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A Long-Term Ultraviolet Aging Effect on Rheology of WMA Binders

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Abstract: Asphalt binder is generally easy to age in the field, especially under thermal and/or ultraviolet (UV) radiation conditions. Current asphalt performance evaluation system gives limited consideration to UV aging, especially, as using warm mix asphalt (WMA) technologies. The objective of this study is to investigate the influence of long-term UV aging on rheology of various WMA binders. The following rheological properties were tested and evaluated in this study: viscous flow, performance grade, creep and creep recovery, amplitude and frequency sweep tests. The experimental design included four asphalt binder sources and two grades; four WMA additives (Cecabase-RT, Evotherm, Rediset, and Sasobit) and control. A total of 20 binders were tested. The test results indicated that a UV aging procedure generally had obvious effect on the complex modulus and phase angle values of various UV aged WMA binders. Their viscosity values were generally different since the WMA additive or binder source played a key role. Moreover, creep and creep recovery generally showed a similar trend for various WMA binders. Similarly, the amplitude and frequency sweep values exhibited a similar trend for various WMA binders but these values were different for various binder sources and grades. Therefore, it is necessary to explore the rheological properties of WMA binders after a long term UV aging procedure in the lab.

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Key words*: Amplitude sweep; Creep and creep recovery; Frequency sweep; Ultraviolet aging; Viscous flow; Warm-mix asphalt.*

Introduction

Due to the sustainable purpose of asphalt paving industry, it has been investigating warm asphalt technologies as a means to reduce the mixing and compaction temperatures of asphalt mixes and decrease the energy consumption and carbon emission. Warm-mix asphalt (WMA) is much like hot-mix asphalt (HMA), but it is produced at lower plant temperatures than conventional HMA [1-3]. In principle, over three WMA technology categories available in the United States for the production of asphalt mixtures at relatively low temperatures in comparison with HMA are broadly based on organic additives, chemical additives, and foaming processes [2, 4, 5].

Previous research completed by Xiao et al. [6] found that the warm mix asphalt additives such as Cecabase RT, Evotherm, Rediset, and Sasobit could be used to produce asphalt mixture effectively. These WMA mixtures had similar or better rheological and engineering properties with conventional HMA mixtures. In addition, some researchers also indicated that these warm mix asphalt additives are cost-effective and environmentally friendly and should be recommended to use to achieve the sustainable purposes of global economy [1, 2, 7-10].

The long-term aging process of asphalt pavement caused by the interaction of the aggregate, air, and the asphalt binder is generally complicated due to the components of asphalt binder nature. Some researchers indicated that laboratory aging methods to simulate field aging of asphalt binders and evaluation of aging characteristics of virgin or modified asphalt mixtures are effective [11].

Due to the air voids of asphalt pavement, asphalt binder is generally easy to age during the performance, especially under thermal and/or UV radiation conditions. Generally, the oxidation of asphalt binder due to the heat transferring from top layer to base layer is affected by the pavement structure, especially, the air voids of pavement. UV aging and thermal aging are two quite different types of aging, but the current asphalt performance evaluation system gives limited consideration to UV aging [12]. UV radiation aging has effects on the performance of both binder and asphalt mixture, especially low-temperature ductility and resistance to cracking. Asphalt binder has generally different sensitivities to thermal and UV radiation. Evaluation methods based on thermally aged asphalt does not truly reflect the influences of UV aging, and there are some limitations on the substitution of UV by thermal aging [12-14).

Chiu et al [15] indicated that various asphalts were found to exhibit different aging severities when subjected to different aging processes. Asphalts from different sources exhibit differentiable degrees of volatile loss when subjected to the extended TFOT. The UV chamber was found to be effective only in aging the surfaces of the binder samples.

The ultraviolet aged asphalt compositions on penetration, softening point and ductility tests were same as thermal aged asphalt ones. Ultraviolet aging and thermal aging give asphalt different influences, rheological property changes greatly after ultraviolet aging [16]. UV aging of asphalt mainly occurs in the early stage of aging and a longer UV aging time resulted in a stiffer aged asphalt binder. Asphalt sulfide with suitable sulfur content can improve low-temperature performance and anti-aging performance of asphalt to some extent [17]. Colored asphalt with red dye showed better resistance to ultraviolet light [18].

Wu et al. investigated the relative effects of UV radiation and the levels of oxidative degradation of asphalt binder and found that a significant amount of UV degradation occurred during aging, which resulted in the oxidation and hardening of bitumen [14]. In addition, Han et al [19] reported that there is a significant influence

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Table 1. Original Binder Basic Properties.

Binder Code	Type	Source	No aging: Viscosity (Pa.s) at 135℃	No aging: Failed temp. (℃)	No aging: G*/sin δ (Pa)	RTFO aging: G*/sin δ (Pa)	RTFO + PAV aging: G*sin δ (kPa) at 25℃	RTFO + PAV aging: stiffness (MPa)	RTFO + PAV aging: m-value at -12℃
A	PG 76-22	Venezuela	1.735	81.2	1613.1 (76℃)	3625.2 (76℃)	2807	130	0.258
B	PG 76-22	Mixed	1.510	80.2	1467.7 (76℃)	3322.3 (76℃)	4095	198	0.285
C	PG 64-22	Venezuela	0.650	70.7	2127.3 (64℃)	4691.8 (64℃)	3462	144	0.349
D	PG 64-22	Mixed	0.450	65.8	1233.1 (64℃)	3703.1 (64℃)	4438	179	0.306

Notes: RTFO~ rolling thin film oven; PAV~ pressure aging vessel.

of layer clay on rheological behaviors and basic physical properties of bitumen binders especially after UV aging.

