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Laboratory Study of Aging Characteristics of Binder Warm Mix Asphalt Chemical Additive: Rutting, Fatigue Resistance, and Chemical Composition

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ABSTRACT

This paper studied Warm Mix Chemical Additives (WMCA) aging behaviors. The three asphalt binders [base asphalt (neat), binder WMCA ZycoTherm (ZYC), and binder WMCA Evotherm M1 (EVM)] were treated with a short-term aging (STA) and long-term aging (LTA). The rheological rutting resistance factor (G*/sin δ) and linear amplitude sweep (LAS) by Dynamic Shear Rheometer (DSR) tests were conducted on all samples to test the indexes of rheological properties, in addition to chemical compositional changes were monitored by the Flame Ionization Detector (TLC-FID) to identify saturates, aromatics, resins, and asphaltenes (SARA). The results show that the value of the complex modulus rutting factor (G*/sin δ) and fatigue behavior of all asphalt binders increases with aging severity. Additionally, after LTA, the values of the Traffic volume indicator (N_f) at 15% share strain of base asphalt gradually decrease, while those of ZYC 0.07 and EVM 0.75 increase. After LTA, the rutting resistance of the ZYC improves while EVM deteriorates. EVM's rutting factor index degrades with aging, but its fatigue aging index improves. In addition, aging has greater effects than that of neat. The SARA change is due to adding WMCA to the binder. Saturates increases after aging. Aging affects the relationship between SARA fractions. The slope in the SARA chemical structure changes because of aging based on coefficient determination (R^2). Aging influences the stability of Neat and binder WMCA. Moreover, after LTA some binder WCMA changes become stable. Based on the aging performance, binder WMCA demonstrated significant improvements has excellent resistance to temperature, and ideal choice for long-term applications.

1. Introduction

Hot Mix Asphalt (HMA) is widely used for roads and is a popular choice due to its durability and ability to resist erosion and extreme weather conditions. The production of HMA requires large amounts of fuel, which further contributes to climate change and also harms the environment. As a result of this environmental impact, Warm Mix Asphalt (WMA) is becoming more popular [1] due to

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reduced production temperatures, which can lead to financial benefits. WMA reduces aggregate heating, mixing, and compaction temperatures by 20–40 °C compared to HMA. Several studies have found that WMA is sustainable and environmentally friendly and produces less carbon emissions [2-6]. In the future, warm mix asphalt (WMA) will continue to grow in demand, offering an eco-friendlier option than traditional hot mix asphalt.

A chemical, an organic, and a foaming technique have all been developed to achieve WMA. During the mixing and compaction, the binders are subjected to aging. Aging causes changes to asphalt's rheological, chemical, and physical characteristics. As asphalt ages, it loses elasticity, prone to cracking and rutting. Additionally, it becomes less adhesive, leading to higher permeability and reduced moisture resistance [7]. There are two types of mechanisms involved in bitumen aging. The primary mechanism of aging is irreversible, affecting the binder's rheological properties due to chemical changes. The processes that contribute to aging are oxidation [8], volatilization [9,10], and exudation (oil from bitumen migrates into aggregates) [11,12]. Second, there is a mechanism that involves reversible physical hardening. A physical hardening process may occur through molecular restructuring, where bitumen molecules (or microstructures) reorganize so that they approach an optimal thermodynamic state under certain conditions [13].

The chemical technique is the most effective because it does not require a more time-intensive process and less hazardous materials. Warm mix asphalt with chemical additives (WMCA) doesn't decrease the viscosity but improves the overall asphalt properties, including better workability, adhesion, and resistance to compaction [14-16]. WMCA reduces surface tension and facilitates smooth interaction between aggregates and asphalt binders. This allows for a decrease in production temperatures without negatively impacting asphalt's properties [17]. Therefore, WMCA is an ideal candidate for warm mixed technology.

The rutting resistance factor ($G^*/\sin\delta$) is a rheological parameter used to predict asphalt binders' rutting resistance at high temperatures [18]. It depends mainly on binder characteristics, a secondary factor. The parameter $G^*/\sin\delta$ tests are measured by evaluating the complex shear modulus (G^*) and phase angle (δ) of the asphalt binder. The δ is a relative measure of a material's viscous and elastic properties. The elastic modulus 0° is for a fully elastic material, while 90° is the elastic modulus of a fully viscous material [19], which is affected by stress frequency and temperature [20]. Each warm agent has a different effect on asphalt binder properties [21]. A study by Raufi *et al*., [22] Investigating ZycoTherm (ZYC) modified binder using the Rolling Thin Film Oven Test (RTFO) for short-term aging, it was found that the modified binder demonstrated enhanced resistance to rutting and exhibited a higher $G^*/\sin\delta$ ratio than the base binder. *Singh* [23] ZycoTherm (ZYC) additive in bitumen has minimal impact on rutting resistance. However, when Evotherm M1 (EVM) is added to bitumen, it enhances the elastic component, increasing resistance to rutting. This indicates that while ZYC might not substantially enhance rutting resistance, other additives like EVM can have a positive impact on this aspect of asphalt performance. EVM can reduce the high-temperature viscosity of bitumen, improving its workability during construction, and increase the bitumen's elastic component, thereby boosting its resistance to rutting [24].

Linear Amplitude Sweep (LAS) is a rheological test used to assess asphalt binders' fatigue resistance. It measures "damage resistance" and evaluates asphalt binders' ability to resist fatigue cracking under repeated loading [25]. The test simulates repeated traffic loading on asphalt pavements. This helps to ensure asphalt roads' longevity and safety. In less than 30 minutes, LAS tests accelerate damage by cyclically increasing load amplitudes. Though the current LAS testing protocol yields encouraging results, the processing and interpretation of the data is time-consuming and necessitates intricate numerical techniques [26]. The research showed that ZYC had no substantial impact on the binder's elastic reactions or fatigue characteristics [23,27]. According to a study by [28,29], ZYC improved the base binder's fatigue behavior as well EVM enhanced asphalt binders' fatigue resistance [30]. The investigation revealed that EVM led to minimal enhancement in rutting resistance when subjected to aging by RTFO and original asphalt (UN) [31].

SARA (Saturates, Aromatics, Resins, and Asphaltenes) analysis determines asphalt binders' chemical composition. Asphalt aging refers to the change in bitumen's chemical composition over time. Asphalt aging can change its properties, including fatigue, viscoelastic behavior, and a complex modulus [32]. The application of SARA analysis has been utilized to examine how the effects of aging and rejuvenation impact both the surface free-energy components and the chemical composition of bitumen [33].

