Publication	**American Society for Testing and Materials (ASTM)**
Journal name	**Advances in Civil Engineering Materials (ACEM)**
DOI	**https://doi.org/10.1520/ACEM20190119**
Volume	**November 2019 -- ACEM Volume 8, Issue 1-- ACEM20190119**
Title	**Investigation of Aging Effect on Asphalt Binders using Thin Film and Rolling Thin Film Oven Test**

Investigation of Aging Effect on Asphalt Binders using Thin Film and Rolling Thin Film Oven Test

Hemanth Kumar V[1], and Suresha S N[2]

ABSTRACT

The effect of short-term aging temperature according to Superpave protocol on rheological properties of asphalt binder using thin film oven (TFO) and rolling thin film oven (RTFO) test was investigated. To evaluate these different aging conditions, two types of unmodified binders and a crumb rubber modified binder (CRMB) was used at three different aging temperatures 163°C, 177°C, and 195°C. To simulate the effect of temperature used during the preparation of CRMB in laboratory and ideal mixing temperature corresponding to 170±20cP, 177°C and 195°C has been incorporated, respectively. The rheological characterizations of these binders were obtained using Dynamic shear rheometer for before and after short-term aging. On the basis of rutting parameter, non-recoverable creep compliances (J_{nr}) and percent recovery (%R), and the RTFO aging process was found to be more effective than the TFO test for all the selected oven temperature. However, the complex shear modulus |G*| of the base binders were equivalent to modified binders at 195°C. Additionally, on the basis of Frequency sweep test and viscosity curve, the effect of short-term aging in a sample was investigated. However, at 195°C, the flow properties were significantly different for unmodified base binder, except for rubberized binders. From this study, based on its characterization it is possible to use TFO or RTFO test at a higher

[1] Department of Civil Engineering, Research Scholar, National Institute of Technology, Mangalore, Karnataka, 575025, India; e-mail: hemanth.visl@gmail.com, ORCID: https://orcid.org/0000-0001-8994-9025
[2] Department of Civil Engineering, Associate Professor, National Institute of Technology, Mangalore, Karnataka, 575025, India; e-mail: sureshasn@nitk.edu.in, ORCID: http://orcid.org/0000-0002-2750-7069

temperature to simulate the aging process for rubber modified binder to the actual hot-mix asphalt process.

Keywords

Short term aging, DSR, rheology, mixing temperature, asphalt binder, crumb rubber modified binder

Introduction

Rolling thin film oven (RTFO) test is one of the most widely used apparatus to produce the short-term aging effects on asphalt binder based on conventional hot mixing temperature (150°C), which incorporates the same condition by asphalt pavement. The choice of suitable apparatus and protocols for determining the asphalt's short-term aging effect is vital for investigating the rheological properties of asphalt binder. To enhance the rheological properties of conventional and rubberized asphalt binders, various additives like Bio-modification [1], warm-mix additives [2-11], slurry oil [12], waste polymer composites [13], FT-paraffin [14] [15], polyoctenamer and cross-linking agent [16], have been used to reduce the mixing temperature of modified binder.

Limited studies have been carried out in determining the aging effect of RTFO and thin film oven (TFO) test, such as improving rolling thin film oven test [17], effect of TFO and RTFO at different temperature levels on asphalt binder [18], critical behavior of RTFO aged binder as per AASHTO aging procedure [19], using TFO and RTFO aging methods for simulation of field aging of binders [20], effect of TFO and RTFO aging on asphalt chemistry and rheology [21,22], viscosity behavior at 135°C, before and after TFO aging according to ASTM D1754 [23], and understanding the aging characteristics of both neat and asphalt rubber (AR) binders using field and laboratory studies [24].

Recently there are enormous factors that have documented the rheological behavior of crumb rubber modified binders under the influence of strategic highway research project (SHRP) testing methods [25], type of crumb rubbers and base binders [26], at extreme temperature regime [27], and chemical, morphology of crumb rubbers with self-healing properties of base binder used [28]. In some of the comparative studies between crumb rubber modifiers (CRM) and styrene-butadiene-styrene (SBS) [29], change in aging characteristics of base binder in the presence of CRM [30], and determining the CRM mixture properties as a function of compaction condition [31] dynamic shear rheometer (DSR) and viscosity parameter has been used.

The relationship between binder viscosity and temperature data from literature survey [1-19, 23-31] was graphically represented using a fitted line plot as shown in Figure-1. The rheological properties of modified and unmodified binders are usually influenced by one or combination of the following factors: (a) type of modifiers, (b) mixing temperature, (c) viscosity of base binder, (d) apparatus used to simulate the aging effect. In this study, the mixing and compaction temperatures were determined as per ASTM D4402 M-15 for modified and unmodified binders by using the 170±20 and 280±30 cP viscosity criteria (ASTM D6925-15) as shown in Figure-2. It is clear that the viscosity of CRM binder decreases with increase in temperature as a common trend. However, most of the researchers are determining the rheological properties of the modified binder by subjecting to 163°C RTFO without considering the ideal mixing temperature as indicated in ASTM D6925-15 and binder preparation temperature [9,10,11,15,19,31]. This motivates to investigate the dependency of short-term aging temperature and oven type on the rheological properties of asphalt binder. Using two different types of short-term aging apparatus TFO and RTFO, binders rheological properties were investigated. Finally, the influence of type of oven, binders, and temperature levels on the rheological properties was presented using a two-way interaction method to compare the rheological data. Such interaction studies help in selecting the suitable modifiers for enhancing the asphalt binder properties and identify its applicability in road constructions.

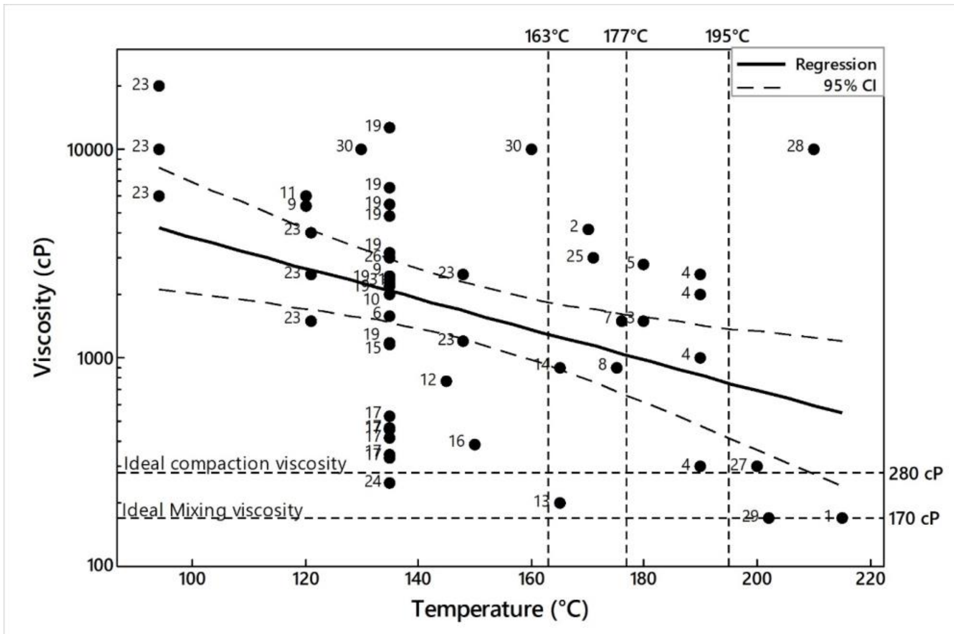

FIG. 1. Viscosity behavior at elevated temperature [1-19, 23-31].

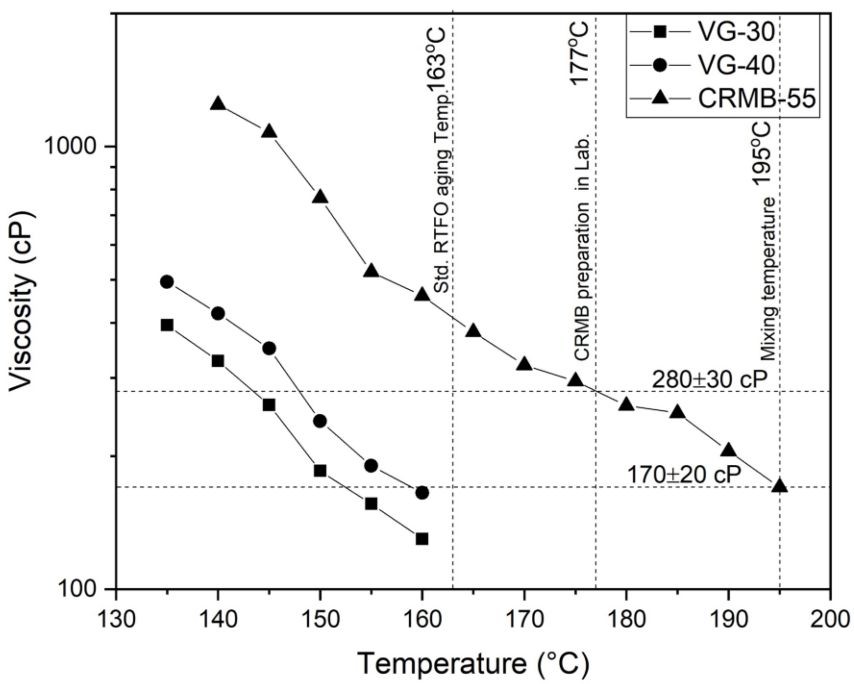

FIG. 2. Viscosity behavior at elevated temperature from the present study.