Some articles indicated that warm asphalt technologies do not significantly improve the rut resistance but increase fatigue life of the mixtures compared to the aged control mixtures after thermal aging [6, 20]. In addition, warm asphalt technologies seemed to affect the moisture susceptibility of the mixtures as they are thermal aged [21, 22]. Xiao et al illustrated that the non-foaming WMA binders have a similar or better rheological properties at high performance temperature before or after a thermal aging process (6). However, the Ultraviolet aging characteristics of WMA binders and mixtures have not been investigated in great detail.

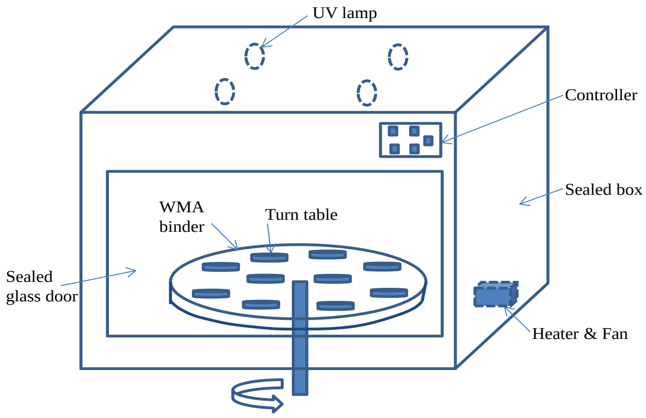
The objective of this study was to investigate the influences of long-term ultraviolet aging procedures on rheological characteristics of WMA binders. The unaged and ultraviolet aged samples were tested to determine the rut and fatigue resistances, respectively. In addition, viscosity, creep and creep recovery, amplitude sweep, and frequency sweep tests were performed to explore the rheological behaviors of various UV aged WAM binders in this study.

Experimental Procedures

The experimental design in this study included the use of four non-foaming warm mix additives: Cecabase RT, Evotherm, Rediset, and Sasaobit (referred to as Ce, Ev, Re, and Sa) and control (referred to as Co). The used amounts of WMA additives were 0.5% (Ce and Ev) and 1.5% (Re and Sa) by weight of asphalt binder recommended by the supplies in this study. Two PG 76-22 (A and B) and two PG 64-22 (C and D) base binders were employed to mix with warm mix additives to produce WMA binders according to the recommendations from material suppliers. The rheological properties of four base binders are shown in Table 1. It can be observed that binders A and B generally have higher viscosity values and failure temperatures than binders C and D because these two binders were modified by 3% SBS. The main purposes to use four binders in this study are to explore the UV aging influence on the rheology of common used WMA binders in the USA.

A 50-gram of asphalt binders was poured to a small pan, which is commonly used for PAV aging process. Similar to PAV aging, these pans were put to a UV aging box as shown in Fig. 1. A total of 20 pans were separated to two groups (each one was 10 pans) and then each group was UV aged at a temperature of 80 ± 5 ℃ for 5 days. These aged control and WMA binders were stored in a metal container (76.2 mm (3 inches) diameter x 55.9 mm (2.2 inches) height) for further rheological tests.

The high temperature rheological properties of each binder were measured using a dynamic shear rheometer (DSR) according to AASHTO T315. In this study, 1 mm gap and 25 mm diameter plate for overall binders was used to obtain DSR values at the high temperatures. Each unaged binder was measured in terms of the complex shear modulus (G*) and phase angle (δ) values starting from 64℃ (PG 64-22) and 76℃ (PG 76-22) until failed in accordance with Superpave mix design specifications.



Temperature:	80±5℃
Light intensity:	53,500 μW/cm^2
UVB intensity:	1,000 – 1,200 μW/cm^2
UVA intensity:	8,000 μW/cm^2
Humidity:	0%
Turn speed of table:	5 rpm
Number of sample:	10
Aging duration:	5 days

Fig. 1. Schematic Diagram and Parameters of Ultraviolet Aging Box.

The intermediate temperature rheological properties of each binder were measured using a 2 mm gap and an 8 mm diameter plate for overall UV aged binders. Each binder was measured in terms of the G* and δ values at 25℃ (PG 64-22), and 31℃ (PG 76-22) in accordance with Superpave mix design specifications.

G* is obtained from the ratio of the stress amplitude to the strain amplitude and is the "sum" of the elastic component and viscous component. δ is the time lag between the applied stress and resulting strain (SP-1). Elastic modulus (G´) represents the elastic storage of energy since the strain is recoverable in an elastic solid and can be defined as G´ = G* cos δ. In addition, viscous modulus (G″) is described as viscous dissipation of energy through permanent deformation in flow and is defined as G″ = G* sin δ. In this oscillation test, the phase angle value is often employed to characterize the elastic or viscous behavior of an asphalt binder.

