures due to moisture damage with various WMA additives [7,10,14]. Another factor influencing the performance of asphalt mixture is aging. The reduction in production temperature for

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WMA leads to a decrease in the extent of hardening of the asphalt binder during production and in-service [7–9,17]. However, long-term aging offsets the initial variation from short-term aging [18,19]. Hence, it is believed that the reduction in stiffness and probable moisture retention in WMA when compared to conventional HMA mixture increases the potential of permanent deformation and moisture damage with the use of WMA technology during the initial service life [7–9]. Furthermore, a strong interlink between aging and moisture damage on the performance of asphalt mixture [20–22] highlights the importance of including aging and moisture for evaluation of WMA performance. Therefore, a clear understanding of moisture damage and aging influence on tensile characteristics and permanent deformation behavior is critical.

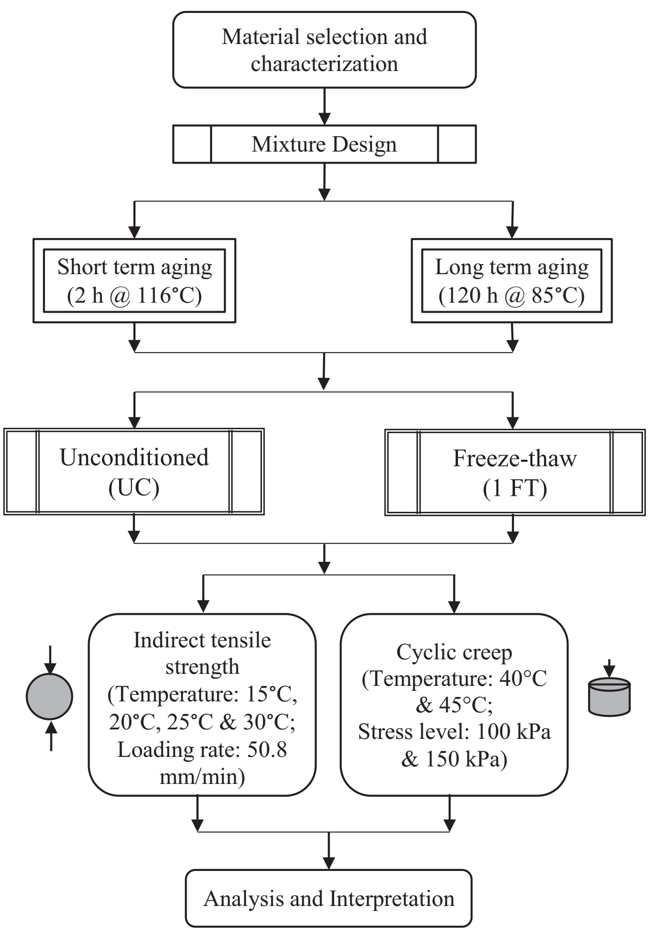

Fig. 1. Research methodology.

The additives used with virgin binder greatly influence the field performance of the asphalt mixture [23]. Comparative laboratory studies of HMA and WMA mixtures have shown increased moisture susceptibility and permanent deformation with use of WMA technology [7,24–26]. However, field assessment in terms of rutting and moisture susceptibility has shown performance of WMA technology comparable to HMA [24,27–31]. Hence, the mixed observations need to be evaluated and studied in greater detail.

In this regard, the performance of one of the most commonly used WMA technologies, i.e., using chemical additive [32], is assessed in terms of tensile strength, moisture susceptibility and permanent deformation for different levels of aging and moisture damage. Further, the synergistic influence of aging, moisture, testing temperature and stress levels on permanent deformation are analyzed to differentiate the critical factor using a three-stage permanent deformation model.

2. Experimental methodology

The methodology adopted to fulfill the objective of the study is shown in Fig. 1. Asphalt mixture design as per Marshall method of mix design was performed and optimum asphalt content was evaluated. Subsequently, the samples were aged and moisture conditioned as per recently modified NCHRP 815 [33] and ASTM 4867 [34] guidelines respectively.

The conditioning process was followed by indirect tensile strength (ITS) test and uniaxial cyclic compression (UCC) test. ITS test was conducted at four temperatures (15 °C, 20 °C, 25 °C and 30 °C) to study the influence of moisture susceptibility at various temperatures. Then, UCC test was conducted with four combinations including two test temperatures (40 °C & 45 °C) and two stress levels (100 kPa & 150 kPa) to evaluate the effect of environmental and loading conditions on permanent deformation behavior. A brief summary of experimental matrix used for the study is shown in Table 1. Three replicates were used to assess the behavior for each combination.

Finally, Zhou's three-stage model was used for predicting the gradient of secondary stage and flow number of asphalt mixture. Additionally, the permanent deformation behavior for moisture conditioned samples was studied to assess the damping effect due to presence of moisture in voids by drying the samples using CoreDry. The tensile strength and flow number values obtained were statistically analyzed to differentiate the influence of test conditions on the behavior of warm mix asphalt.

Table 1
Experimental matrix of the study.

Test	Aging	Moisture conditioning	Temperature	Loading condition	Total combination
ITS	STA, LTA	UC, FT	15 °C, 20 °C, 25 °C, 30 °C	50.8 mm/min	16
UCC	STA, LTA	UC, FT	40 °C, 45 °C	100 kPa, 150 kPa	16

3. Materials

3.1. Aggregates

Crushed stone aggregates were used in the study for producing asphalt mixtures. The aggregate gradation and physical properties of aggregates are shown in Fig. 2 and Table 2 respectively.