The possible advantages of using TFO or RTFO testing at a higher temperature for modified asphalt binder could be more convenient to determine the rheological properties. In this study, the results of the aging characteristics of both modified and unmodified asphalt binders by using the TFO and RTFO test at three aging temperatures are presented. Rutting parameter such as G*/sinδ, percent recovery (%R), and non-recoverable creep compliances (J_{nr}) was evaluated using high-temperature performance grade test (PG grade) and Multiple stress creep and recovery test (MSCR) respectively. Frequency sweep test, temperature sweep test, and viscosity curve test was also used to determine aging characteristics of the asphalts before and after TFO and RTFO test. The experimental procedure followed in this study is shown in Figure 3.

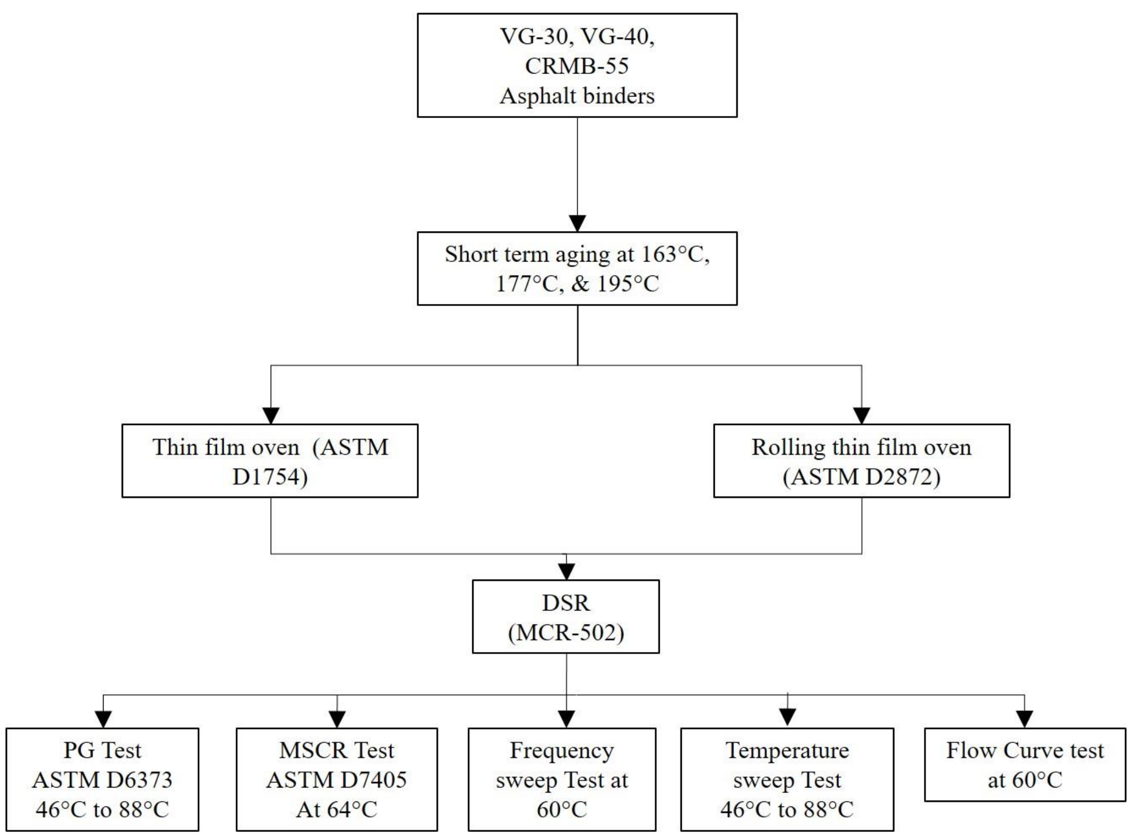

FIG. 3- *Flow chart of experimental design procedures.*

Objectives

This paper aims at utilizing the TFO and RTFO test to simulate the short-term aging process in a laboratory at three different aging temperatures. The focus was to investigate the rheological behavior at different aging simulation temperatures and the study the rheological parameter sensitivity towards the method and condition of short term aging. Effectively, the following objectives were established:

- Investigate the effect of TFOT and RTFOT type of aging on rheological properties of the of asphalt binders
- Investigate the selection of aging temperature for unmodified and modified asphalt binders using rheological properties of the asphalt binder.

Materials and Test Program

Materials

One asphalt with modified with crumb rubber (CRMB-55), was used. The modified binder was according to the Bureau of Indian Standards (BIS) specification for modified binders (BIS 2004) [36]. VG-30 and VG-40 viscosity grade unmodified asphalt binder was taken as the neat asphalt binder and this conforms to the BIS specification for unmodified binders (BIS 2013) [35]. Table 1 shows the properties of the material parameters.

TABLE 1 - The properties of virgin asphalt VG-30, VG-40, and CRMB-55

Specifications	VG-30	VG-40	CRMB-55
Absolute viscosity at 60°C, Poise	2809.57	3785.41	-
Kinematic viscosity at 135°C, cSt	450.13	520.29	-
Viscosity at 150°C, Poise	-	-	7.65
Penetration at 25°C, 100 g, 5 s, 0.1mm	58	42	38
Softening point (R and B), °C	53	56	63
The elastic recovery of half thread in Ductilometer at 25°C, %	50	45.5	60

Aging Procedure

In the laboratory, short-term aging temperature was set to 163°C, 177°C, and 195°C based on the viscosity criteria, the temperature at which 0.17±20 Pa.s is attained for CRMB-55 binder, while the aging process as per the standard 85 min were fixed and all asphalts samples were aged through RTFO and TFO test, respectively. After aging at three different temperatures, the samples were collected for further investigation of rheological properties.

Rheological Tests

The dynamic shear rheometer (MCR-502) was used to evaluate the rheological responses by applying shear strain within the linear visco-elastic region (LVER) and recording the shear stress. Asphalt binder samples were prepared and tested as per ASTM D7175 [39] using dynamic shear rheometer. Initially, to investigate the aging effect of RTFO and TFO, the aged samples were subjected to high-temperature performance grading (PG) test according to ASTM D6373[40]. . Rutting parameter was determined by testing short-termed aged binder using 25 mm diameter plate with a 1 mm gap height at 46°C-88°C. Following ASTM D6373 standard, asphalt binder samples were evaluated at 10 rad/sec, which signifies the shearing action at the traffic speed of 90 km/hr. (55 mph) [32-34][42-44].

In addition, the rutting behavior of the asphalt binder was also assessed using the advanced method of multiple shear creep and recovery (MSCR), as defined in the ASTM D7405-15 [41] standard. In this study, 10 cycles per stress level 0.1 kPa and 3.2 kPa at 1-sec loading was applied to a binder, respectively. The sample was allowed a 9 s of relaxation period. MSCR is also an effective method for determining a modifier's effect in terms of elasticity of an asphalt binder. The testing temperature of 64°C was chosen, which indicates PG grade of the neat binder. In this study 25 mm diameter plate with a gap of 1 mm was used to measure the rheological parameters. There are three criteria's for aged binder obtained from MSCR test results, the J_{nr} (kPa^{-}1) value, which cannot be greater than 4.5; the J_{nr} diff (%) must be less than 75; and depending upon the J_{nr} at 3.2 kPa stress level, classification can be done as shown in Table 2.

TABLE 2. MSCR classifications [28]

Limits $J_{nr3.2}$ (kPa^{-1})	MSCR class	ESAL
≤4.5 kPa^{-1}	S - Standard	<10 million and more than the standard traffic speed (>70 km/h)
≤2.0 kPa^{-1}	H - Heavy	>10–30 million or slow-moving traffic (20–70 km/h)
≤1.0 kPa^{-1}	V – Very Heavy	>30 million or standing traffic (<20 km/h)
≤0.5 kPa^{-1}	E – Extreme	>30 million and standing traffic (<20 km/h)

To ensure uniform temperature distribution (2°C per min) within the samples, dynamic shear rheometer (MCR-502) equipped with an convection temperature device (CTD-180) was used to perform temperature sweep test. The rheological responses of all asphalt binders at 60°C temperature were also obtained from frequency sweep tests. The loading frequencies were ranging from 0.1 rad/s to 100 rad/s. the strain amplitude within LVER following SHRP specification was used to measure complex modulus (|G*|), and phase angle (δ). Additionally, a viscous flow measurements was performed between shear rate 0.1 to 10 sec^{-1} at 60°C temperature using DSR with 25mm diameter plate-plate geometry, and 1mm gap.

Statistical analysis, method

The analysis of variance (ANOVA) is used to evaluate the factors which are composed of three types of asphalt binders, 3 different aging temperatures, and 2 types of oven (TFO and RTFO) on the binder rheological properties and to determine which factors have the severe effect on the performance measurement of asphalt binder. In this study asphalt type, temperature, and oven type are regarded as fixed effects. The effect of interactions between the asphalt type, oven type, and temperature was studied by utilizing the two-way ANOVA method. The statistical analyses were conducted using Minitab computer software.

Two-way ANOVA test method was used to compare the rheological performance properties all the asphalt binder samples. Minitab 17 software was used to perform statistical variations on the rheological properties data. Three groups of datasets corresponding to three type of binders associated with two type of short term aging (TFOT and RTFOT), and three-level of different temperature (163°C, 177°C, and 195°C) with mean of three replicates with total dataset of 18 data points were statistically used for each type of rheological test.

Results and Discussion

The results of the rheological characterization of VG-30, VG-40, and CRMB-55 asphalt binder were obtained after aging at three different temperature using TFOT (ASTM D1754) [38] and RTFOT (ASTM D2872) [37]. The following subsections present the effect of type of short aging on results obtained in this study and their further discussion.