This study aimed to understand how aging affects the performance and chemical composition of various asphalt binders by investigating the impact of aging on the rheological characteristics, such as resistance to rutting and fatigue, as well as the chemical composition of three types of asphalt binders: base asphalt binder (Neat), and two WMCA (ZYC and EVM). Additionally, the degree of aging of three binder types was assessed by comparing changes in various indices before and after aging with short term aging (STA) and long term aging (LTA). The binder's chemical composition was analyzed before and after aging using the Flame Ionization Detector (TLC-FID) to the better understanding of the chemical changes that occur during the aging process. Additionally, the sensitivities of rutting, fatigue resistance, chemical compositions, and colloidal index to aging were studied.

2. Experimental

2.1 Asphalt Binder

In this research, AC 20 bitumen sourced from a Taiwanese company was employed as the control asphalt binder (Neat). This bitumen exhibits a penetration grade of 72.9, a softening point of 48.7°C, a specific gravity of 1.035, and viscosities of 20800 cP at 60°C and 521 cP at 135°C.

2.2 Additive

A chemical technology of WMA namely ZycoTherm SP (ZYC) and Evotherm M1 (EVM), which have potential benefits for reducing mixing temperatures, improving adhesion, and reducing environmental impact [34-37]. ZYC is a liquid anti-strip additive based on organosilane that has distinct advantages over traditional WMAs [38]. The addition of ZYC can drop the HMA mixing temperature from 120-135°C and the compaction level to 105-120°C. This study used ZYC at dosages of 0.05, 0.07, and 0.1%, following recommendations from the supplier and previous research [31, 38].

EVM, a third-generation warm mix asphalt additive manufactured by Ingevity, is not extensively documented due to limited information from MeadWestvaco Company warm mix asphalt technology. It is composed of two groups: a hydrophilic group at the end of the cation and a lipophilic group at the end of the nonpolar alkane [30]. EVM has been shown to offset greenhouse gases generated during its production by up to 23 times [34]. It is a water-free additive that reduces mixing temperature up to 45ºC [34], improves adhesion, and acts as a liquid antistrip in paving application [4,39,40]. EVM has been used in dosages of 0.5%, 0.75%, and 1% (by weight of binder) in research studies and according to supplier recommendation [41-43].

ZYC and EVM are anti-stripping agents used to modify aged asphalt to address several critical issues related to asphalt mixture performance and durability. These agents are particularly important in the context in preventing rutting, fatigue cracking, and traffic stability forces, which is a common and detrimental wear pattern on asphalt, especially regarding the potential long-term effects.

2.3 Asphalt Preparation

Asphalt was heated to 160°C and dripped with WMCA according to the dosage. Afterward, a four-blade shear mixer and a stirrer were used for 15 minutes at 135-140°C to ensure homogeneity.

2.4 The Aging Procedure

RTFO test, which determines asphalt short-term aging (STA), is conducted under the ASTM D2872 [44]. This test reflects advancements in scientific measurement and analysis techniques, which allow for precise and accurate evaluation of materials' properties during asphalt production and distribution. The test involves heating 35 grams of asphalt sample at 163°C for 85 minutes.

The Universal Simple Aging Test (USAT) [45] is utilized for long-term aging (LTA) of asphalt binders. This method involves aging the binders in a forced-draft oven for 40 hours at 100°C on a plate with three slots, each holding approximately one gram of asphalt binder, resulting in a film thickness of roughly 300 µm. If there are any open areas, they are covered manually using a spatula gently.

2.5 *Rheological Asphalt*
2.5.1 Rutting resistance factor (G/sin δ)*

Tests were performed using an Anton Paar MCR 102e Dynamic Shear Rheometer (DSR) according to AASHTO T 315 [46]. The testing utilized parallel geometry, with a sample diameter of 8 mm and a height of 2 mm.

The G*/sin δ, rutting factor, varies with temperature and is used as an indicator of asphalt performance under high-temperature conditions [47] at 46, 52, 58, 64, and 70°C at original asphalt and STA followed by AASHTO T 315 [46], and also LTA.

2.5.2 Linear Amplitude Sweep (LAS)

A Dynamic Shear Rheometer (DSR) with an 8 mm parallel plate and a 2 mm gap was used to evaluate the asphalt binder's performance under all conditions. The LAS test uses a 35% reduction in the initial modulus as failure criteria [26]. During the test, peak shear strain and peak shear stress are recorded every 10 load cycles (1 second). The phase angle (δ) and the complex shear modulus (|G*|) are documented. The viscoelastic continuum damage (VECD) method is used to determine the fatigue life of the material at different strain amplitudes. The VECD model calculates the number of cycles until failure (N_f) or fatigue life by analyzing the relationship between the applied strain and the number of cycles to failure [48]. Eq. (1) calculates the number of cycles until failure.

$$N_f = A\,(\gamma_{max})^B \tag{1}$$

The VECD equation includes the bitumen fatigue performance parameter (N_f) and the maximum strain experienced by bitumen in a particular pavement structure (represented as a percentage, denoted as γmax). The VECD model coefficients "A" and "B" are affected by material properties. Generally, binders with superior fatigue resistance exhibit larger "A" values but smaller absolute "B" values.

2.6 Chemical Properties (SARA)

SARA composition was determined using a thin layer chromatograph technique using the Flame Ionization Detector (TLC-FID) analyzer according to ASTM D 4214 [49], and the Gaestel index (I_C) was utilized to measure bitumen colloidal stability [50,51]. The TLC-FID method can identify the SARA components of bitumen, namely saturates, resins, aromatics, and asphaltenes. The burnout times for each component are as follows: saturates take less than 0.2 minutes, aromatics take between 0.2 to 0.3 minutes, resins take between 0.3 to 0.4 minutes, and asphaltenes take between 0.4 to 0.48 minutes. The following Eq. (2) is used to calculate the Gaestel index [52]:

$$I_C = \frac{Saturates\ (\%) + Asphaltenes\ (\%)}{Resins\ (\%) + Aromatics\ (\%)} \quad (2)$$

I_C is the Gaestel index. The higher I_C indicates the less stable the entire system. As the Gaestel index increases from 0,5 to 2,7, the colloidal system of bitumen becomes unstable. $I_C > 0.5$, bitumen becomes harder and $I_C < 0.22$ bitumen becomes softer [53,54].

3. Results

3.1 G/sin δ*

3.1.1 Evaluation of G/sin δ before aging*

The G*/sin δ parameter reflects asphalt's ability to resist rutting deformation under elevated temperatures. Higher values of G*/sin δ suggest that the asphalt behave more like an elastic material, which is desirable for better rutting resistance [55]. Figure 1 shows that the G*/sin δ values of Neat, ZYC, and EVM decrease with increasing temperature. This indicates that the binder becomes less resistant to rutting as it increases in temperature. Furthermore, Neat's G*/sin δ value is higher than other binder WMCA. At 70 °C all binder WMCA shows < 1 kPa indicating failure at the highest temperature of the asphalt binder. As a result, it did not meet the specified criteria for rutting performance.