3.2 Asphalt and additive

The asphalt mixtures tested in this study were produced using a virgin viscosity grade VG-30 asphalt along with warm additive Evotherm-J1. Evotherm-J1 is a chemical additive that helps in reducing the production temperature by reducing the surface tension between polar aggregates and non-polar asphalt at least by 30 °C. In this study,

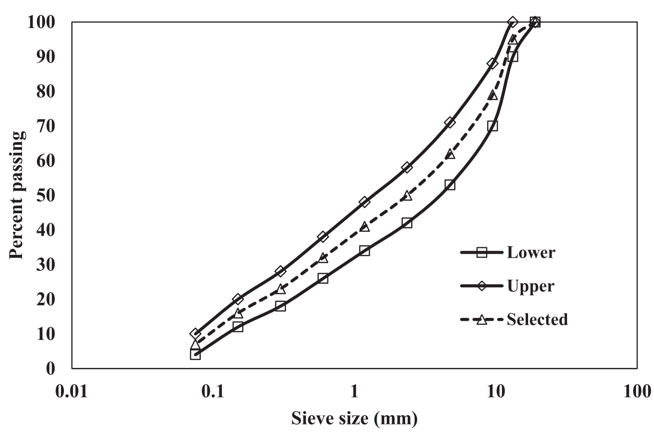

Fig. 2. Aggregate gradation adopted.

Table 2
Physical properties of aggregates as per MoRT&H-2013 [35].

Property	Test	Results	Specification limits
Cleanliness	Grain size analysis	1.18	Max. 5% passing 0.075 mm sieve
Particle shape	Combined flakiness and elongation index	29.4	Max. 35%
	Angularity number	4	–
Strength	Aggregate impact value	20	Max. 24%
Water absorption	Water absorption	0.87	Max. 2%

Table 3
Physical properties of asphalt as per IS: 73-2013 [36].

Characteristics	VG-30 with Evotherm-J1	Specification Limits
High-temperature PG*	PG 64-xx	
Specific Gravity	1.03	
Penetration at 25 °C, 100 g, 5 s, 0.1 mm	52	min 45
Kinematic viscosity at 135 °C, cSt	504	min 350
Softening point, °C	50	min 47
Ductility at 25 °C on residue from RTFO test, cm	92	min 40

* Specification as per ASTM D6373 [37].

Evotherm-J1 was added at a rate of 0.4% to the weight of the asphalt and the mixing and compaction temperatures adopted were 130 ± 3 °C and 116 ± 3 °C respectively based on the manufacturer's recommendation. The physical properties of the asphalt with addition of warm mix additive used in this study are provided in Table 3.

4. Experimental methods

4.1. Mixture design

The asphalt mixtures were designed for HMA mixtures using Marshall method as per Asphalt Institute MS-2. The design graphs are shown in Fig. 3 where the narrow range of 5.35–5.85% asphalt content is found to satisfy the MoRT&H criteria. Hence, as per MoRT&H specification the minimum asphalt content requirement of 5.4% [35] was selected as optimum asphalt content (OAC) and the same OAC was used for producing WMA mixture. The properties of the design mixture at OAC for WMA are presented in Table 4 where the ratio of air voids of WMA to HMA is also evaluated along with Marshall parameters as specified by IRC: SP: 101-2014 [4] to assess compactability.

4.2. Aging

Aging of the samples was conducted as per NCHRP 815 recommendations to AASHTO R30 protocols [33]. Two levels of aging were carried out in the study. Firstly the short term aging (STA) and secondly the long term aging (LTA). STA allows binder absorption and represents the plant-mixing effects on the asphalt mixture whereas LTA simulates the aging during the first 1–3 years of service life [33]. For STA, loose mixtures were prepared and kept in a forced draft oven for 2 h ± 5 min at 116 ± 3 °C. The mixtures were stirred after 60 ± 5 min to maintain uniform conditioning. The conditioned mixtures were produced at 7 ± 1% air void content for mechanical testing. For LTA, the STA compacted samples were kept in the oven for 120 ± 0.5 h at a temperature of 85 ± 3 °C.

4.3. Moisture conditioning

Aged asphalt mixtures were subjected to moisture conditioning as per ASTM D4867 [34]. The specimens were saturated using partial vacuum in order to achieve a degree of saturation of 70–80%. However, in case the saturation is not achieved in 10 min, the water was heated to 40 °C and the same level of partial vacuum was applied to get the desired degree of saturation. Then, the specimens were sealed and kept in a deep freezer at a temperature of −18 ± 2 °C for at least 15 h and then transferred to a water bath at 60 ± 1 °C for 24 h. This process is termed as 1 freeze-thaw cycle (1 FT) in this work. After the completion of the conditioning process, the specimens were tested for specific tensile and permanent deformation characteristics.