Effect of type of short-term aging on rutting parameter

The rutting parameter of three asphalt binder, which is aged at three different temperature using TFOT and RTFOT oven was determined using DSR by performance grading (PG) test as per ASTM D6373. Generally, when a higher G*/sinδ response is associated with higher test temperature is identified as a better asphalt binder and be selected for further analysis. The average G*/sinδ for all the three types of asphalt binder, before and after TFOT, RTFOT aged condition at three different temperature is presented in Figure 4. As expected, the average G*/sinδ for all the asphalt binder (VG-30, VG-40, and CRMB-55) increased as the oven temperature increased from 163C° to 195°C. The increasing trend of the VG-30 and VG-40 was such that at 195°C was overlapped with CRMB-55 as shown in Figure 4, in which observation of stiffing could be made with an increase in oven temperature.

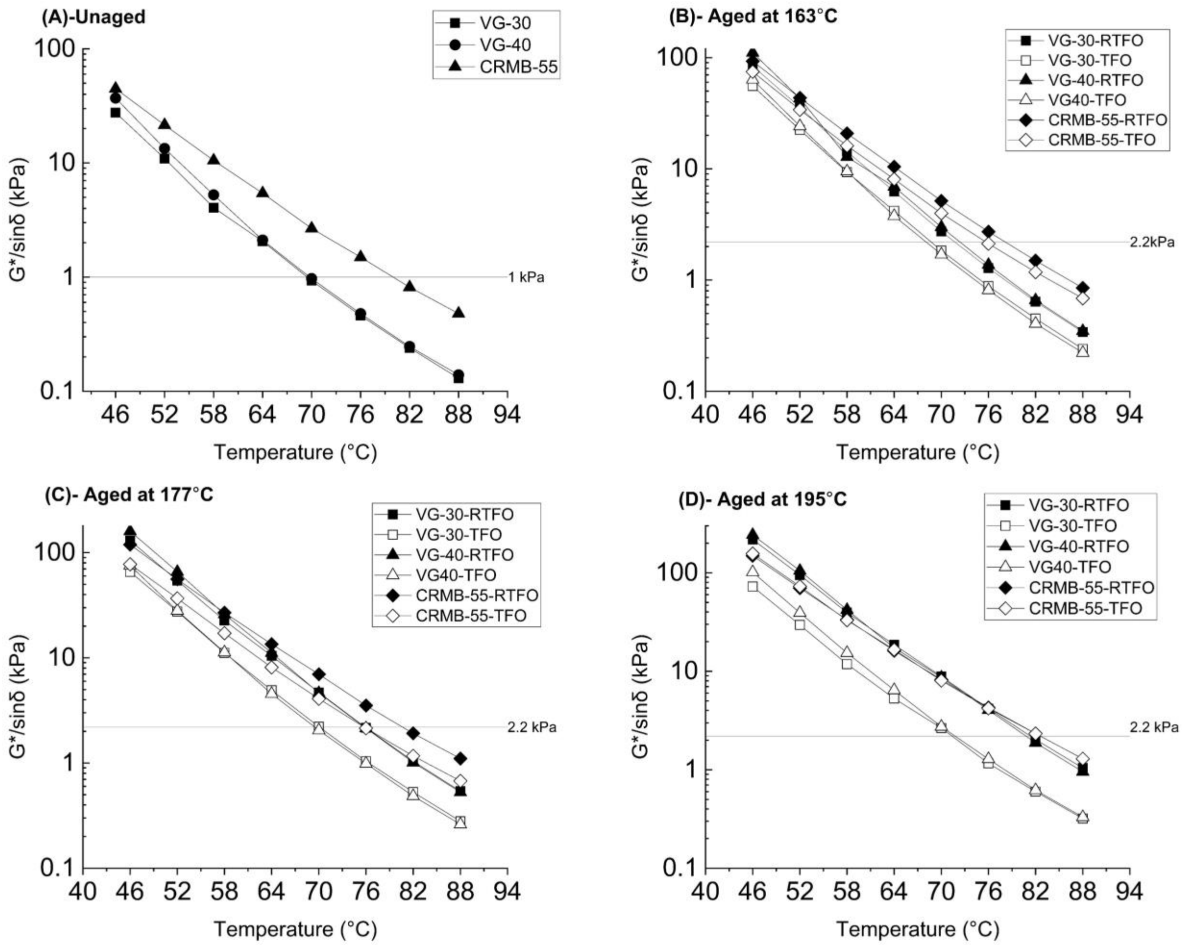

FIG. 4-G*/sinδ for VG-30, VG-40 and CRMB-55 of different aging residue: (a) Unaged (b)163°C (c) 177°C (d) 195°C

The Preliminary full analysis of variance (ANOVA) for G*/sinδ indicated that at 163°C, 177°C and 195°C had a significant difference between TFOT and RTFOT aged conditions for VG-30 and VG-40. However, for CRMB-55 at 195°C, the difference between TFOT and RTFOT was found to be less significant. These findings correlate with what was observed and inferred in Figure 4. Therefore, a factorial analysis was performed using ANOVA considering only the effects of asphalt type, Temperature, oven type, and their interactions. The factorial analysis suggests that the G*/sinδ of an asphalt binder was greatly affected by the type of Oven and the temperature used for aging Table 3, with a p-value of 0.014 and 0.034, respectively. Therefore, the type of oven and aging temperature played a role in the determination of G*/sinδ but there was no significant interaction effect between asphalt type, oven and temperature were observed.

Interaction plot and table for rutting parameter (G*/sinδ) are shown in Figure 5 and Table 3, respectively. From these plots, it can be concluded that asphalt type and the oven temperature will not significantly affect the rutting parameter, whereas asphalt-oven and temperature-oven plays a fair role in the measurement of G*/sinδ.

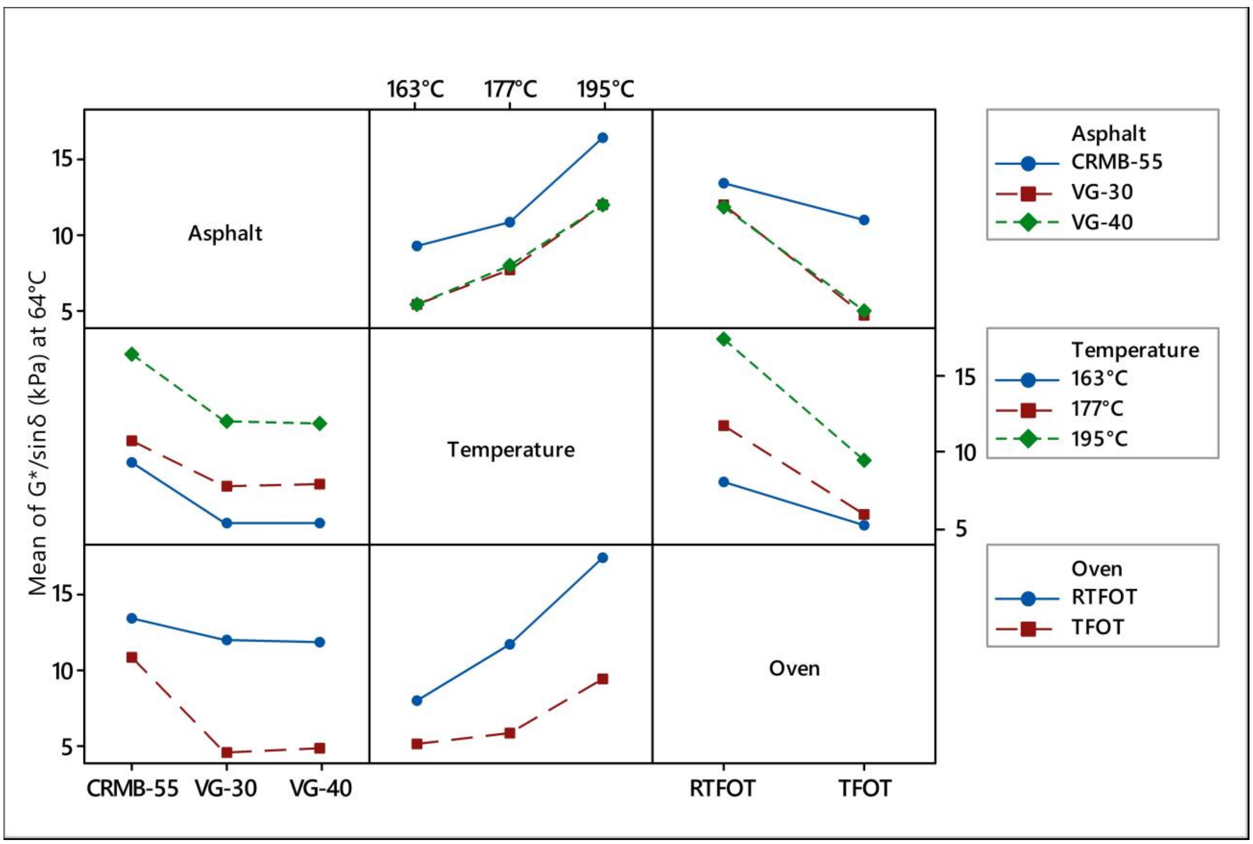

FIG. 5 Interaction plots for Rutting parameter G*/sinδ (kPa)

TABLE 3 - Results of ANOVA on G*/sinδ (kPa) at 10 rad/s on Performance grade test

64°C Source	DF	Adj SS	Adj MS	F-Value	P-Value
Asphalt	2	57.925	28.962	3.56	0.129
Temperature	2	143.843	71.922	8.84	0.034
Oven	1	139.001	139.001	17.09	0.014
Asphalt*Temperature	4	1.409	0.352	0.04	0.995
Asphalt*Oven	2	21.9	10.95	1.35	0.357
Temperature*Oven	2	19.339	9.669	1.19	0.393

Temperature Sweep test

Temperature sweep test was performed with a frequency of 10 rad/s and the temperature ranging from 46°C to 88°C. From Figure 6, we can easily see an upward trend of the phase angle with the temperature rises. In other words, TFOT method of aging has less effect on phase angle when compared to RTFOT at all the three different aging temperature.