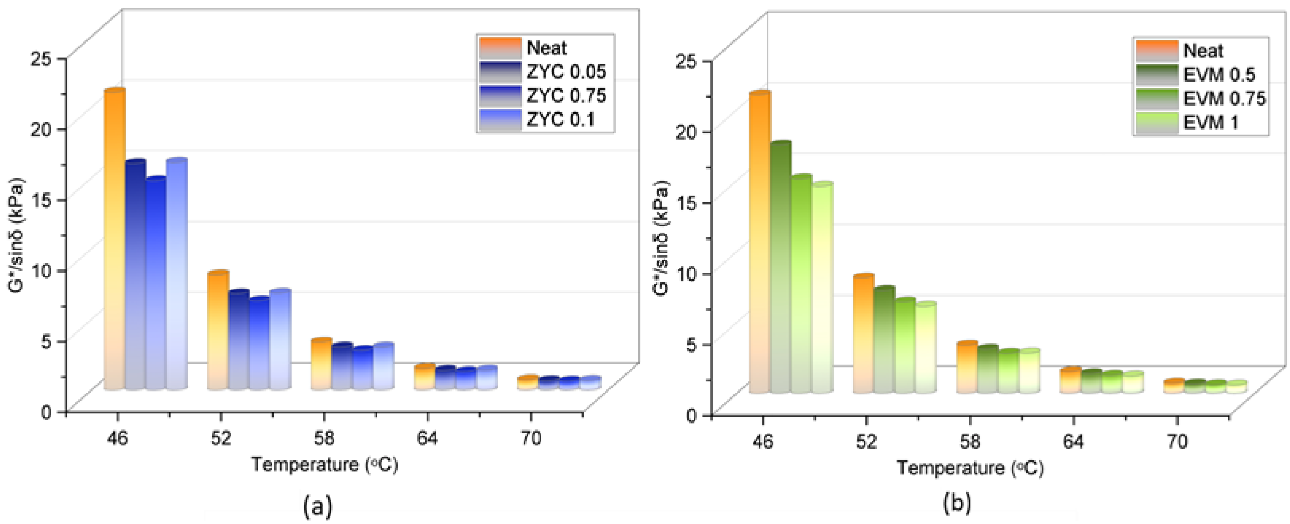

Fig. 1. G*/ sin δ results at UN (a) ZYC (b) EVM.

3.1.2 Evaluation of G*/sin δ after aging

As shown in Figure 2 below, at increasing temperatures after aging (STA), the binder's G*/sin δ decreased. In addition, after aging (LTA), the binder's G*/sin δ value increased. After LTA, the growth rate of a binder is higher than that during STA. Figure 2 (b) shows that the G*/sin δ value under the STA condition of binder WMCA ZYC is higher than that of Neat, while binder WMCA EVM is prone to rutting. The additive decreases the intermolecular connections between asphalt molecules. A decrease in interactions leads to a decrease in viscosity, which results in a lower G*/sin δ ratio [24]. Furthermore, ZYC G*/sin δ ranks is 0.05 > 0.1 > 0.07. At 70 °C all binder WMCA shows < 2.2 kPa indicating a failure at the highest temperature. In contrast, EVM 1% at 64 °C is already failing.

Test results of LTA are shown in Figure 2 (b). G*/sin δ value for LTA is ≤ 5000 kPa. This indicates that the binder has adequate rutting resistance, which is essential for LTA performance. LTA tests are conducted at lower temperatures, significantly above the low-temperature specification for a given performance grade (PG) binder. Lower temperatures stiffen the binder and make it more resistant to rutting. At 19 °C ZYC 0.05 is more improved than Neat, while 0.07 is slightly similar to Neat, and 0.1 along with all EVMs is prone to rutting.

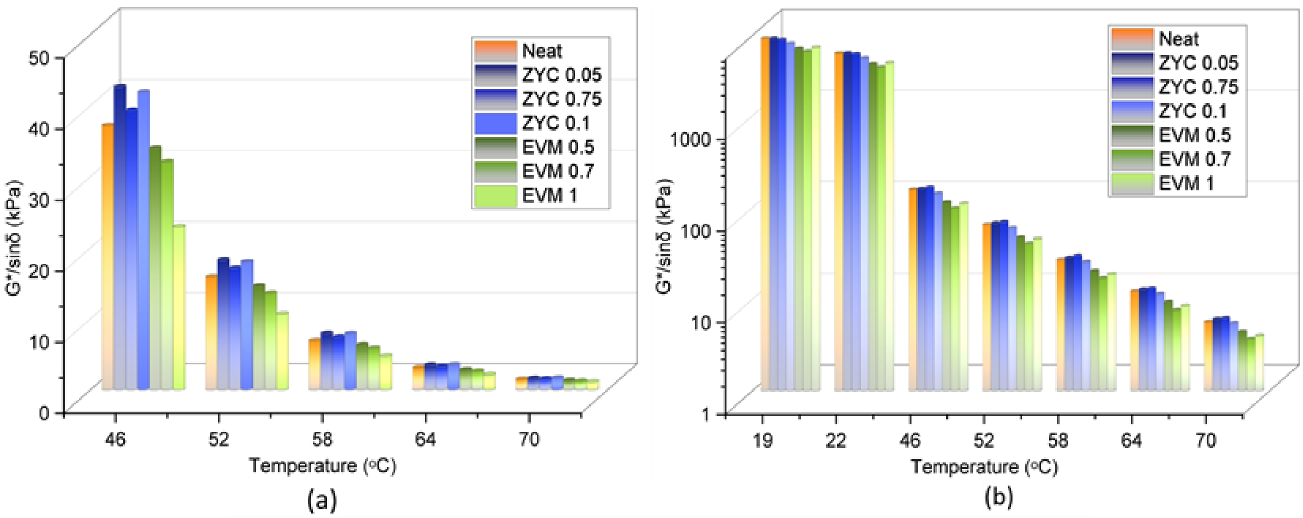

Fig. 2. G*/ sin δ results at Aging of binder (a) STA (b) LTA.

3.1.3 Evaluation of rutting factor aging index (GAI)

When the rutting factor aging index (GAI) is smaller, asphalt has a lower degree of aging [56]. GAI obtained according to Eq. (3) below. Figure 3 below is the GAI values of the Neat and binder with WMCA after STA and LTA respectively.

$$GAI = {(G^*/\sin\delta)_{STA/LTA}}\Big/{(G^*/\sin\delta)_{UN}} \quad (3)$$

According to Figure 3 (a), all ZYC-modified asphalt is greater than Neat, especially 0.07%. EVM shows greater value than Neat at 46 and 52 °C while at higher temperatures the value is slightly the same. In contrast, EVM 1% has the lowest value. As can be seen in Figure in 3 (b), the value decreases. The ZYC value is higher than the Neat at all temperatures, especially at 0.07%. In contrast, all EVM values are smaller than Neat, especially 0.75.