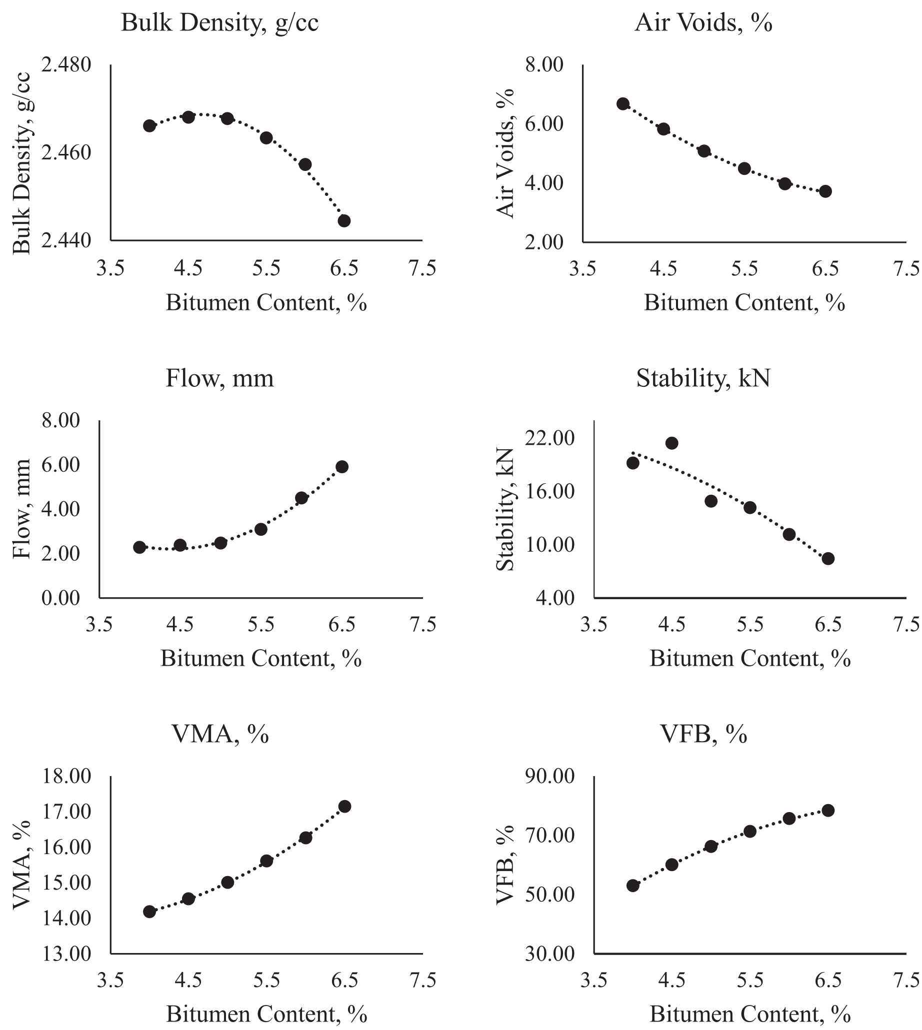

Fig. 3. Design graphs for OAC determination.

Table 4
Marshall Parameters and Volumetric Properties as per MoRT&H [35].

Properties	Results	Specifications
Optimum Asphalt Content (OAC), %	5.4	Min. 5.4
Marshall Stability, kN	11.88	Min. 9
Flow Value, mm	3.55	2–4
Air Voids, %	3.82	3–5
Voids in Mineral Aggregate, %	13.87	Min. 12
Voids Filled with Asphalt, %	72.49	65–75
Marshall Quotient	3.35	2–5
Ratio of air voids*	1.01	0.9–1.1

* Specification as per IRC: SP: 101-2014 [4].

4.4. Indirect tensile strength

The influence of aging and moisture conditioning on the tensile characteristics of the WMA was evaluated using ITS test as per ASTM D6931 [38] protocol. For performing the ITS test, the STA and LTA samples are divided into two subsets as unconditioned (UC) and conditioned (1 FT). Subsequently, the samples were kept in a water bath at test temperature for 2 h. The test temperature has a significant influence on the tensile characteristics with the inflection point for tensile strength and tensile strain being observed at 15 °C [39]. Hence, test temperature of 15 °C, 20 °C, 25 °C and 30 °C considering the standard protocol [38] and local climatic conditions [40] were selected for the study to assess the tensile strength variation with temperature along with the influence of aging and moisture conditioning protocol.

For performing the ITS test, STA and LTA samples were loaded at a rate of 50 mm/min across its vertical diametric plane until the sample fails. The peak load at which the sample fails is determined and tensile strength is calculated using Eq. (1) as shown below.

$$S_t = \frac{2000P}{\pi d t} \tag{1}$$

For assessing the moisture susceptibility, tensile strength ratio (TSR) is calculated by determining the ratio of ITS for conditioned and dry samples as given in Eq. (2).

$$TSR(\%) = \frac{S_{tc}}{S_{tu}} \times 100 \tag{2}$$

where S_t is the tensile Strength (kPa), P is the peak load (N), d and t are the diameter and thickness of the sample respectively and S_{tc},S_{tu} are the tensile strength (kPa) of conditioned and unconditioned samples respectively.