In addition, some tests such as viscous flow measurement, creep and creep recovery, and frequency and amplitude sweep were also performed at 60℃ for each binder. Creep and creep recovery tests were run at a stress of 50 Pa (loading for 10 s and 50 s recovery) due to the stiffness of UV aged binder, a typical high stress levels on a pavement. In addition, viscous flows of the binders were measured at varying shear stresses. Moreover, for the frequency sweep tests, frequency ranges from 0.01 to 100 Hz were run at the lowest possible strain. Typically, a frequency of 1.59 Hz simulates the shearing action corresponding to traffic speed of about 55 mph. Additionally, the amplitude sweep test was performed in terms of 1 Hz frequency at 60℃ in this study.

Results and Discussions

Failure Temperature

The samples were tested at a starting temperature (i.e., 64°C for PG 64-22 and 76°C for PG 76-22 base binder) and then the temperature was increased to the next PG grade (e.g., 70°C and 76°C) until failed (1.000 kPa for base binders). Two replicates were tested for each specimen.

Fig. 2 illustrates that the addition of warm mix additive does not result in an obvious change in failure temperature regardless of asphalt binder source and grade. In addition, only slightly differences can be noticed between any two WMA binders. However, there are some differences in failure temperature for various binder sources; for example, binder C generally has a higher failure temperature compared to binder D even though both of them are PG 64-22 binders. As expected, the polymer modified WMA binders (PG 76-22) have higher failure temperatures than PG 64-22 WMA binders.

Fatigue Factor (G*sin δ)

In general, asphalt concretes are more susceptible to fatigue at an intermediate service temperature when asphalt binder is prone to oxidation and when the light oil is lost during a long-term performance and the bond between asphalt binder and aggregate is easier to break under the repeated traffic loading. Fatigue factor can still be used to explain the fatigue resistance of asphalt pavement.

In comparison with the G* sin δ values of control binders, as shown in Fig. 3, only a slightly increase or decrease can be observed from WMA binders. In other words, the G* sin δ values of UV aged binders are similar due to the addition of WMA additive regardless of asphalt binder source and grade.

The G*sin δ values were statistically analyzed at the 5% level of significance (0.05 probability of a Type I error) with respect to the effects of the warm mix additive and binder source. Statistical analysis results shown in Table 2 indicate that there are no significantly different G*sin δ values amongst overall binder sources. Additionally, statistical analysis in terms of binder source and grade (Table 3), apart from binders A and B, it can be noted that there are significant differences in G*sin δ values between any two binders containing various WMA additives. As a result, it might conclude that asphalt binder (source and grade) plays an important role in determining the G*sin δ values. The reason may be the nature of asphalt binder compositions.

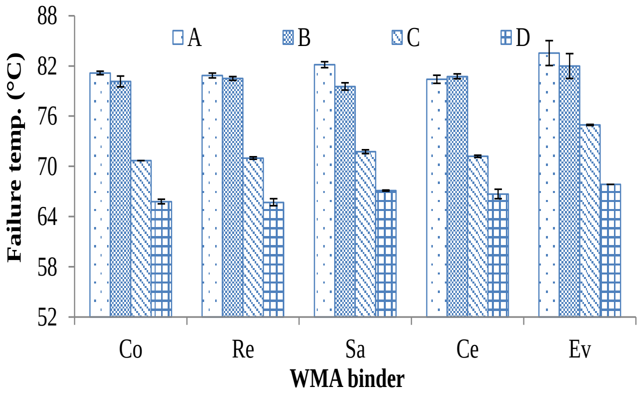


Fig. 2. Failure Temperature Values of Unaged WMA Binders.

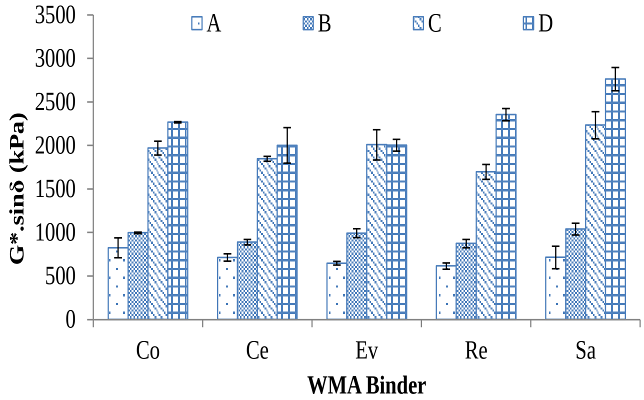


Fig. 3. G*sin δ Values of UV Aged WMA Binders.

Table 2. Statistical Analysis of G*.sin δ and Phase Angle Values of UV Aged Binders in Terms of WMA Additive.

	G*sinδ					Phase Angle				
	Co	Ce	Ev	Re	Sa	Co	Ce	Ev	Re	Sa
Co	-	N	N	N	N	-	N	N	N	N
Ce		-	N	N	N		-	N	N	Y
Ev			-	N	N			-	N	Y
Re				-	N				-	Y
Sa					-					-

Note: Co~Control, Ce~Cecabase RT, Ev~Evotherm, Re~Rediset, Sa~Sasobitd binder, Y: P-value < α = 0.05 (significant difference); N: P-value > α = 0.05 (No significant difference).

Table 3. Statistical Analysis of G*.sin δ and Phase Angle Values of UV Aged Binders in Terms of Binder Source and Grade.