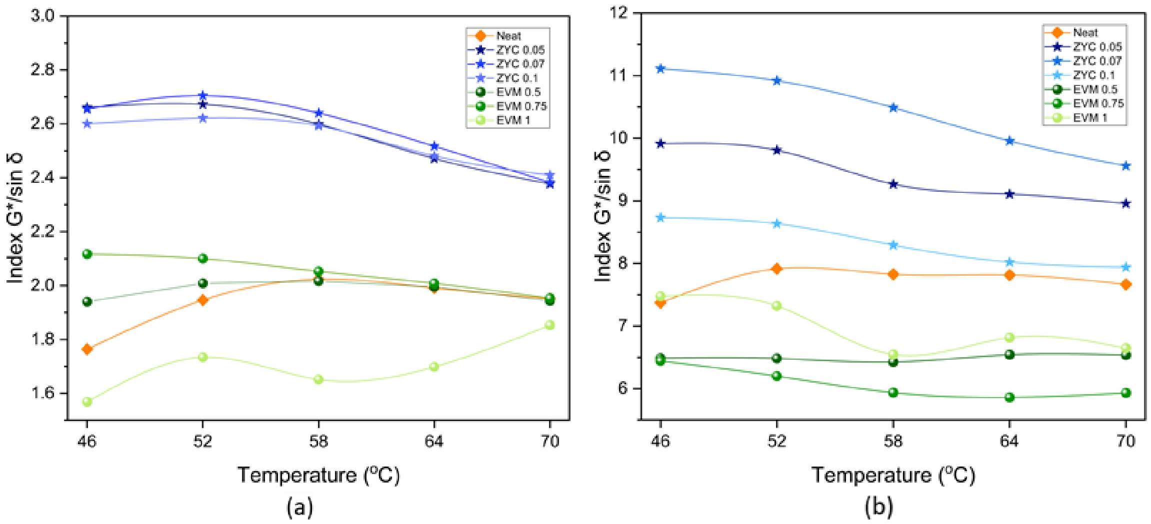

Fig. 3. GAI of Neat, ZYC and EVM after (a) STA (b) LTA.

3.2 Fatigue Behaviour (LAS)
3.2.1 Fatigue behaviour before aging

Figure 4 below shows the performance of asphalt binder ZYC and EVM at strain levels 2.5, 5 & 15 % at UN. The low value of share strain in asphalt leads to increased sensitivity to loading stresses, rapid crack propagation, and reduced structural capacity of the pavement [56]. Figures 4 (a) and (b) show that all binder WMCA values are lower than Neat at 2.5 and 5% share strains. In contrast, at 15% the value increases which means it improves its ability to resist damage.

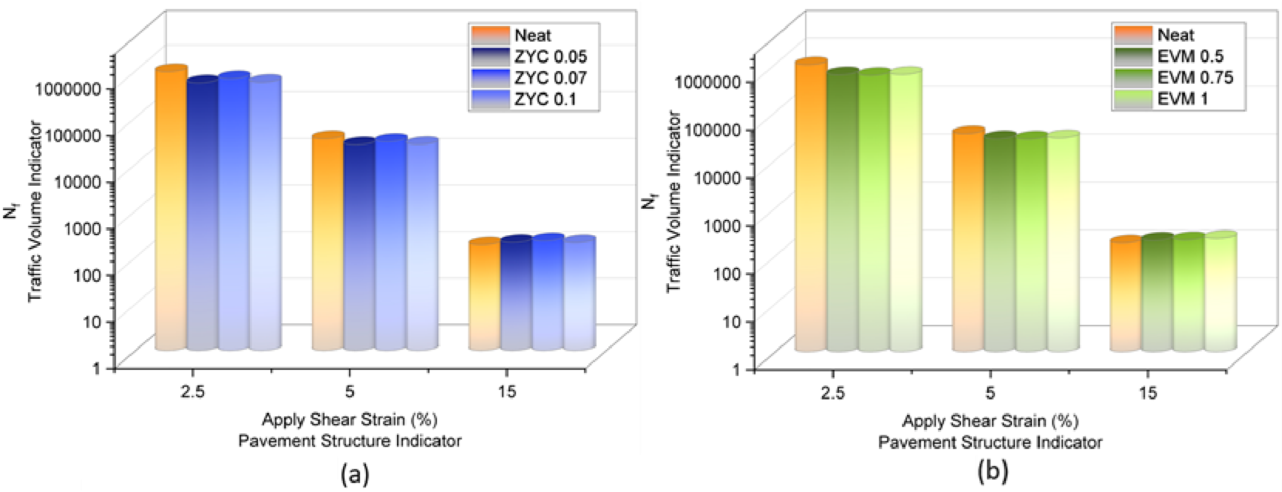

Fig. 4. The strain levels on cycles to failure (N_f) of asphalt binder at UN (a) ZYC, and (b) EVM

3.2.2 Evaluation of fatigue behaviour after aging

Changes in fatigue resistance ability occur at aging conditions in each share strain of asphalt as shown in Figure 5. N_f of asphalt binder decreases with an increase in the percentage of strain present in the binder. Moreover, after aging the N_f value of asphalt binder increases. The increase rate of N_f after LTA is significantly higher than that of STA.

As shown in Figure 5 (a) and (b) below, at the STA ZYC is significantly more resistant than Neat at 2.5 and 5% share strain values of 0.05 greater than other doses. However, at 15% ZYC 0.07 becomes even more resistant. Figure 5 (b) below at 2.5 share strain all doses are resistant to fatigue and EVM 1 has the largest value than Neat. At 5 and 15 share strains EVM 0.5 was susceptible to fatigue, but EVM 1 showed improved resistance compared to other doses.

The change in results is visible at LTA in Figure 5 (a) and (b) below. All binder WMCA at a strain share of 2.5%, ZYC 0.05 becomes susceptible to fatigue compared to Neat, while ZYC 0.07 shows the greatest resistance compared to other asphalts. The 5% strain share of EVM 0.05 decreased to be vulnerable to fatigue, while EVM 0.75 was more resistant. The 15% strain share of EVM 0.05 and 1 became more vulnerable than Neat, while ZYC 0.07 showed the highest resistance.