4.5. Uniaxial cyclic compression test

To assess the permanent deformation behavior of asphalt mixture, uniaxial cyclic compression test is found to be representative of field conditions [41,42]. A square waveform is preferred for uniaxial cyclic compression (UCC) test as the loading applied for haversine waveform does not allow the asphalt mixture to undergo constant loading [42]. For UCC test, Marshall samples with 101.4 ± 3 mm diameter and 63.5 ± 3 mm height were prepared and subjected to aging and moisture conditioning as per aforementioned procedure. The samples were then preconditioned in an environmental chamber at test temperature ±0.5 °C for 5 ± 0.5 h before testing. The testing protocol as per BS DD 226: 1996 [43] includes preloading the samples with a static stress of 10 ± 1 kPa for 600 s ± 6 s followed by a holding load of 2 kPa for 20 s ± 0.5 s. Then, the specimens were subjected to the test stress level till 10,000 cycles or until specimen fails. The specimen is considered to be failed when the deformation is more than 10 mm (LVDT range) or an angle of more than 5° is made between the loading surface of the platens. Square pulse waveform at a frequency of 0.5 Hz was applied with a loading and rest period of 1 sec each. The test was conducted at 2 different temperatures (40 and 45 °C) and 2 stress levels (100 and 150 kPa) to evaluate the influence of environmental conditions and loading pattern on the behavior of asphalt mixtures. The temperature of 40 °C was selected as per British standard [44] recommendation and an increased temperature of 45 °C was chosen to represent higher pavement temperature [45]. The design stress level for unconfined test ranges between 69 and 207 kPa [44], where the stress level of 100 kPa and 150 kPa for a specimen of diameter 96 mm corresponds to an axial load of $(724 \pm 14) \times 10^{-3}$ kN and $(1086 \pm 21) \times 10^{-3}$ kN respectively [43]. A typical value of 100 kPa was selected for the study as per BS DD 226 [41] recommendation whereas the increased stress level of 150 kPa was chosen to mimic the higher loading conditions. The axial strain at the end of rest period immediately after application of load was determined using the relation in Eq. (3).

$$\varepsilon_{d(n,T)} = \frac{\Delta h}{h_0} \tag{3}$$

where $\varepsilon_{d(n,T)}$ is the axial strain at T (°C) temperature after n load applications, Δh is the axial deformation and h_0 is the initial height of the sample after preloading.

4.6. Permanent deformation model

The typical illustration of permanent deformation behavior in asphalt mixture is shown in Fig. 4. Typically,

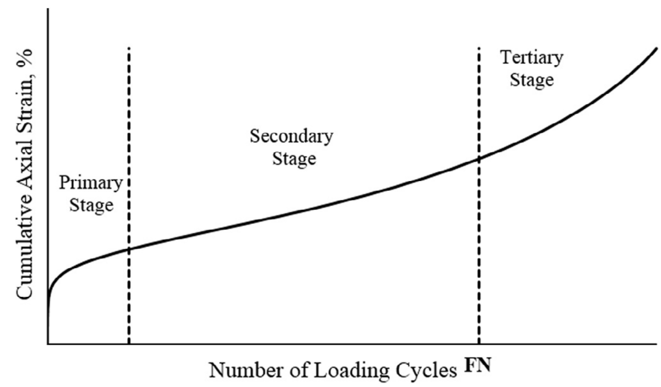

Fig. 4. Different stages of permanent deformation.

the curve for cumulative axial strain obtained from uniaxial cyclic creep test shows three stages viz., primary, secondary and tertiary stage [46,47]. Primary stage involves a rapid accumulation of permanent strain which tends to decrease with subsequent loading cycles reaching a constant rate. The initiation of the constant rate of permanent strain accumulation is termed as secondary stage. Further, as the cracks propagate, the strain rate begins to exponentially increase with loading cycle, marking the onset of tertiary stage [48]. Hence, to predict these three stages of permanent deformation, a composite model is proposed in which a power law, linear and an exponential model is recommended for the primary, secondary and tertiary stage respectively [47] as shown in Eqs. (4), (5) and (6) respectively.

$$\text{Primary stage}: \varepsilon_p = aN^b; \quad N < N_{PS} \tag{4}$$

$$\text{Secondary stage}: \varepsilon_p = \varepsilon_{PS} + c(N - N_{PS}); \quad N_{PS} \leq N < N_{ST} \tag{5}$$

$$\text{Tertiary stage}: \varepsilon_p = \varepsilon_{ST} + d(e^{f(N-N_{ST})} - 1); \quad N \geq N_{ST} \tag{6}$$

where N_{PS}, N_{ST} are data cycle corresponding to initiation and end of secondary stage respectively, ε_{PS}, ε_{ST} are cumulative permanent axial strain (%) corresponding to initiation and end of secondary stage respectively and a,b,c,d,f are regression parameters.

Model parameters a and b represents the intercept and slope of the linear portion in the primary stage indicating the initial deformation and strain rate respectively. The rate of permanent deformation of the secondary stage is specified by parameter c whereas d and f denotes the intercept and slope of the exponential part of tertiary stage.

The initiation of shear deformation, marked by the onset of the tertiary stage, termed as flow number (FN), along with gradient of secondary stage has been used to analyze the resistance to permanent deformation of the asphalt mixture. Studies on permanent deformation show that FN evaluated from Zhou's model is able to predict and mimic the permanent deformation behavior of the asphalt mixture [49,50].