	G*sinδ					Phase Angle			
	A	B	C	D		A	B	C	D
A	-	N	Y	Y	A	-	N	Y	Y
B		-	Y	Y	B		-	Y	Y
C			-	Y	C			-	Y
D				-	D				-

Note: Co~Control, Ce~Cecabase RT, Ev~Evotherm, Re~Rediset, Sa~Sasobitd binder, Y: P-value < α = 0.05 (significant difference); N: P-value > α = 0.05 (No significant difference)

Phase Angle

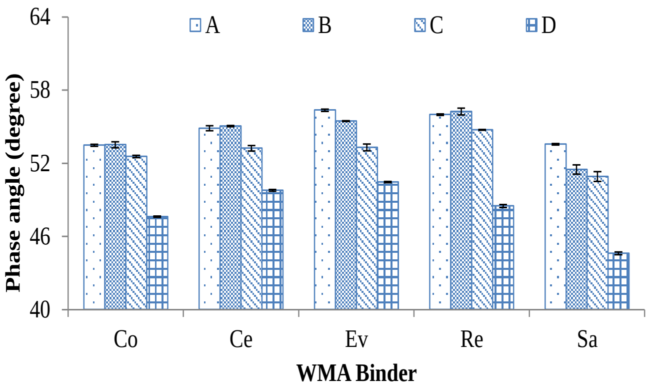


Fig. 4. Phase Angle Values of UV Aged Binders.

Phase angle, an indicator of viscosity and elasticity of binders, is defined as the time lag between strain and stress under traffic loading and is highly dependent on the temperature and frequency of loading. Under normal pavement temperatures and traffic loadings, asphalt binders act with the characteristics of both viscous liquids and elastic solids. In this study, all UV aged binders were tested at an intermediate temperature of 25℃ or 31℃ and thus exhibited elastic properties.

As shown in Fig. 4, phase angles of WMA binders are slightly greater as using Cecabase RT, Evotherm and Rediset additive regardless of binder source and grade. However, statistical analysis shown in Table 2 illustrates that Sasobit binders have significantly different phase angles compared to other WMA binders while there are no significant differences between Sasobit binders and control binders. Apart from Sasobit binders, no significantly different phase angles can be found between any other WMA binders and control binders.

Regarding to the influence of binder source and grade, as shown in Fig. 4, it can be noted that binders A and B generally have similar phase angle but binder C has an obvious higher phase angle than binder D. Table 3 indicates that, apart from binders A and B, it can be found that there are significant differences in phase angle between any two binders. Therefore, for these binders, the elastic characteristics of UV aged residue are generally based on binder source and type rather than the addition of WMA additive in general.

Viscous flow

The viscosity of asphalt is used to determine the flow characteristics of an asphalt binder to provide some assurance that it can be pumped and handled at the hot mixing facility. The absolute viscosity values of WMA binders were measured at varying shear stresses at 60°C and are shown in Fig. 5. It can be seen that, for all binders, the addition of Sasobit additive reduced their viscosity of at 60°C. In addition, binders A, B and C with Sasobit have the lowest viscosity values amongst all binders. Moreover, it can be seen that the binder exhibits an increasing shear rate as the shear stress increases and no obvious difference can be found for these various UV aged binders. As expected, WMA binders A and B show higher viscosity values greater than 10,000 Pa.s while WMA binders C and D only have viscosity values of less than 5,000 Pa.s at 60°C in this study.