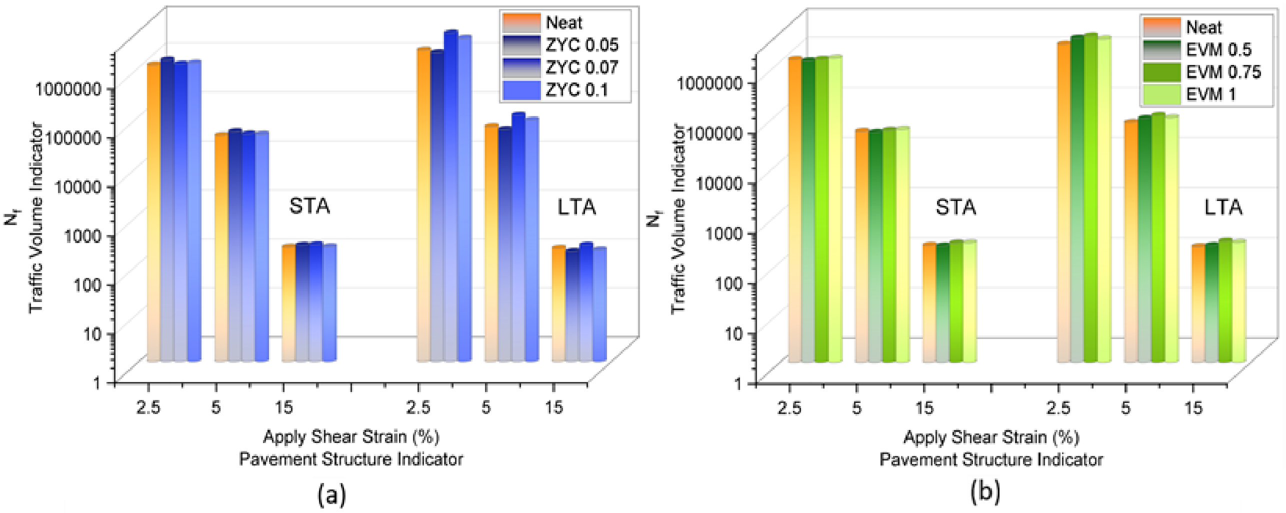

Fig. 5. The strain levels on cycles to failure (N_f) of asphalt binder at aging (a) ZYC, (b) EVM

Table 1 below summarizes the "A" and "B" parameters of neat and binder WMAC based on VECD analysis at UN and aging conditions. When "A" values are higher, the binder retains its structural integrity under loading conditions, leading to less accumulated damage which helps in predicting the binder's resistance to fatigue damage. Under the UN condition, Neat has the largest value. Whereas, under the aging condition, it becomes susceptible to fatigue. As a comparison to another binder WMCA, ZYC 0.05 and 0.07 are the best performers in terms of aging.

The slope ("B" values) of the fatigue model increases as the asphalt binder ages which indicates a higher susceptibility to fatigue cracking at different strain levels [57-60]. The "B" parameter represents the sensitivity of bitumen's fatigue behavior to strain levels. As strain amplitude increases, fatigue life decreases at a faster rate as "B" increases. Parameter "B" has an identical rank to parameter "A"; however, the two variables do not appear to be related. This phenomenon can be explained by the minimal effect of WMCA on asphalt binder viscosity, which does not result in decreased stiffness or enhanced fatigue life as measured by N_f. Compared to the neat binder, the binder with WMCA demonstrates superior performance in terms of fatigue resistance.

3.2.3 Evaluation of the fatigue aging index

The aging index assesses the asphalt binder's capacity to withstand traffic loads and fatigue. A higher aging index indicates better performance, suggesting that the pavement can withstand higher traffic loads and maintain its structural integrity for a longer period. The fatigue aging index (FAI) is calculated based on Eq. (4).

$$FAI = {}^{(N_f)_{STA/LTA}}\Big/_{(N_f)_{UN}} \quad (4)$$

Table 1
Asphalt binder for fatigue resistance ranking

Con.	Additive (%)	A Parameter	B Parameter	2.5% N_f	Rank	5% N_f	Rank	15% N_f	Rank
UN	Neat	76678488	4.77	966819	1	35364	1	187	7
	ZYC 0.05	31196893	4.40	555946	7	26418	6	211	5
	ZYC 0.07	40985278	4.47	683605	2	30898	2	228	2
	ZYC 0.1	32831914	4.42	572301	4	26745	5	208	6
	EVM 0.5	34945442	4.43	601100	3	27810	7	213	4
	EVM 0.75	32938695	4.41	581045	5	27399	4	216	3
	EVM 1	33957816	4.39	606770	6	28892	3	232	1
STA	Neat	88902146	4.77	1120944	7	41001	6	217	6
	ZYC 0.05	122645803	4.86	1430398	1	49323	1	237	4
	ZYC 0.07	89807480	4.73	1176408	4	44290	3	245	2
	ZYC 0.1	101310018	4.81	1229251	2	43675	4	220	5
	EVM 0.5	82744526	4.75	1060884	5	39298	7	212	7
	EVM 0.75	84790341	4.71	1131380	6	43194	5	244	3
	EVM 1	91731083	4.74	1192813	3	44659	2	245	1
LTA	Neat	263645930	5.19	2260321	6	61753	6	205	5
	ZYC 0.05	238902870	5.21	2986158	7	74714	5	216	4
	ZYC 0.07	824282427	5.56	3293348	1	85812	2	265	1
	ZYC 0.1	638597068	5.55	2859512	2	76819	4	249	2
	EVM 0.5	391255525	5.32	2017272	4	54482	7	178	7
	EVM 0.75	408969787	5.26	5049221	3	106971	1	238	3
	EVM 1	341038797	5.22	3949900	5	84297	3	190	6

Figure 6 displays FAI Neat and binder WMCA with different share strains. At the STA all asphalt binders display an increased aging index, but the trend decreases when the strain share percentage is greater.

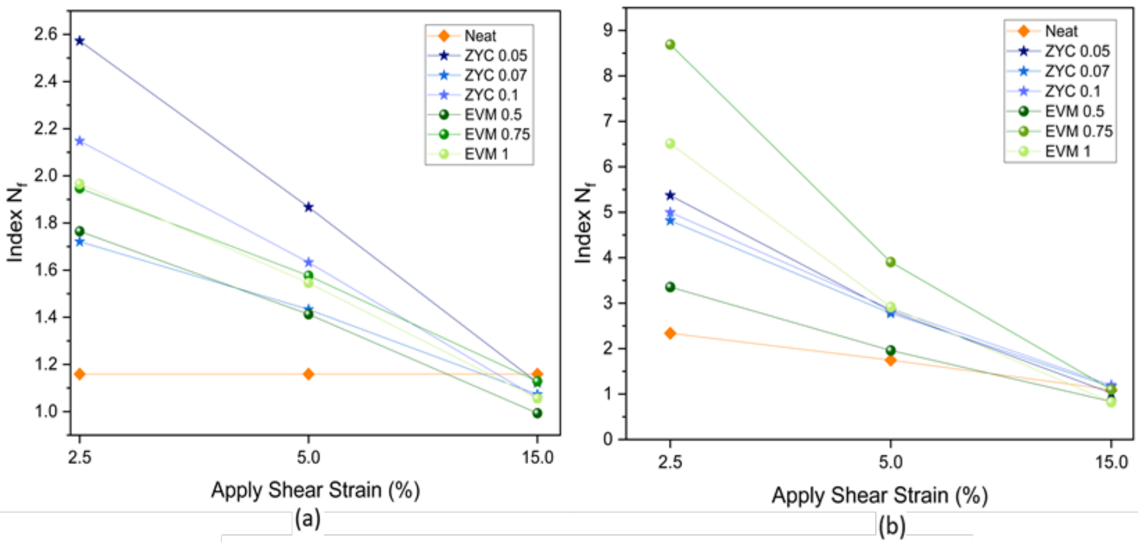

Fig. 6. FAI of Neat, ZYC and EVM after (a) STA (b) LTA.