4.7. Analysis of moisture effect

The permanent deformation behavior of samples subjected to freeze-thaw cycles were analyzed for determining the effect of damping due to the presence of moisture in the sample as mentioned by Mehrara & Khodaii 2011 [51]. For the study, two sets of samples (with and without moisture) were evaluated with three replicates tested for each set. Both the sets were subjected to one freeze-thaw cycle. In the second set of samples moisture was taken out using CoreDry which utilizes high vacuum technology for drying the samples. Then, uniaxial cyclic compression test was conducted on the samples and the damping effect is determined by comparison of flow number computed using three-stage permanent deformation model.

5. Results and discussions

5.1. Indirect tensile strength

The influence of moisture, aging and temperature on the tensile strength of WMA mixtures were studied by carrying out ITS test. The results for tensile strength at 15 °C and 20 °C with same materials and protocols have been reported in author's earlier study [22]. The critical conditions and main effects on the tensile strength of WMA mixtures can be graphically analyzed from Fig. 5. In addition, Fig. 5 also presents the average percent air voids at each condition just above the respective data point. Moreover, the standard error (S.E.), calculated by dividing the standard deviation by square root of sample size, is also presented on the top-right corner of the respective graph. It can be noticed that the tensile strength increased with aging and reduced with increase in temperature as expected due to viscoelastic nature of asphalt mixtures. The tensile strength of WMA mixtures decreased substantially with moisture conditioning resulting in reduced cracking resistance of asphalt mixtures. Moreover, the rate of reduction in tensile strength with moisture and temperature was also found to be influenced by variation in percent air voids. Interestingly, for example in case of STA samples subjected to moisture conditioning, the tensile strength at 15 °C was lower than 20 °C. Such a trend could be possibly due to variation in the percent air voids as shown in the Fig. 5 as also noticed by other researchers [52].

Furthermore, the moisture susceptibility of WMA mixtures was evaluated using tensile strength ratio (TSR) for STA and LTA conditions at 15 °C, 20 °C, 25 °C and 30 °C as shown in Fig. 6. The impact of reduction in test temperature from 20 °C to 15 °C on the tensile strength ratio was found to be substantial in case of STA mixtures with 38% reduction whereas 15% reduction was noticed for LTA mixtures. This observation points out that the impact of test temperature on moisture damage is substantial at STA condition than LTA condition which negatively impacts the tensile characteristics of WMA mixtures. Since, studies have shown a good relation between retained stiffness (ratio of stiffness after and before conditioning process) and TSR, the probable reason for lower TSR reduction with increase in temperature could be higher retained stiffness for LTA samples in comparison to STA samples [53]. On the other hand, TSR values did not vary

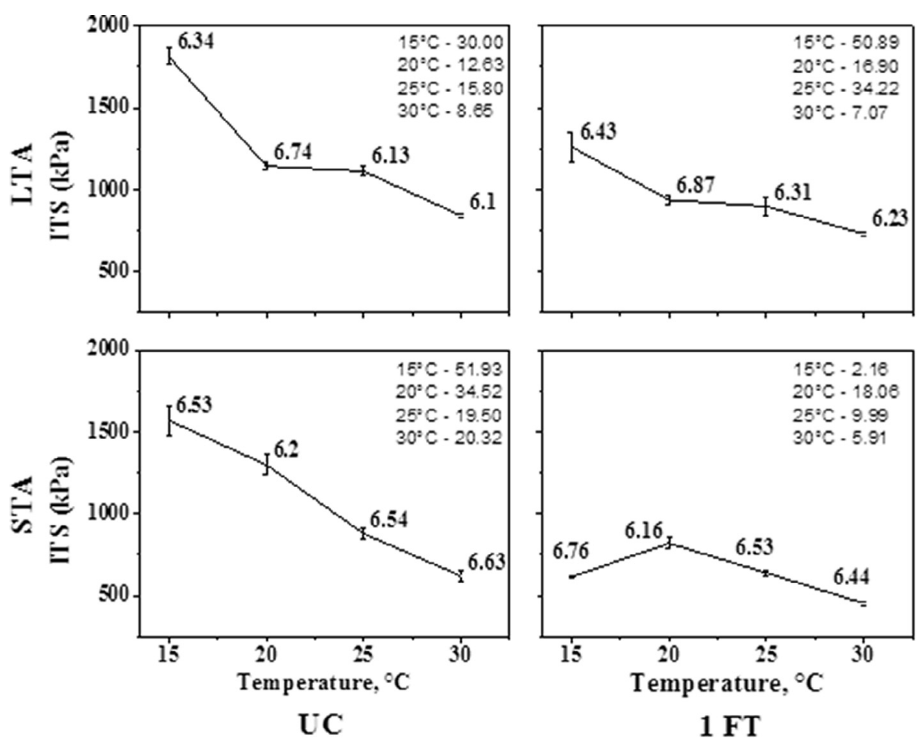

Fig. 5. Influence of test conditions on tensile strength.