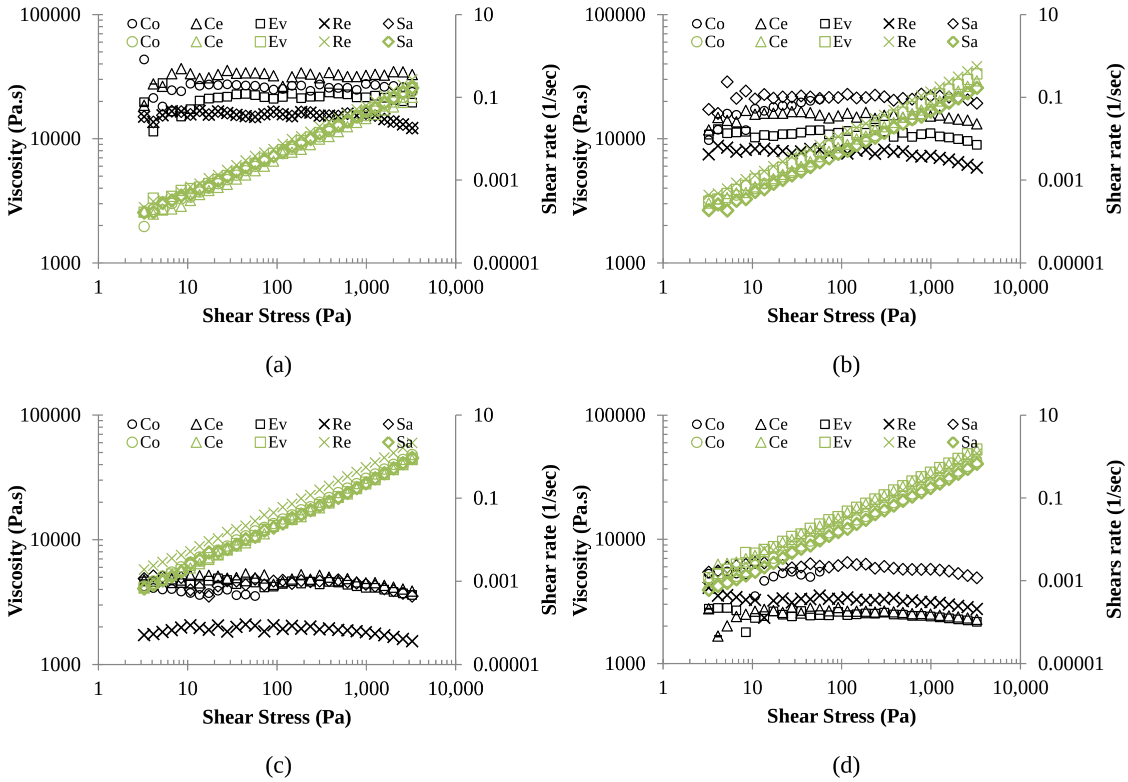


Fig. 5. Viscosity Values of UV Aged WMA Binders at 60℃, (a) ~ (d) Binders A~D.

Creep and Creep Recovery

Creep is defined as the slow deformation of a material measured under a constant stress. In a creep test, a fixed shear stress is applied to the sample and the resultant strain is monitored for a predetermined amount of time. This gives an idea of the permanent deformation that the binder will undergo. After a predetermined period of time, the stress is removed, and the strain is further monitored. This allows the material to recover for a longer duration of time [23].

Since the actual change of strain depends on the applied stress, compliance is used as a measure of creep rather than strain. The compliance is expressed as the ratio of strain to the applied stress. Thus, a lower value of compliance at any given stress level implies higher deformation resistance. Fig. 6 shows the creep compliance curves for all binders at a temperature of 60℃. It can be noted that, after the loading is removed, the creep compliance slowly decrease and show a elastic recovery.

In Fig. 6(a) and 6(b), it can be seen that, the binder A has lower creep compliance values while the binder B exhibits higher ones. The reason for this may be that the binder A yields higher deformation resistance under a similar loading stress. This result indicates that binder A shows a better deformation resistance compared to binder B due to the reduction of compliance value. In addition, the test results illustrate that the compliance value have decreased due to the removal of stress after a 10-second loading and each of binders exhibits an obvious elastic property at this temperature. In Fig. 6(c) and 6(d), Binder C has a greater deformation resistance than binder D. With respect to the influences of various WMA additives on creep compliance, no significant trends can be found for all UV aged binders in this study.

Amplitude Sweep Tests

The amplitude sweeps were performed to determine the complex modulus and phase angle values in terms of the strain responses at 60^{o}C. The effects of strain on complex modulus and phase angle values of UV aged binders are presented in Fig. 7. The test results illustrate that the increase of shear strain does not obviously result in a decrease of complex modulus. However, the phase angle of the UV aged binder reduces as the shear strain increases. With respect to the effect of UV aging process, aged sample generally has a high complex modulus and a low phase angle due to the increased stiffness. In addition, aside from UV binder D, the binders containing Rediset additive have the greatest complex modulus and the lowest phase angle values. Similar to the previous statement, the addition of Rediset in an asphalt binder results in an increase of its stiffness and thus improves its rutting resistance. Other WMA additives do not show obvious trends in complex modulus and phase angle in this study.

In addition, the amplitude sweep results indicate that the complex modulus values of UV aged samples from binders A and B are