3.3 Chemical Test (SARA)
3.3.1 SARA fraction before aging

Figure 7 shows the SARA test results of Neat compared to binder WMCA of ZYC and EVM at UN. The percentage of SARA fraction change is affected by WMCA. As can be seen in Figure 7 (a), saturates becomes reduced, but as the dosage increases, the fraction content of aromatics increases, resins decreases and asphaltenes increases in comparison to Neat. According to Figure 7 (b), the percentage of WMCA makes saturates and aromatics increase compared to Neat, except for EVM 0.5%. This trend is also evident for resins and asphaltenes, where fraction content decreases as dosage increases.

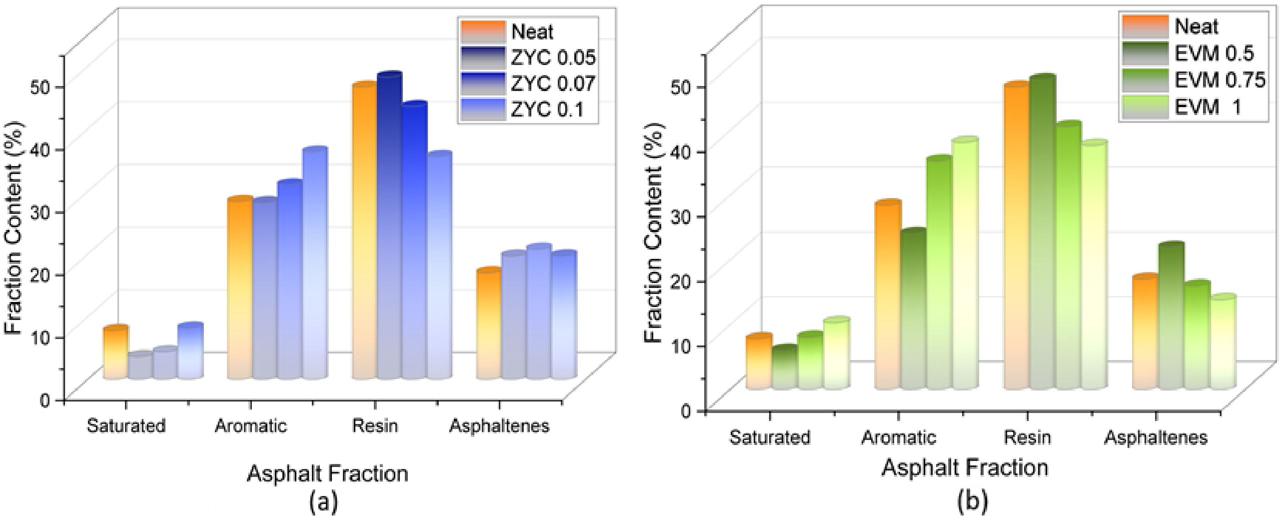

Fig. 7. SARA test for UN (a) ZYC and, (b) EVM.

3.3.2 Evaluation of SARA after aging

Figure 8 below displays SARA result of Neat and binder WMCA at aging condition. As seen in Figure 8 (a), saturates increased after aging. The aromatics percentage fraction content decreased at STA and increased significantly at LTA. Resins increased at STA but decreased at LTA. Asphaltenes did not change significantly at STA but were lower than Neat, and at LTA all asphalt binders decreased.

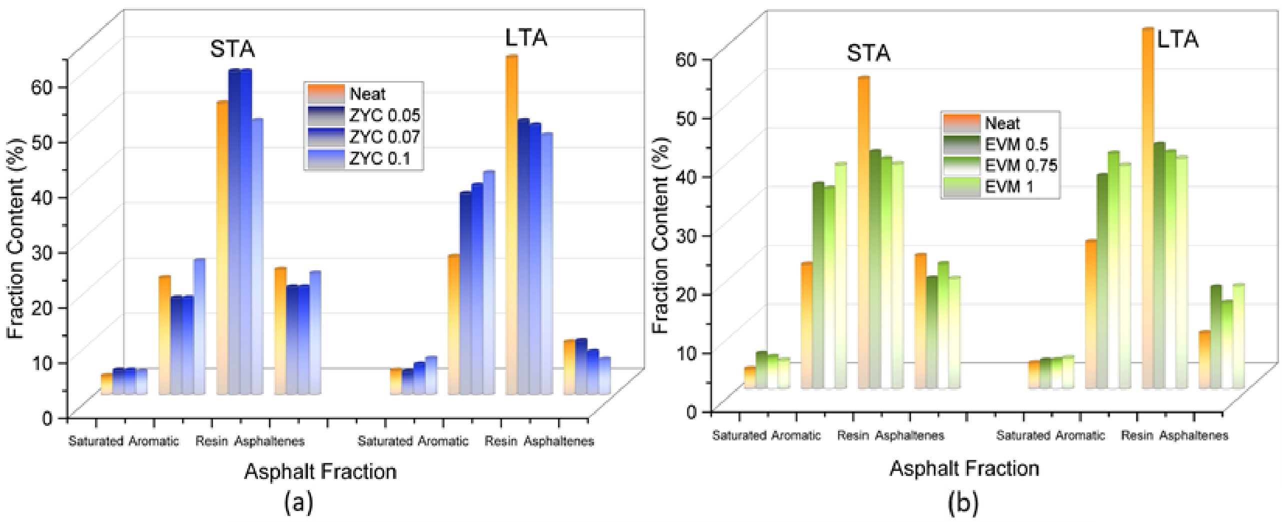

Fig. 8. SARA test of aging asphalt binder (a) ZYC and, (b) EVM.

As described in Figure 8 (b), saturates increased at STA and did not change significantly at LTA with almost the same fraction content as Neat. Aromatics increased significantly during aging compared to Neat. At aging conditions, the resins decreased significantly. At STA asphaltenes were lower than Neat and increased at LTA, which proves that increasing asphaltenes enhances their performance, particularly at high temperatures due to the increase in binder stiffness and elasticity.