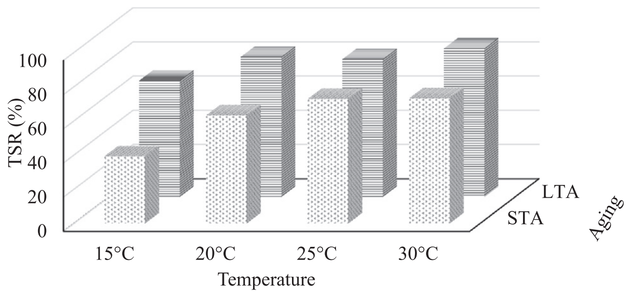

Fig. 6. Variation of TSR with aging and temperature.

from 20 °C to 30 °C for both STA and LTA mixtures. Interestingly the TSR values for LTA mixtures above 20 °C were only found to be higher than 80% acceptance criteria [35]. This shows the importance of interactive effect of aging, moisture conditioning and temperature on the tensile characteristics of WMA mixtures when used to assess the moisture susceptibility.

5.2. Uniaxial cyclic compression test

The mechanical responses of the WMA subjected to various aging and moisture conditions were investigated using UCC test at temperatures of 40 °C and 45 °C. Further, two stress levels of 100 kPa and 150 kPa were adopted. A typical representation of the trends obtained for permanent deformation of WMA mixtures at various test conditions is shown in Fig. 7. It can be noticed that both aging and moisture conditioning influenced the permanent deformation behavior of WMA mixtures. Further, to explore the main effects of aging, moisture and stress level, the resistance of asphalt mixtures to permanent deformation was evaluated in terms of gradient of secondary stage and flow number. Zhou's three-stage model [47] was selected for the prediction of permanent deformation behavior of WMA mixtures. It is important to note that lower gradient of secondary stage and higher flow number indicates higher resistance to permanent deformation [48]. The variation in flow number with aging and moisture conditioning and the interactive effect of temperature and stress levels are discussed in the subsequent sections.

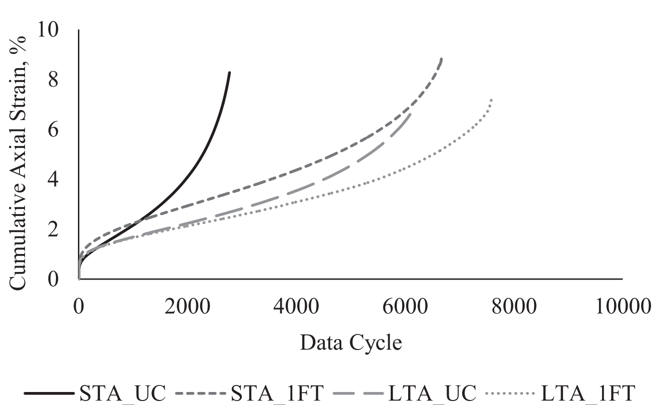

Fig. 7. Typical permanent deformation trends.

5.2.1. Main effects on flow number at 40 °C

The effect of aging, moisture and stress level on flow number at 40 °C is illustrated in Fig. 8 and Table 5. In addition, the average percent air voids are inset at each condition in Fig. 8. In general, it can be noticed that flow number increased with aging and flow number decreased with increase in stress level at both STA and LTA conditions as expected [54]. It is interesting to notice that with moisture conditioning the gradient of secondary stage decreased and the flow number increased at all levels of aging and stress indicating higher resistance to permanent deformation. The possible mechanics which could be contributing to such observation are increased hardening of binder with moisture conditioning [55] and due to dampening effect of moisture in the air voids to dynamic loading [51]. Thus it is believed that above mentioned reasons could contribute to increased stiffness [56] in the mixture which might result in increased resistance to permanent deformation [57]. In addition, it can be noticed that moisture conditioning had a higher effect on increase in flow number at STA condition than LTA condition. This shows that with aging the influence of moisture reduces on the permanent deformation behavior of WMA mixtures. Similar trends were observed with the gradient of secondary stage, further verifying the influence of environmental and loading conditions on WMA performance.

5.2.2. Main effects on flow number at 45 °C

The effect of aging, moisture and stress level on gradient of secondary stage and flow number at 45 °C is demonstrated in Fig. 9 and Table 5. Similar effects of aging, moisture and stress level on flow number as noticed at 40 °C (Fig. 8) were also noticed at 45 °C (Fig. 9). Nonetheless, it was interesting to notice that effect of moisture was more profound at 100 kPa stress level compared to 150 kPa stress level at 45 °C. The observation points that the effect of moisture diminishes with increase in temperature and stress level probably due to reduction in the mixture stiffness. Moreover, the difference in behavior noticed with aging at 100 kPa stress level can be probably attributed to the difference in air voids (shown on the top of the bars in Fig. 9) highlighting the profound impact of air voids on permanent deformation behavior.

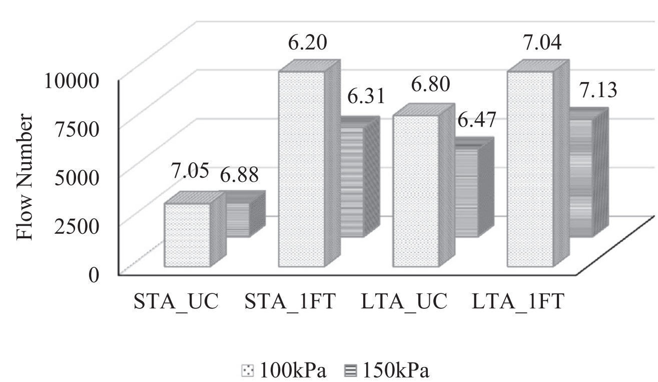

Fig. 8. Main effects on flow number at 40 °C.