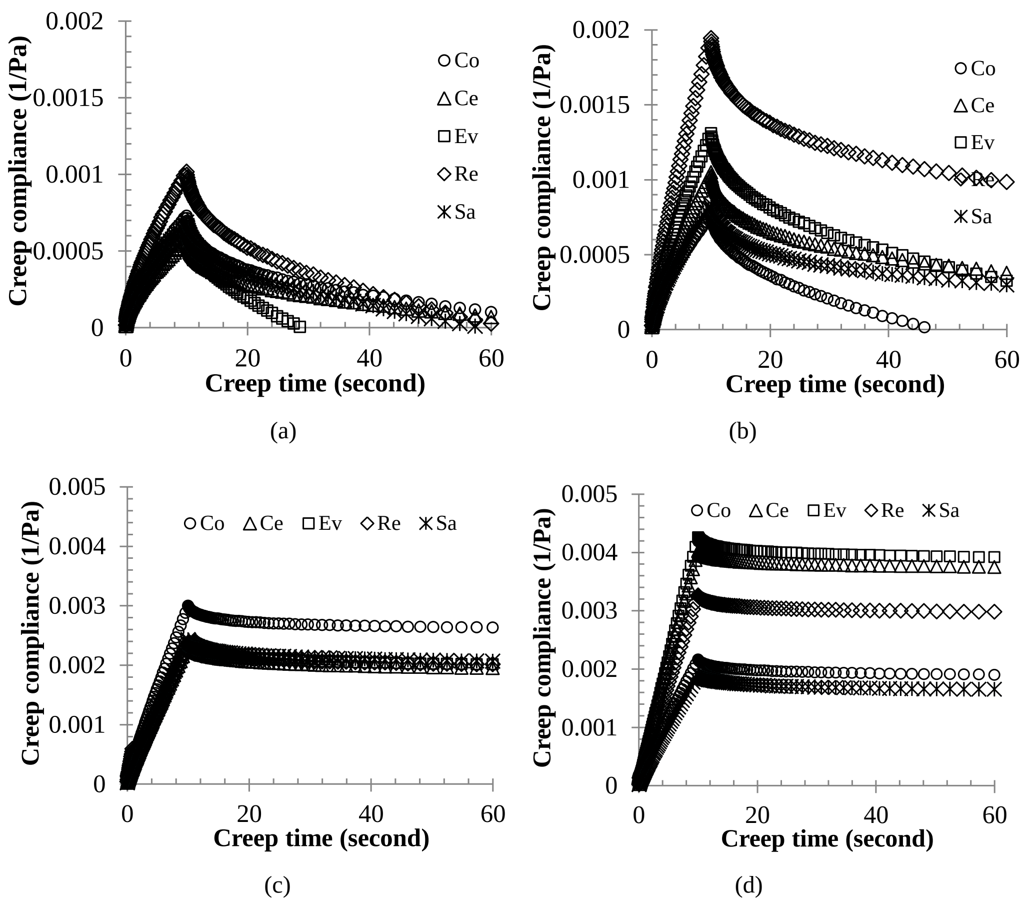


Fig. 6. Creep Compliance and Creep Compliance Recovery of UV Aged WMA Binders, (a) ~ (d) Binders A~D.

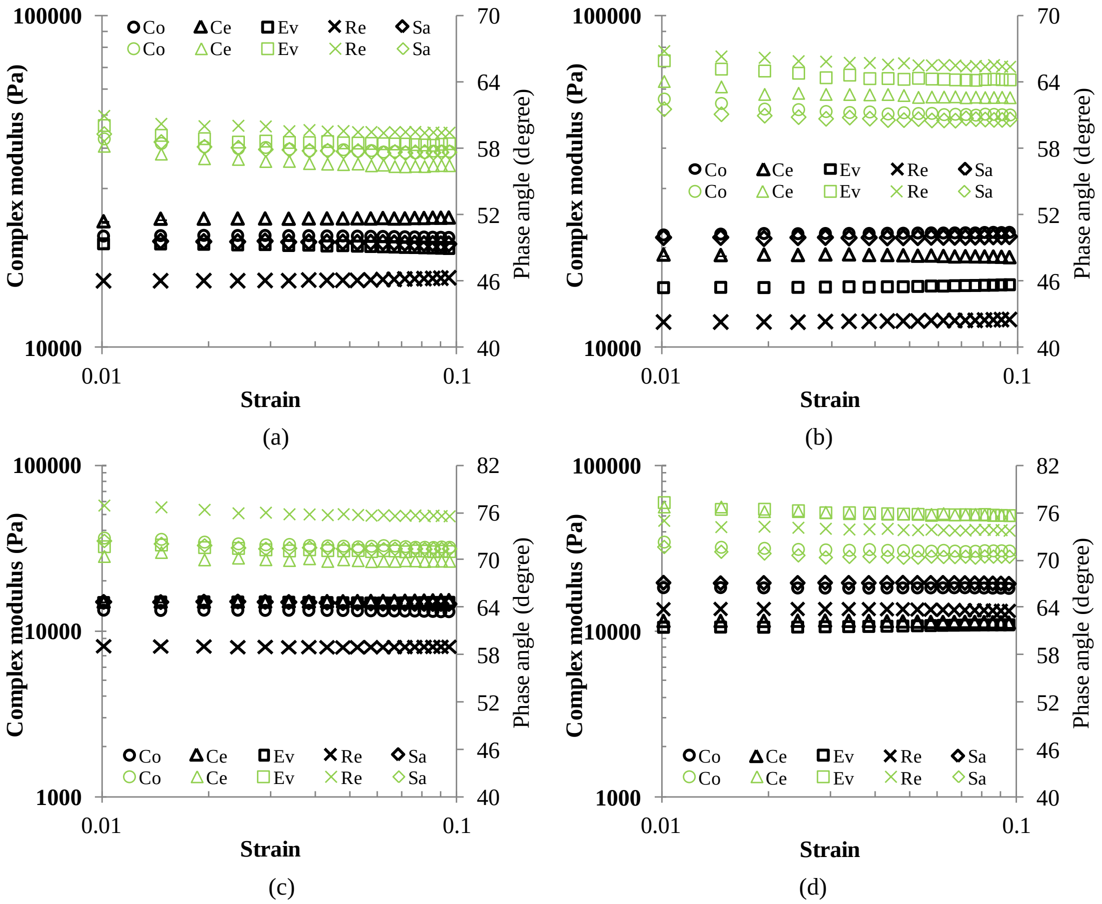


Fig. 7. Complex Modulus and Phase Angle Values of UV Aged WMA Binders, (a) ~ (d) Binders A~D.

higher while phase angles are lower compared to those values of binders C and D due to the binder source and grade regardless of the stress level.

Unlike purely elastic substances, asphalt binder, a visco-elastic substance, has an elastic component and a viscous component. The viscosity of a visco-elastic substance gives the substance a strain rate dependent on time [23]. Purely elastic materials do not dissipate energy when a load is applied, then removed while a visco-elastic substance loses energy. Hysteresis is observed in the stress-strain curve, with the area of the loop being equal to the energy lost during the loading cycle [23].