The slope in SARA indicates the chemical structure of fractions changes significantly with aging. A change in these properties can make the asphalt more durable or stronger. In Figure 9, the linear regression equation for SARA UN, STA, and LTA conditions is shown.

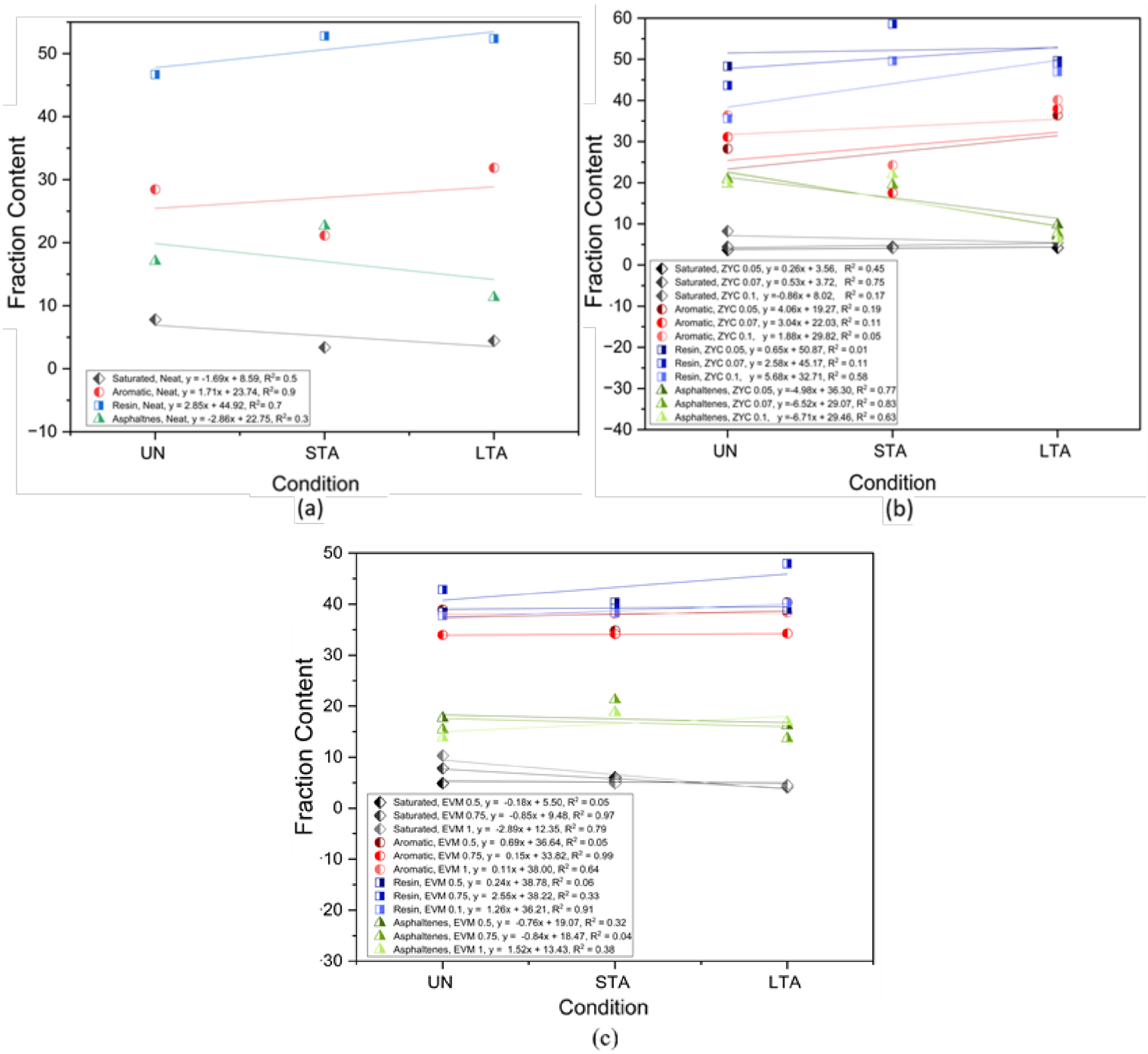

Fig. 9. Correlation and Determination SARA (a) Neat, (b) ZYC and, (c) EVM.

The linear regression slope value changes after aging. Every binder with WMCA more than 0.5 is ranked as follows: (a) Neat: aromatics > resins > saturates. (b) ZYC: asphaltenes (0.07 > 0.05 > 0.1). (c) EVM: saturates (0.75 > 1), aromatics (0.75 > 1), resins: (1).

3.3.3 Evaluation of SARA aging Index

To determine the saturates aging index (SAI), aromatics aging index (AAI), resins aging index (RAI), and Asphaltene aging index (PAI) asphalt binder WMCA according to Eqs. (5)-(8). The results are displayed in Table 2 below.

$$SAI = {(Saturates)_{STA/LTA}}\Big/{(Saturates)_{UN}} \tag{5}$$

$$AAI = {(Aromatics)\ _{STA/LTA}}\Big/{(Aromatics)_{UN}} \tag{6}$$

$$RAI = {(Resins)_{STA/LTA}}\Big/{(Resins)_{UN}} \tag{7}$$

$$PAI = {(Asphaltenes)\ _{STA/LTA}}\Big/{(Asphaltenes)_{UN}} \tag{8}$$

Table 2 describes the SARA index under different aging conditions. A higher SAI is expected to demonstrate increased resistance to oxidative aging and to maintain its stability. The SAI values obtained under aging conditions show that almost all binder WMCA is greater than Neat. A lower AAI in asphalt binders indicates lower aging sensitivity, which can significantly improve performance including reduced viscosity, increased elasticity, and an increase in the binder's resistance to deformation, all of which can resist a deterioration in binder performance. Only the binder WMCA EVM performs lower than Neat at STA. After the LTA ZYC 0.1, and EVM 0.5, 1 perform lower than Neat. Resins can mitigate the impact of asphalt aging on mechanical properties, and adhesion of asphalt to aggregate. A higher IAI indicates better performance. All ZYCs show higher values at STA, but at LTA ZYC 0.1 and EVM 0.75 have the highest values compared to Neat. Higher PAI content in asphalt binders leads to increased stiffness and elasticity and improved aging resistance [61]. As shown in Table, only EVM 1 has a higher value at the STA, while at the LTA all EVMs display a higher value.