Table 5
UCC test results.

Temperature	Stress	Aging	Moisture conditioning	Air voids	Gradient of secondary stage	Flow number	Std. error
40 °C	100 kPa	STA	UC	7.05	0.00072	3232	179.31
			1FT	6.20	0.00020	>10000	–
		LTA	UC	6.80	0.00025	7745	347.85
			1FT	7.04	0.00018	>10000	–
	150 kPa	STA	UC	6.88	0.00157	1750	4.62
			1FT	6.31	0.00077	5587	264.13
		LTA	UC	6.47	0.00062	4502	37.82
			1FT	7.13	0.00052	6021	133.66
45 °C	100 kPa	STA	UC	6.14	0.00100	3690	225.17
			1FT	6.05	0.00033	>10000	–
		LTA	UC	7.06	0.00062	2823	47.05
			1FT	6.75	0.00023	7835	435.90
	150 kPa	STA	UC	6.78	0.00380	1030	52.83
			1FT	6.29	0.00184	2089	84.22
		LTA	UC	6.97	0.00165	1608	92.09
			1FT	6.83	0.00117	2793	132.28

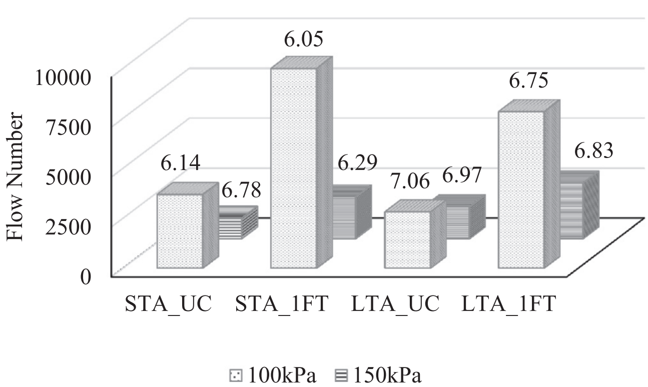

Fig. 9. Main effects on flow number at 45 °C.

5.2.3. Damping effect

Damping effect refers to the reduction in strain rate due to contribution of moisture present in the air voids of the sample toward energy dissipation [51]. The influence of moisture on the permanent deformation behavior is shown in Fig. 10 where 1 FT and 1 FT_Dry represents samples with and without presence of moisture respectively after being subjected to a freeze-thaw (1 FT) cycle. The results showed a reduction of 17.3% in FN values for the 1 FT_Dry samples when compared to the 1 FT samples. Since all other variables are kept constant, it is believed that the damping effect of moisture present in the sample resulted in the increased resistance to permanent deformation. This is due to the water pressure in the samples which acts as a damper and resists the rapid increase in the permanent deformation [51].

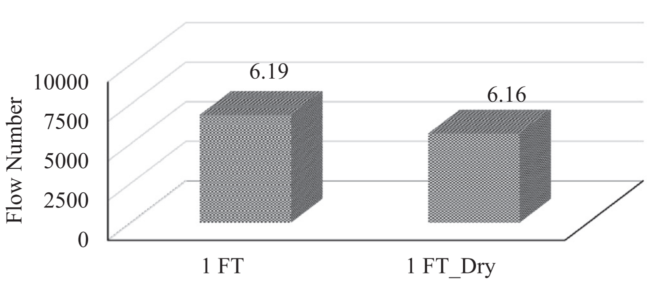

Fig. 10. Analysis of moisture effect.

5.3. Comparative analysis of experimental factors

This study investigated the impact of moisture and aging on the tensile and creep behavior of WMA mixtures using ITS and UCC tests respectively. The impact of the main factors can be graphically analyzed from Fig. 11. As expected, aging had a positive impact on both tensile and creep characteristics of WMA mixtures due to the increased stiffness with aging. Interestingly, studies have shown the mechanical properties of WMA comparable to HMA for aged samples [18,19]. Also, the tensile strength of HMA and WMA has been assessed in the previous work where moisture susceptibility was found to be similar for both WMA and HMA mixtures subjected to LTA [22]. However, the moisture effect was not straight forward as expected. For example, in case of tensile strength the moisture conditioning process had a negative effect whereas in case of creep behavior the moisture effect was not negative. Similar trends have been observed for moisture effect on tensile strength [8,22] and rutting resistance [51] of HMA mixtures. Further, studies have reported the moisture resistance of WMA to be satisfactory from both laboratory and

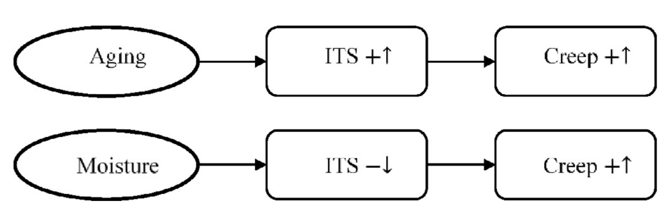

Fig. 11. Effect of aging and moisture on performance.

field investigations [29,30,58]. Hence, the potential cost benefit due to temperature reduction and comparable performance to HMA makes the WMA technology environmental friendly alternative to conventional HMA mixtures.