The temperature from 46°C to 88°C with the strain level (within the LVE region) were applied and the results of each asphalt binder with three different aging levels using TFOT and RTFOT are shown in Figure 6. As expected, the phase angle (δ) was increased with increasing the test temperature (i.e., Behaving like fluid). Those values among the binders seem to be similar expect CRMB-55 as the temperature increases. The behavior of RTFO and TFO aged samples such as, VG-30, VG-40 and CRMB-55 asphalt binder clearly indicated that TFOT has less impact on phase angle at all the three different aging temperature expect CRMB-55, which closely shows the similarity between two types of ovens i.e., RTFOT and TFOT at 195°C when compared to other two binders. And also it can be observed that RTFOT aged samples such as VG-30 and-40 changes its phase angle and becomes very stiff as an increase in oven aging temperature from 163 to 195°C, which is closed to the stiffness of CRMB-55 binder.

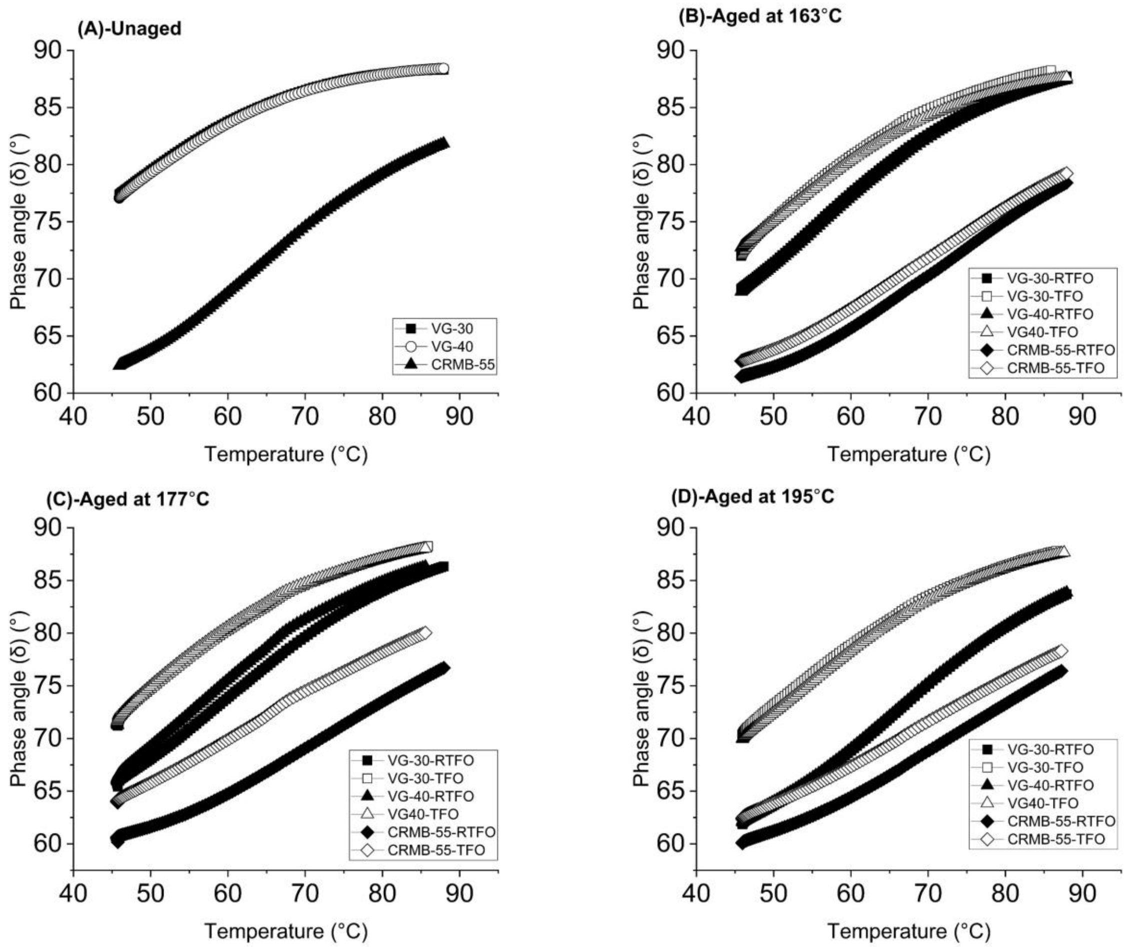

FIG. 6-Phase angle vs. temperature sweep for VG-30, VG-40 and CRMB-55 of different aging residue: (a) Unaged (b)163°C (c) 177°C (d) 195°C

Multiple stress creep and recovery test

According to ASTM D, 7405 [41], the MSCR test was conducted at 64°C on the RTFOT aged as well as TFOT aged binders at different temperature as shown in Figure 7. The MSCR %R and J_{nr} values of the test binder samples indicates that the criteria for the selection of the binder also depends upon the type of the oven used with proper temperature as an input. Both VG-30 and VG-40 shows a significant difference in terms of %R and J_{nr} values for TFOT and RTFOT method of aging.

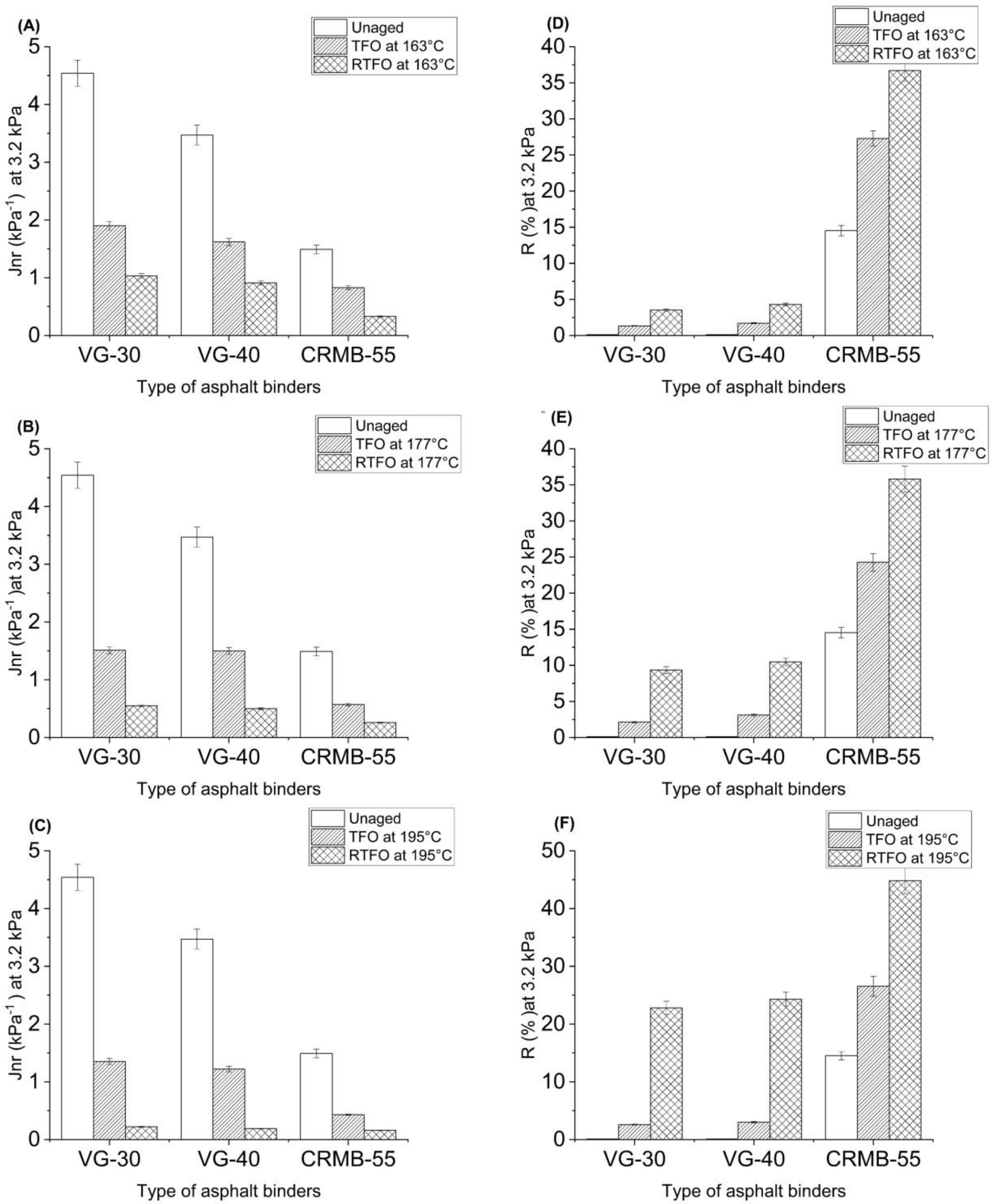

FIG. 7-J_{nr} and %R values at 3.2 kPa stress level for VG-30, VG-40 and CRMB-55 of different aging residue: (a) Unaged (b)163°C (c) 177°C (d) 195°C

The results of the MSCR test are given in Figure 7, J_{nr} and %R data are recorded at 3.2 kPa stress level were analyzed separately. Using TFO and RTFO at three different aging temperature, %R and %J_{nr} were compared with each other. Results of ANOVA on the %R and J_{nr} are summarized in Table 4 and Table 5 respectively, which indicates that all three main effects (asphalt, oven, and temperature) and all the interactions (asphalt*temperature, asphalt*oven and temperature*oven) are significant for J_{nr} values (P<0.0001) but for %R, all three main effects with only interaction between temperature*oven are significant Table 5. Comparison of the effects of the oven was also done at different temperature by means of Dunnett's multiple range test with a significance level of 0.05. The results are summarized in Table 6, which indicates that the effects of RTFO and TFO test are not significantly different at an oven temperature of 163°C and 177°C RTFO. But at 195°C, the RTFO test is a more effective aging process than the TFOT from the perspective of J_{nr} values.