Table 2
SARA index

	SAI		AAI		IAI		PAI	
Asphalt	STA	LTA	STA	LTA	STA	LTA	STA	LTA
Neat	0.43	0.57	0.74	1.12	1.13	1.12	1.33	0.66
ZYC 0.05	1.21	1.15	0.62	2.08	1.21	1.03	0.99	0.50
ZYC 0.07	1.00	1.24	0.56	1.22	1.34	1.12	0.93	0.37
ZYC 0.1	0.50	0.79	0.67	1.10	1.39	1.32	1.11	0.32
EVM 0.5	1.23	0.99	0.89	0.93	1.05	1.08	1.06	0.98
EVM 0.75	0.70	0.63	1.00	1.18	0.91	0.94	1.38	0.95
EVM 1	0.51	0.93	1.00	1.01	1.01	1.04	1.35	1.26

3.3.4 Colloidal index before aging

Figure 10 below illustrates the correlation between the Gaestel index (Ic) and binder WCMA at UN and aging conditions. At UN conditions, both binder WMCAs show that all are categorized into the stable index. With an increase in asphaltenes levels, bitumen colloidal stability shows an increasing trend. However, with different dosage amounts the colloidal index does not indicate an increasing hardening or softening of the asphalt binder.

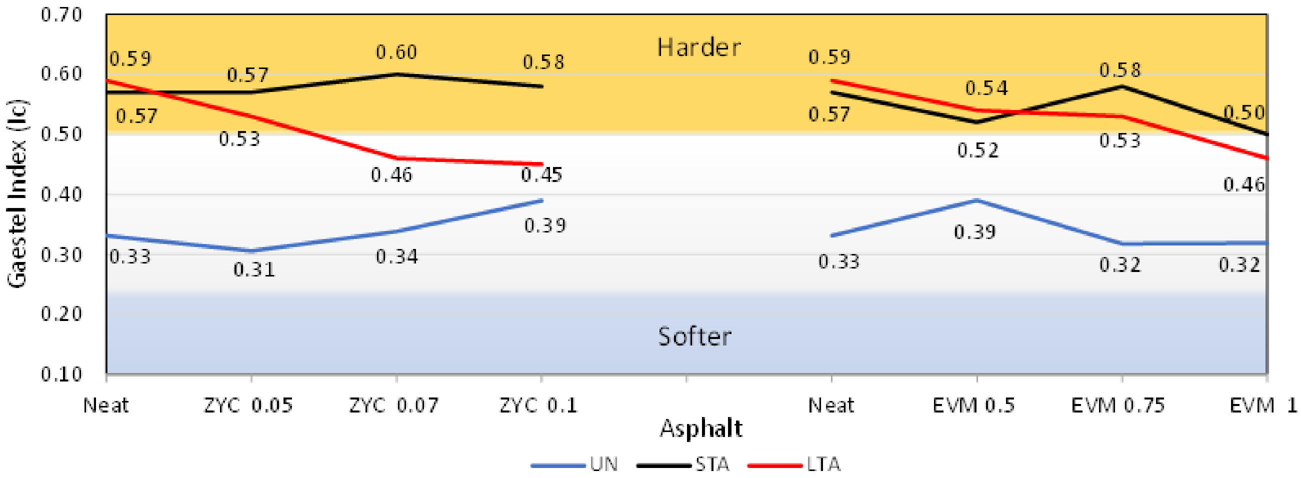

Fig. 10. Colloidal stability of asphalt binder at UN, STA, and LTA.

3.3.5 Evaluation of the Colloidal Index After Aging

Data shown in Figure 10 that the colloidal system of all binder WMCA at STA has hardened and has become unstable. Some binder WCMAs at LTA were unstable, while others were stable, including ZYC 0.07, 0.1, and EVM 1%. This shows that the effect of the additives used in the asphalt binder improved the lubricant and the formation of microscopic lattice structures in the binder [62].

3.3.6 Evaluation of the Changing Colloidal Index

To determined colloidal aging index (CAI) based on the following Eq. (9) below and the result shows in Table 3 below:

$$CAI = {(Colloidal\ index)_{STA/LTA}}\Big/{(Colloidal\ index)_{UN}} \tag{9}$$

Table 3 shows the changing of colloidal index at aging condition. Change in the colloidal index indicates asphalt binder sensitivity to asphalt structure stability. The higher the index, the greater the sensitivity of asphalt against stability is greater. If the index difference is in the range from 0 to 0.28 then the binder is stable. From Table 3 it is clear that Neat, ZYC 0.07 & 0.1 have high sensitivity and are stable to changing conditions.

Table 3
Changing of colloidal index.

Binder	STA	LTA
Neat	1.72	1.78
ZYC 0.05	1.87	1.33
ZYC 0.07	1.78	1.83
ZYC 0.1	1.49	1.57
EVM 0.5	1.73	1.38
EVM 0.75	1.36	1.67
EVM 1	1.16	1.45

4. Conclusions

The aging characteristics of binder WMCA were studied in this research. From the analysis conducted, the following conclusions can be inferred.

I. The G*/sin δ of Neat and binder WMCA decreases with increasing temperature, and aged ZYC shows higher G*/sin δ values. This implies resistance to rutting. In term GAI binder WMCA ZYC indicating aging degree of asphalt.
II. Asphalt binder N_f decreases with increasing share strain but increases after aging. With 2.5 and 5% strain share, ZYC is significantly more fatigue resistant than Neat, whereas EVM 1 is improved at 5 and 15%. Strain share increases and the aging index decreases. The 0.05 ZYC yields better results. In addition, the sensitivity of EVM 0.75 increases at LTA.
III. WMCA affects SARA fraction content changes. With aging, WMCA ZYC shows an increased content saturation fraction. LTA showed a significant increase in aromatics. STA increased resins, but LTA decreased it. Asphaltenes did not change significantly at STA but at LTA all asphalt binders decreased. Binder WMCA EVM saturation increased at STA but not at LTA. Aromatics increases during aging & resins decreases significantly. Asphaltene was lower at STA and higher at LTA.
IV. SAI for most binder WMCA values is greater than Neat at aging, which implies improved oxidative resistance and stability. At STA, only the binder WMCA EVM shows performing lower than Neat. AAI shows at LTA ZYC 0.1, and EVM 0.5, 1 performs lower than Neat, indicates reduced viscosity, increases elasticity, and enhances deformation resistance. IAI All ZYCs display higher values at STA, but at LTA ZYC 0.1 and EVM 0.75 have the highest values indicating it can mitigate the impact of asphalt aging on properties and the adhesion of asphalt to aggregate. PAI only EVM 1 has a higher value at the STA, while at the LTA all EVMs display a higher value indicates increased stiffness and elasticity and improved aging resistance.
V. The colloidal system of all binder WMCA at STA has hardened and become unstable. Some binder WMCA at LTA was stable. Otherwise, Neat, ZYC 0.07 & 0.1 show are stable to changing conditions indicating asphalt binder sensitivity to asphalt structure stability.
VI. Based on the aging performance, binder WMCA demonstrated significant improvements that has excellent resistance to temperature, and ideal choice for long-term applications.

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