It is important to understand here that, the loading pattern and mixture behavior under tensile and creep is different. In an ITS test, the load is applied on a thin strip along the diameter of the sample. Under such loading conditions, in an asphalt mixture the predominant factor influencing the tensile characteristic would be the adhesive and (or) cohesive forces between aggregate minerals and asphalt. As noticed in this study such adhesive and (or) cohesive forces could weaken due to moisture ingress which would result in the formation of a weak plane along which the sample fails [59]. However, the load application in UCC test is on a plane, where the aggregate matrix and mixture stiffness induced by asphalt would be the predominant factors offering resistance to creep. Thus as noticed in this study, stiffness growth due to aging could be predominant than the moisture damage and hence the resistance to creep increased. It was also interesting to notice that moisture conditioning process adopted in this study did not negatively affect the creep resistance. The reasons as reported by various researchers and found in the study conducted include, damping effect of moisture in air voids and aging of asphalt mixture due to freeze-thaw cycles [51,54,56,57]. Furthermore, it was interesting to notice that in both tensile strength and creep resistance tests, the influence of moisture conditioning process reduced with aging.

5.4. Statistical analysis of main effects and interaction

5.4.1. Indirect tensile strength

The main effects of moisture, aging and temperature and the interaction effects on the tensile strength of WMA mixtures were statistically analyzed using Univariate ANOVA at a significance level of 5%. The summary of ANOVA results is presented in Table 6. The results from Table 6 indicate that the main effects and two-way interactions are significant with p-value less than 0.001. The results in the Table 6 also indicate that both moisture and temperature had higher influence on tensile strength when compared to aging. Furthermore, it is interesting to notice that the interaction of aging, moisture and temperature on tensile strength was also significant highlighting the importance of assessing synergistic influence of test parameters on moisture susceptibility of WMA mixtures.

Table 6
ANOVA for tensile strength results.

Source	F	p-value	Significant
Main effects			
A	360.362	5.58E−19	Yes
M	900.007	5.31E−25	Yes
T	512.750	4.05E−27	Yes
Two-way interaction			
A × M	60.373	7.34E−09	Yes
A × T	60.884	2.55E−13	Yes
M × T	124.302	1.03E−17	Yes
Three-way interaction			
A × M × T	13.771	6.15E−06	Yes

Note: A: Aging; M: Moisture; T: Temperature.

Table 7
ANOVA for flow number results.

Source	F	p-value	Significant
Main effects			
A	67.91	2.05 × E−09	Yes
M	1499.00	1.87 × E−28	Yes
S	1721.00	2.14 × E−29	Yes
T	552.60	9.32 × E−22	Yes
Two-way interaction			
A × M	122.90	1.72 × E−12	Yes
A × S	17.10	2.37 × E−04	Yes
A × T	171.30	2.14 × E−14	Yes
M × S	311.80	4.64 × E−18	Yes
M × T	1.26	2.68 × E−01	No
S × T	26.44	1.31 × E−05	Yes
Three-way interaction			
A × M × S	25.10	1.91 × E−05	Yes
A × M × T	61.40	6.06 × E−09	Yes
A × S × T	61.00	6.47 × E−09	Yes
M × S × T	56.10	1.56 × E−08	Yes
Four-way interaction			
A × M × S × T	1.14	2.93 × E−01	No

Note: A: Aging; M: Moisture; S: Stress; T: Temperature.

5.4.2. Permanent deformation

The results of flow number obtained from uniaxial cyclic compression test by the Zhou's three stage model were statistically analyzed using Univariate ANOVA. The ANOVA results at a confidence level of 95% are given in Table 7. Both main effects and the interactions of test parameters had significant effect on the permanent deformation characteristics of asphalt mixtures. In addition, the effect of moisture and stress level was found to be more profound in comparison to aging and test temperature. However, the synergistic influence of test parameters on permanent deformation was not significant. Hence, the interactive effect of moisture, aging, temperature and stress level should be critically analyzed to assess permanent deformation behavior of WMA mixtures.

6. Conclusions

In this study, the influence of aging and moisture on the two different mechanical behavior of warm mix asphalt mixture using chemical additive was studied. Further in this study, aging was simulated with different protocol than conventional approach to account for reduced production temperature in case of warm mix asphalt. The cracking resistance was assessed in terms of tensile strength and the permanent deformation resistance in terms of flow number. From the test results of experimental factorial considered in this study, the following conclusions are drawn.

1. The main and interactive effect of moisture, aging and temperature significantly influenced the tensile strength of warm mix asphalt mixtures. Hence, the synergistic influence of moisture, aging and temperature should be considered in the assessment of tensile strength. Also, the variation in tensile strength of mixtures was strongly related to variation in percent air voids.
2. Aging and interestingly moisture conditioning process adopted in this study was found to increase the resistance to permanent deformation of warm mix asphalt mixtures. However, the assessment of moisture damage effect on flow number was found to be strongly influenced by the aging and stress levels.
3. The presence of moisture in the air voids was found to increase the resistance of asphalt mixtures to permanent deformation. Thus it would be appropriate to test the asphalt mixtures after removing water to minimize the impact on the mechanical behavior and associated variability.
4. Statistical analysis indicated that moisture and stress level predominantly influenced the flow number of warm mix asphalt mixtures. Nevertheless, synergistic influence of aging, moisture, temperature and stress levels was vital in assessing the permanent deformation of asphalt mixture.

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Declarations of interest

None.

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