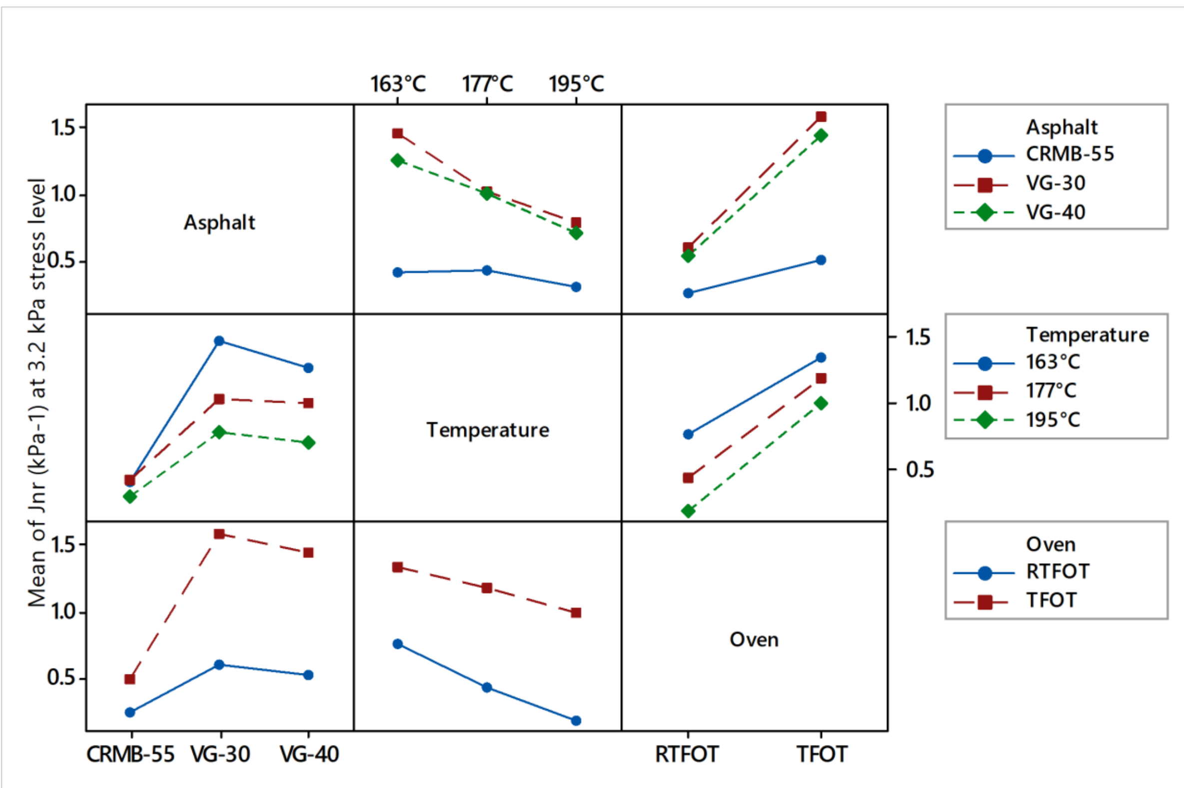

FIG. 8 Interaction plot for J_{nr} at 3.2kPa stress level at 64°C

Interaction plots for J_{nr} and % R are shown in Figure 8 and 9, respectively. From Figure

8, it can be concluded that J_{nr} value significantly affects the type of asphalt binder and oven type used for evaluation of non-recoverable creep compliances. Whereas from Figure 9, it can be concluded that, %R value is significantly affected by the combination of temperature selection of the oven and type of the oven used for the investigation of the percent recovery.

TABLE 4 - Results of ANOVA on J_{nr} (kPa-1) at 3.2 kPa on MSCR test

64°C Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Asphalt	2	1.81871	0.90936	324.13	<0.0001
Temperature	2	0.61214	0.30607	109.1	<0.0001
Oven	1	2.30409	2.30409	821.26	<0.0001
Asphalt*Temperature	4	0.19462	0.04866	17.34	0.009
Asphalt*Oven	2	0.49871	0.24936	88.88	<0.0001
Temperature*Oven	2	0.04348	0.02174	7.75	0.042

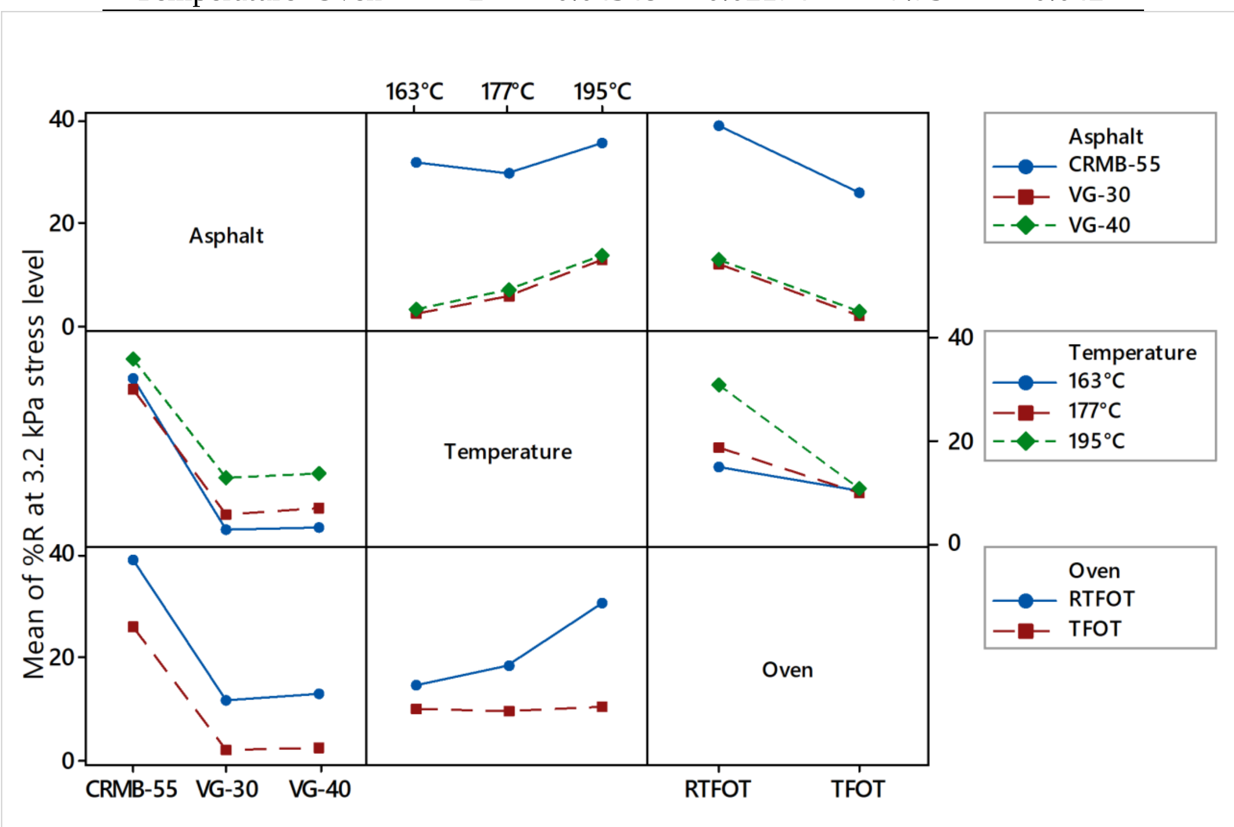

FIG. 9 Interaction plot for %R at 3.2kPa stress level at 64°C

TABLE 5 - Results of ANOVA on %R at 3.2 kPa on MSCR test

64°C Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Asphalt	2	2539.36	1269.68	319.18	<0.0001
Temperature	2	224.7	112.35	28.24	0.004
Oven	1	556.22	556.22	139.83	<0.0001
Asphalt*Temperature	4	34.56	8.64	2.17	0.235
Asphalt*Oven	2	8.77	4.39	1.1	0.416
Temperature*Oven	2	186.85	93.42	23.49	0.006

TABLE 6 - Comparison of TFO and RTFO test at three temperature on the J_{nr} values at 3.2 kPa stress level

Temp.	Dunnett Grouping	Mean	N	Oven
163°C	A	0.757	3	RTFOT
	A	1.337	3	TFOT
177°C	A	0.436	3	RTFOT
	A	1.193	3	TFOT
195°C	A	0.190	3	RTFOT
	B	1.000	3	TFOT

*inducates with the same letter are not considerably different.

Frequency sweep test

The frequency sweep test was conducted from 0.1 rad/s to 100 rad/s for all the three types of binders at all the three different aging temperature, which represents conditions of pavements affected by the traffic speed at a specific temperature (60°C was adopted as test temperature). For the |G*| (complex shear modulus) and δ (phase angle), it was identified that there was a significant difference between TFOT and RTFOT aged sample binders.