Fig. 8(a)-8(d) show the elastic and viscous modulus values of four UV aged binders with various WMA additives. It can be seen that, for PG 76-22 binders (Fig. 8(a) and 8(d)), in most cases, the elastic modulus values of WMA binders for binder A are close to 10,000 Pa and greater than those values of WMA binders from binder B. Additionally, binders A and B with Rediset additive have the lowest elastic modulus values in terms of various strain responses. Moreover, as shown in Fig. 8(c) and 8(d), PG 64-22 binders generally have lower elastic modulus values than PG 76-22 binders while no trends can be found for viscous modulus values in this research. Furthermore, the control UV aged binders have different elastic and viscous modulus values with UV aged WMA binders but no trends can be observed.

Frequency Sweep Tests

In this study, the frequency sweep tests were performed under stress proportional to frequency which employed a range of frequency from 0.01 to 100 Hz. The overall frequency sweep tests were run with the 25 mm diameter and 1 mm testing gap geometry at 60^{o}C. Some published articles indicated the frequency sweep tests at various frequencies and temperatures could identify the linear viscoelastic response of the binder [24-26]. In the stress proportional to frequency tests, complex modulus and phase angle were evaluated in accordance with various frequencies and stresses.

Fig. 9 displays the influence of frequency sweeps on the complex modulus and phase angle of various samples from four binders (UV aged states) at 60^{o}C. It can be found that an increase of loading frequency yields an increase in complex modulus values regardless of with or without WMA additive and binder source and grade. Moreover, the samples for binders A and B generally have slightly higher complex modulus values than those samples from binders C and D due to binder grade. Furthermore, it can be observed that the complex modulus values increase quickly at a relative high frequency (more than 10 Hz). As presented in Fig. 9, the addition of WMA additive does not noticeable change complex modulus values in terms of various loading frequencies.

The results shown in Fig. 9 illustrated that the phase angles reduce quickly at a low frequency (less than 5-10 Hz). The reason is that the UV aged binder generally exhibit higher elastic characteristics with an increasing frequency. In addition, Fig. 9 shows that binders A and B generally have lower phase angle values in terms of various loading frequencies due to the binder grade.

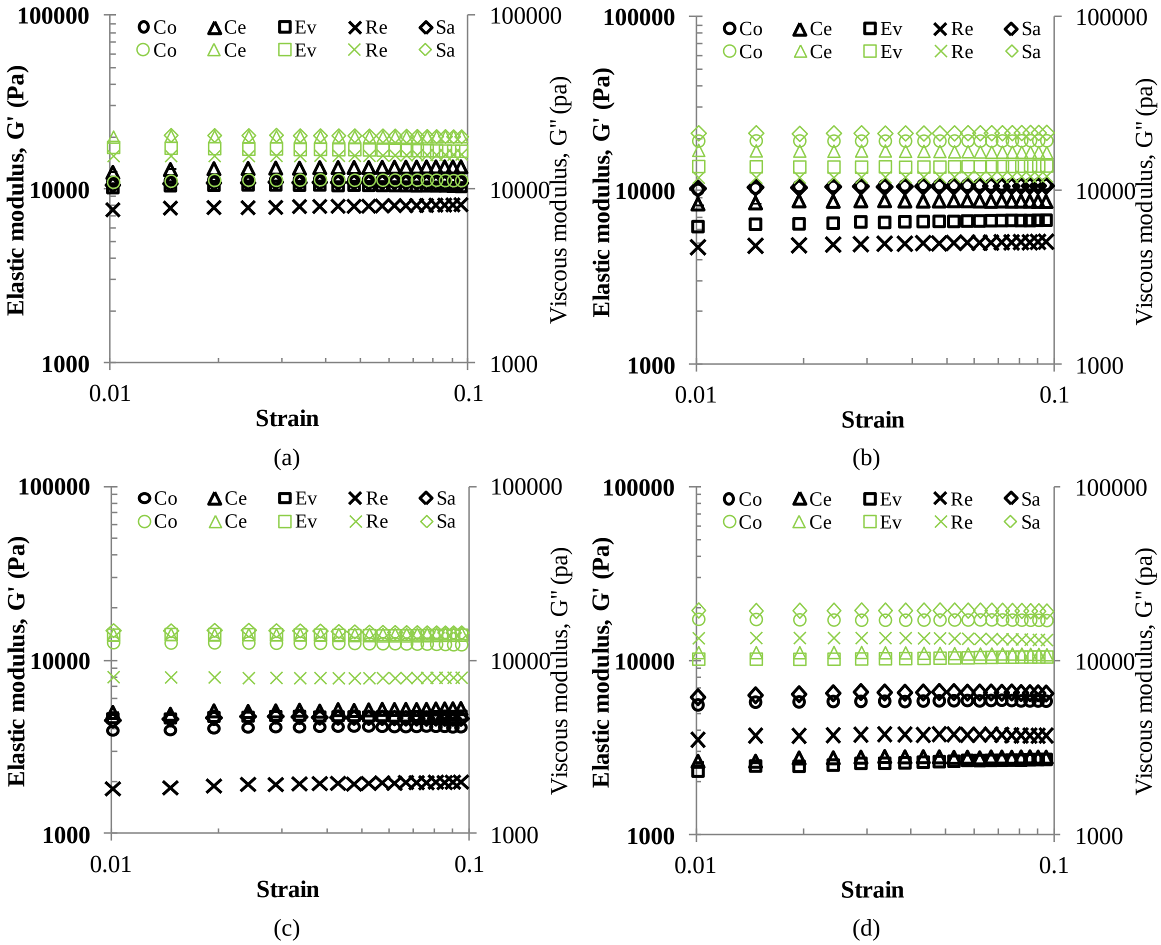


Fig. 8. Elastic Modulus and Viscous Modulus Values of UV Aged WMA Binders, (a) ~ (d) Binders A~D.