Study of frequency sweep test at 10 rad/sec at 60°C indicates that there is a definite increase in |G*| as shown in Figure 10 and decrease in Phase angle as shown in Figure 12 as the level of oxidation increases. It can be observed that as the oxidation level i.e., the aging temperature has increased from 163°C to 195°C for VG-30 and VG-40, |G*| starts to exhibit similar to CRMB-55 for an RTFO aged condition. However, from the ANOVA analysis as shown in Table 7, it was observed that temperature and oven are the main effects and from the interaction of temperature*oven causes the significant difference between the TFOT and RTFOT aged samples at 163°C, 177°C, and 195°C. Since these two |G*| and phase angle are most significant rheological functionality that can be related to oxidation aging, the examination of the frequency sweep test in this study was done particularly with reference to 60°C at 10 rad/sec.

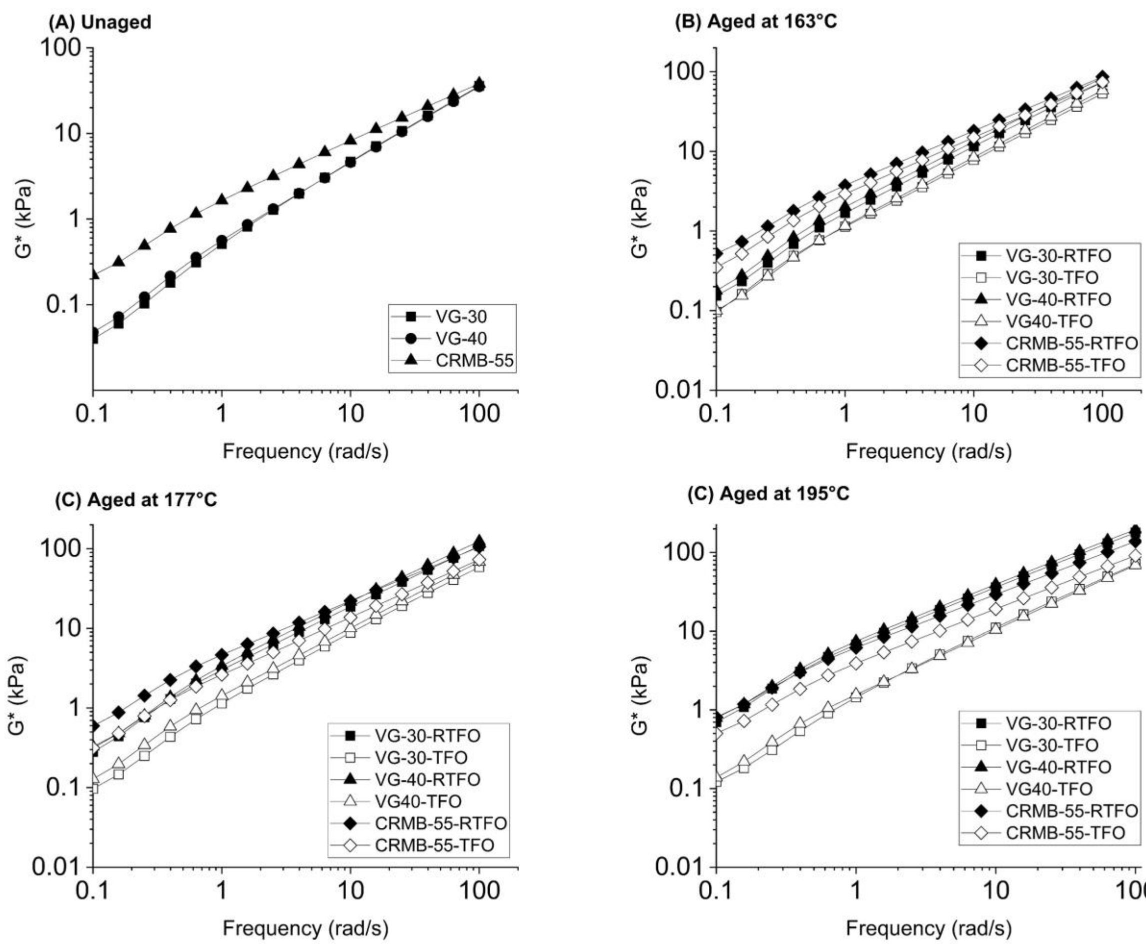

FIG. 10- |G*| vs. frequency sweep for VG-30, VG-40 and CRMB-55 of different aging residue: (a) Unaged (b)163°C (c) 177°C (d) 195°C

Interaction plot for complex shear modulus |G*| are shown in Figure 11. From these plots, it can be concluded that the complex shear modulus |G*| kPa could be significantly affected by the combination of the temperature and type of the oven selection during the frequency sweep tests.

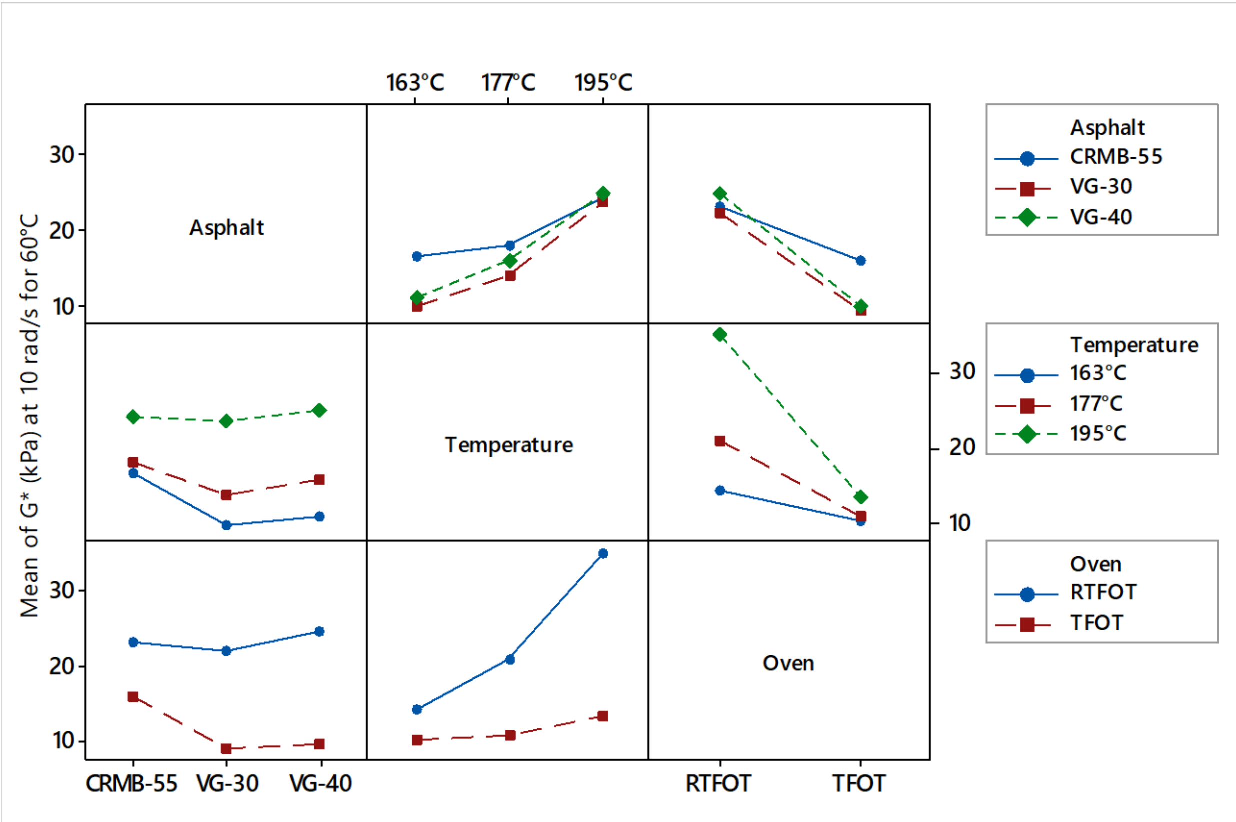

Figure 11 Interaction plot for |G*| at 10 rad/s for 60°C test temperature

TABLE 7 - Results of ANOVA on |G*| (kPa) at 10 rad/s from frequency sweep test

60°C Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Asphalt	2	46.07	23.033	1.76	0.282
Temperature	2	451.14	225.57	17.28	0.011
Oven	1	620.51	620.512	47.52	0.002
Asphalt*Temperature	4	26.91	6.728	0.52	0.732
Asphalt*Oven	2	49.75	24.873	1.9	0.262
Temperature*Oven	2	236.16	118.081	9.04	0.033

Figure 12 also indicates that the phase angle at 163°C and 177°C aging condition for VG-30, VG-40 and CRMB-55 has a significant difference between TFOT and RTFOT, It can also be seen that as the aging temperature increases CRMB-55 shows a similar trend for both TFO and RTFO aged condition at 195°C, whereas for VG-30 and VG-40 have proven to be very largely different. The results of ANOVA on the data are summarized in Table 8, which indicates that asphalt and oven are the main effects with ($P<0.001$), which shows a significant difference between the TFOT and RTFOT, but there are no interaction effects.