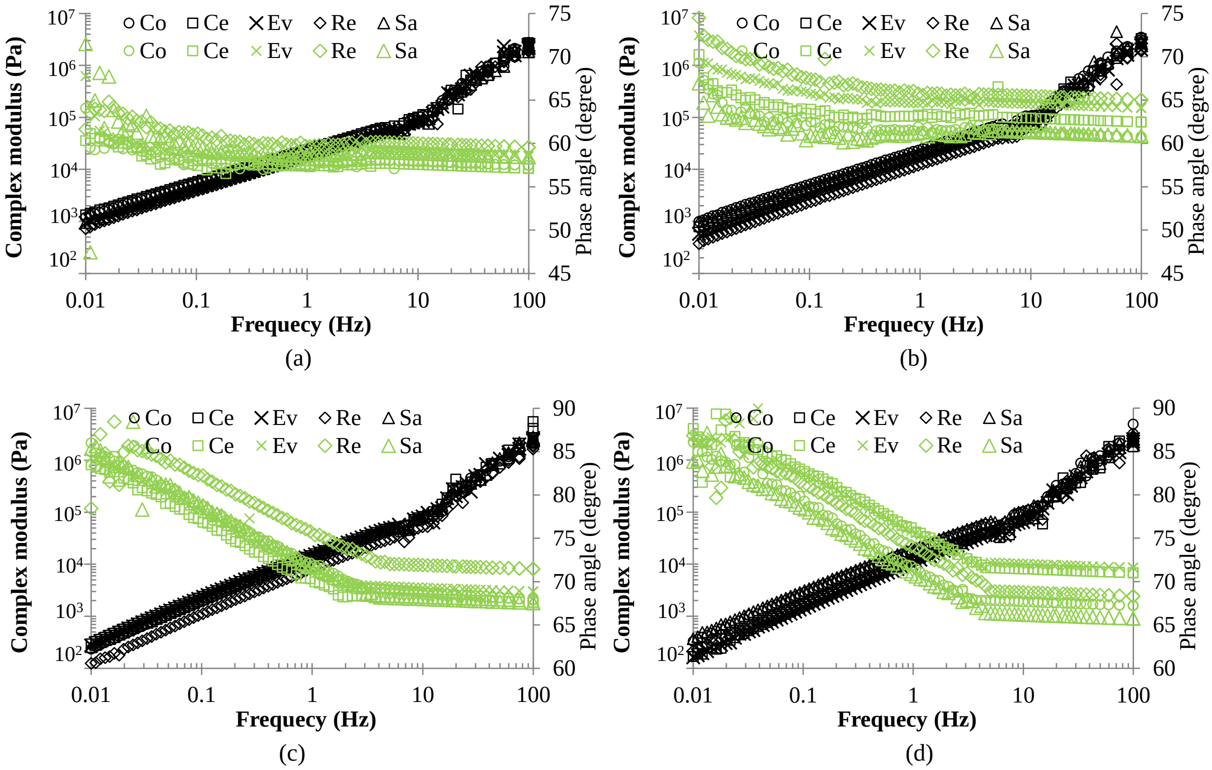


Fig. 9. Complex Modulus and Phase Angle Values of UV Aged WMA Binders, (a) ~ (d) Binders A~D.

Moreover, even though there are some differences in phase angle between different UV aged WMA binders, no obvious trends can be observed in this research.

Findings and Conclusions

In this limited study, it can be found that, after a UV aging process, there were no significantly different G*sin δ values amongst overall binder sources but the binders containing Sasobit additive generally had statistically different phase angles. In addition, apart from binders A and B, there are significant differences in G*sin δ and phase angle values between any two binders containing various WMA additives due to the nature of asphalt binder compositions. Viscous flow indicated that the binders exhibited an increasing shear rate as the shear stress increased and no obvious difference could be found for these various UV aged binders.

Creep and creep recovery results illustrated that the compliance value had decreased due to the removal of stress after a 10-second loading and each UV aged binder exhibited an obvious elastic property at 60℃. With respect to the influences of various WMA additives on creep compliance, no significant trends could be found for all WMA binders in this study. The amplitude test results illustrated that the increase of shear strain did not obviously result in a decrease of complex modulus (keep constant) but reduced the phase angle of the UV aged binder. The control UV aged binders had different elastic and viscous modulus values with WMA binders but no obvious trends could be observed.

Frequency sweep test results indicated that an increase in frequency yielded an increase in complex modulus values for all UV aged binders regardless of with or without WMA additive and binder source and grade. The addition of WMA additive did not noticeably change complex modulus values in terms of various loading frequencies. Even though there were some differences in phase angles between different UV aged WMA binders, no obvious trends could be observed

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