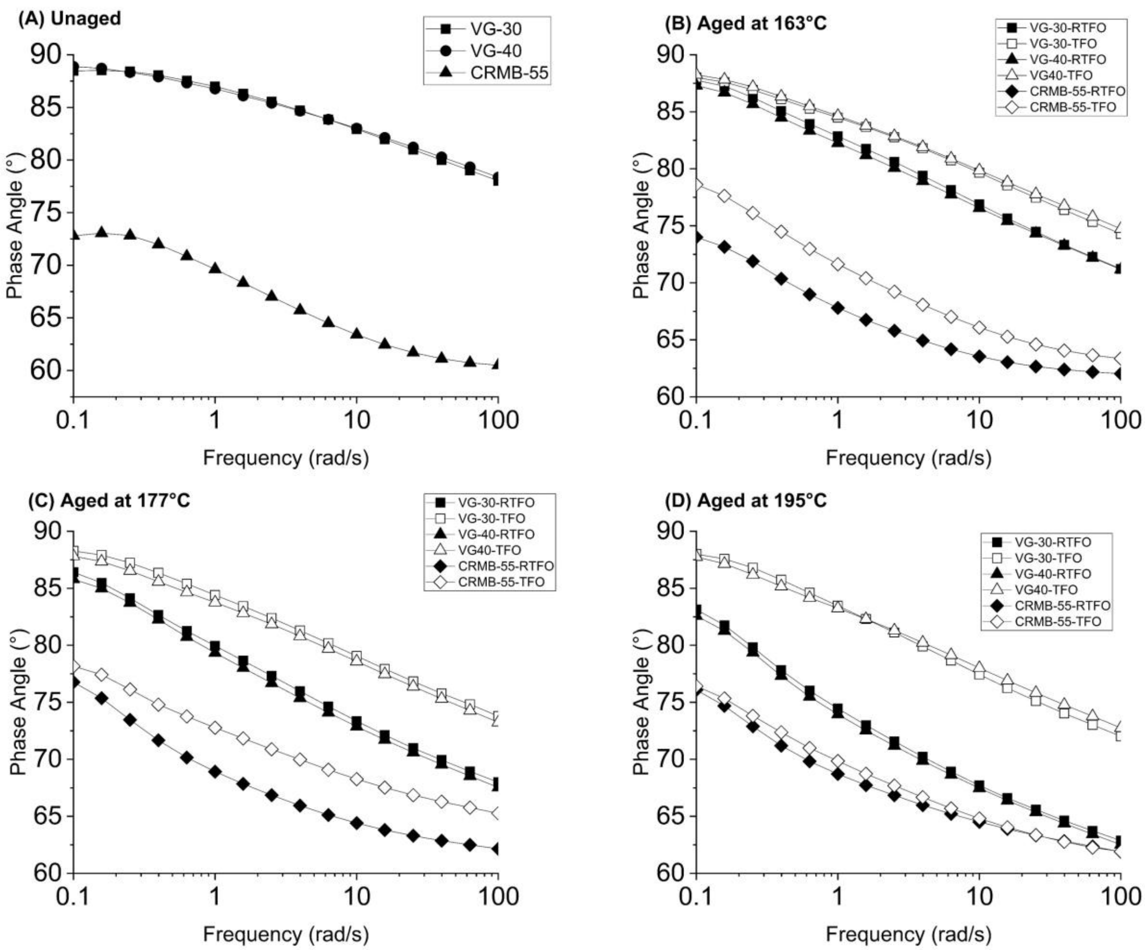

FIG. 12-Phase angle vs. Frequency sweep for VG-30, VG-40 and CRMB-55 of different aging residue: (a) Unaged (b)163°C (c) 177°C (d) 195°C

Interaction plot for phase angle is shown in Figure 13. From these plots, it shows that there is no significant contribution of temperature and oven type selection process. But for CRMB-55 binder type, both RTFOT and TFOT seems to be affecting in a similar way.

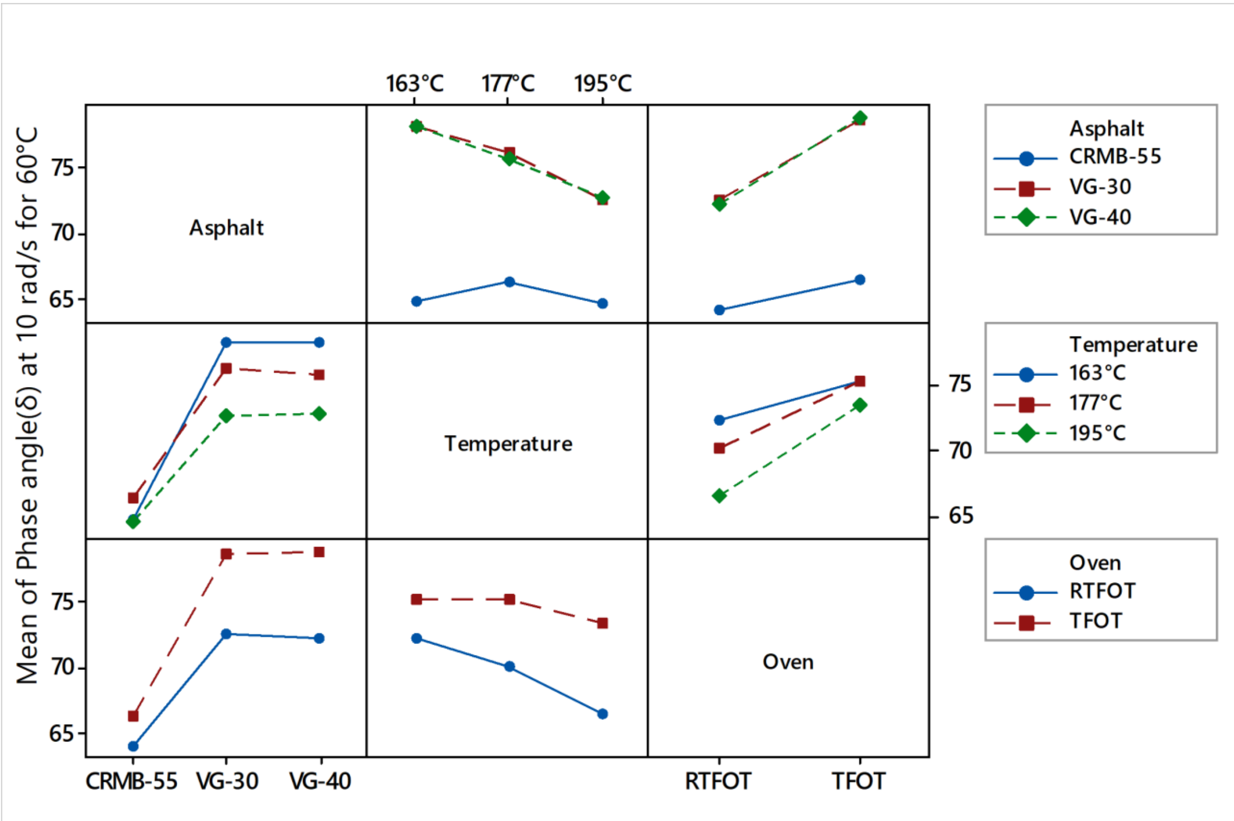

FIG. 13 Interaction plot of phase angle (δ) at 10 rad/s for 60°C test temperature

TABLE 8 - Results of ANOVA on Phase angle (°) at 10 rad/s on frequency sweep test

60°C Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Asphalt	2	428.81	214.406	50.36	0.001
Temperature	2	45.77	22.884	5.38	5.380
Oven	1	109.87	109.866	25.81	0.007
Asphalt*Temperature	4	20.92	5.231	1.23	0.423
Asphalt*Oven	2	16.69	8.344	1.96	0.255
Temperature*Oven	2	11.95	5.976	1.4	0.345

Viscosity Curves

The flow curves of the asphalt binder VG-30, VG-40, and CRMB-55 at the temperature 60°C are reported in Figure 14. For all the three different aging temperature used in TFOT and RTFOT, viscosity was observed to be significantly different from each other for all the three types of binders. The selected test temperature was chosen by considering that critical flow behavior at 60°C for this type of materials.

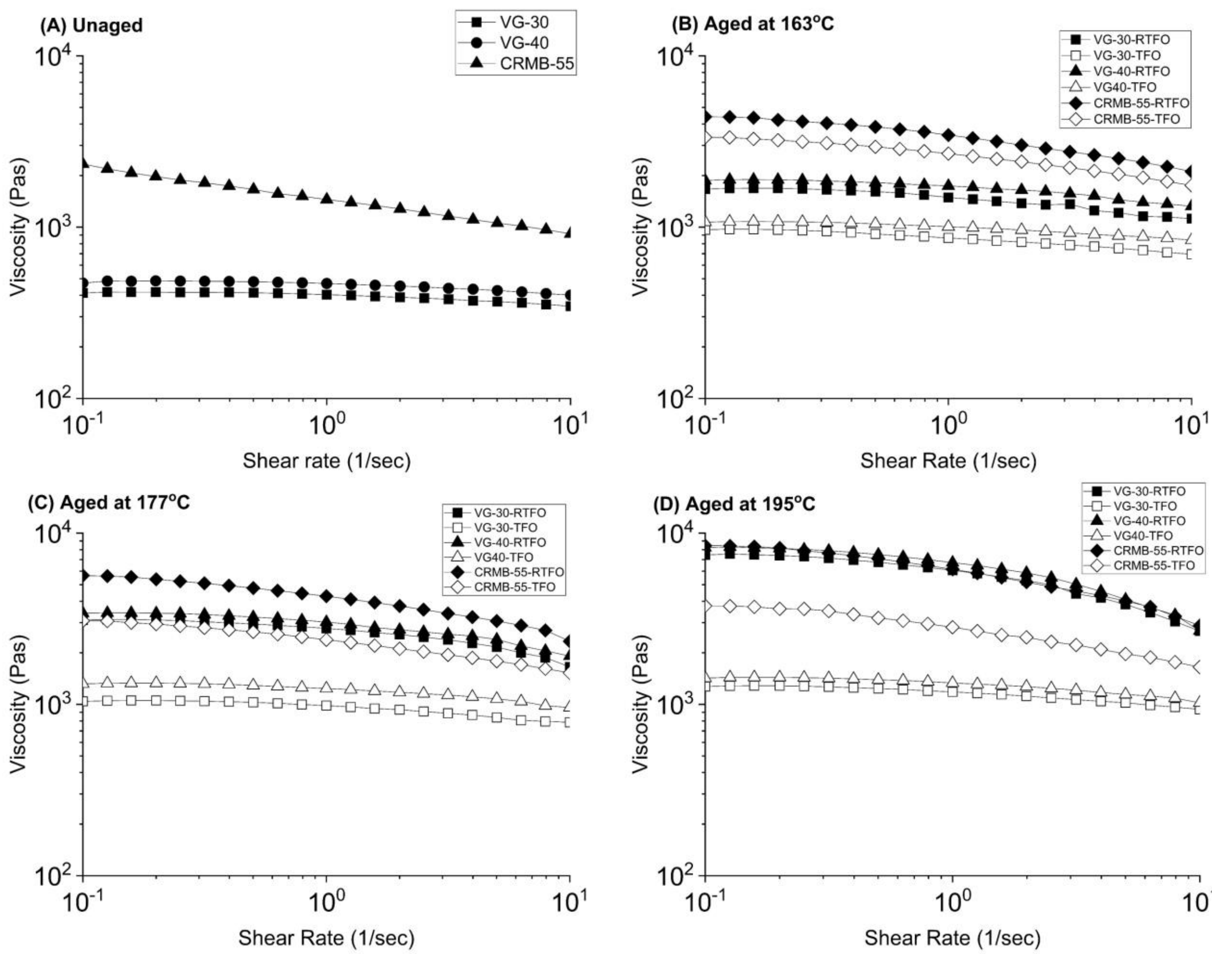

FIG. 14-Viscosity vs. Shear Rate for VG-30, VG-40 and CRMB-55 of different aging residue: (a) Unaged (b)163°C (c) 177°C (d) 195°C

Figure 14 illustrates viscous flow curves, as a function of shear rate, for the three different aging levels (a) 163°C (b) 177°C (c) 195°C. Most of the binders indicated the Newtonian flow behavior at 60°C for 163°C and 177°C level of aging, expect at 195°C level of aging. The viscosity of the Newtonian materials are observed to be independent of shear rate, and conventional asphalt binders normally exhibit Newtonian flow behavior at a temperature greater than 60°C. However, the viscosity of CRMB-55 seemed to decrease with an increase in shear rate, therefore exhibiting a shear-thinning flow behavior at 60°C. This phenomenon is also known as pseudoplastic and observed in a crumb rubber modified binder.

Results of ANOVA on the viscosity curve test are summarized in Table 9 which indicates that the three main effects such as, asphalt type, temperature, and oven type effects significantly between TFOT and RTFOT aged samples in determining the viscosity at 60°C. When the viscosity curve plotted for different aging levels, it was observed that the base binder (VG-30 and 40) stiffened more, which is equivalent to CRMB-55 at 195°C of aging level in RTFOT type of oven. The viscosity properties measures at 60°C shifts parallel from TFOT towards the RTFOT as the oven aging temperature increases. Therefore, the rate of parallel shifting of curves depends on the influence of the aging process; it shifts more for a higher oven temperature than for lower oven temperature.

Interaction plot for viscosity curve at 60°C test temperature are shown in Figure 15. From these plots, it can be concluded that there is an effect of temperature and oven type selection on the viscosity measurement. Therefore it is very vital to select the aging temperature and oven type for the measurement of the specific rheological parameters.

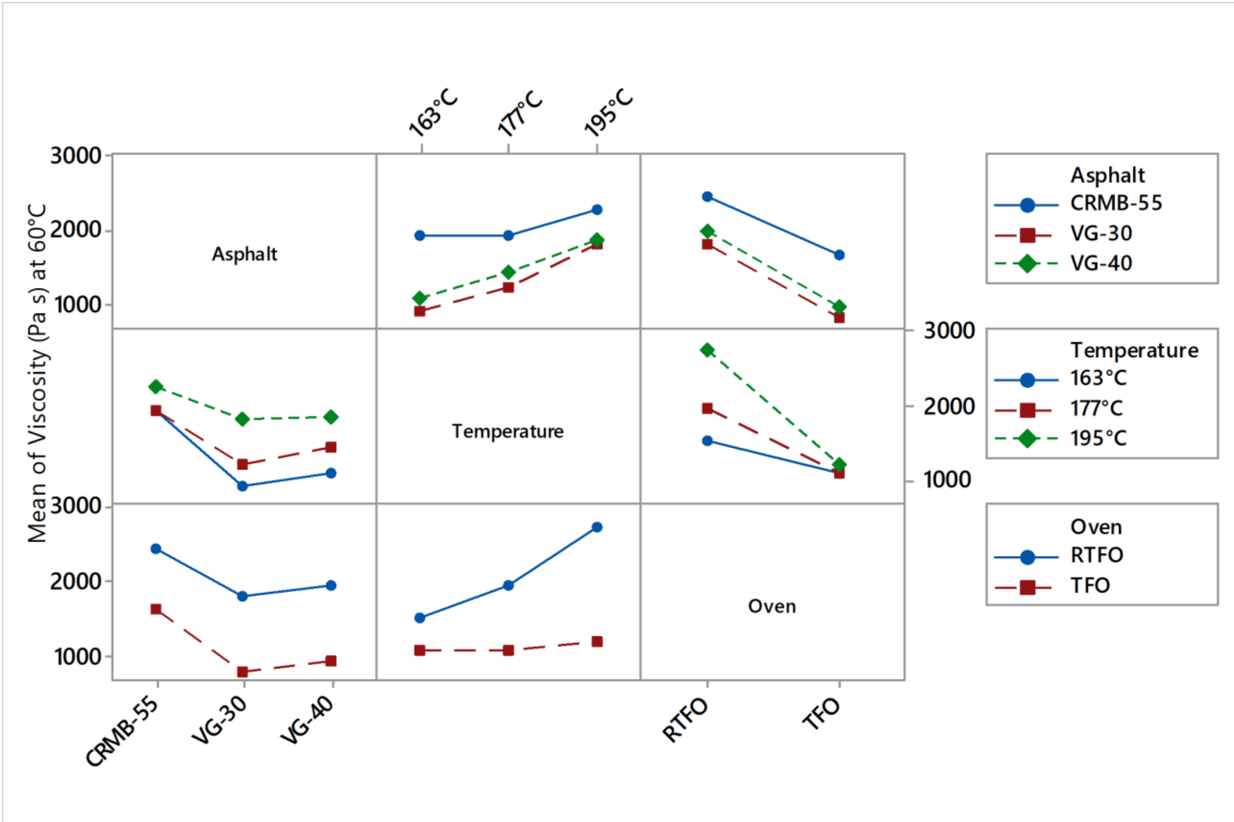

FIG. 15 Interaction plot for viscosity at 60°C test temperature

TABLE 9 - Results of ANOVA on viscosity at 60°C on the flow curve test

60°C Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Asphalt	2	1805793	902896	102.52	<0.0001
Temperature	2	1395446	697723	79.22	0.001
Oven	1	4060623	4060623	461.07	<0.0001
Asphalt*Temperature	4	188420	47105	5.35	0.067
Asphalt*Oven	2	50358	25179	2.86	0.169
Temperature*Oven	2	959347	479674	54.47	0.001

Summary and Conclusion

The TFOT and RTFOT tests were used by many researchers and government agencies according to ASTM standards, which indicates the major changes in properties of the asphalt during the conventional hot-mixing at about 163°C as indicated by the rutting parameters such as G*/sinδ, %R and J_{nr} , |G*| and phase angle, and viscosity. It recognizes an aged sample, which changes the properties of the asphalt binder as observed in the pavements. The rheological properties of asphalt binder would be affected more substantially, if the short-term aging temperature differs from 163°C, i.e. mixing temperature used in hot mix asphalt plants. .

Results of the tests on asphalt binders presented in this paper have indicated that higher oven temperature results in increased stiffens properties, specifically for RTFOT oven when compared to TFOT oven. The change in G*/sinδ for specimen VG-30 and VG-40 was equivalent to CRMB-55 at higher oven temperature, particularly with RTFOT. The higher temperature of 195°C would magnify the asphalt properties change compared to lower test temperature of 163°C. On the basis of MSCR test results, the effect of RTFOT is slightly more severe than that of the TFOT for all three different oven temperatures of 163°C, 177°C, and 195°C. On the basis of frequency sweep test results, the effect of TFO and RTFO test are not significantly different for oven temperature of 195°C, whereas the VG-30 and VG-40 were significantly different for oven temperature of 163°C and 177°C in terms of |G*| and phase angle measured from 0.1 to 100 rad/sec at 60°C. From the standpoint of viscosity measures by varying the shear rate from 0.1 to 10 (sec^{-1}) at 60°C, the effect of TFO and RTFO test are significantly different from each other at any of the three aging temperatures. Therefore, there is no reason to favor the TFOT process over the RTFOT process, especially for the rheological measured parameters using PG test, MSCR test and viscosity test except in frequency sweep test when the oven temperature is raised to 195°C. The laboratory test results in this study showed that the use of 177°C and 195°C by RTFO and TFO aging method improves in the selection of the binders based on its rheological performance in several unique ways as summarized below.

• In PG grading test, G*/sinδ value with respect to types of binders, RTFO and TFO aging process and different aging temperatures, oven type and temperature used for aging process plays a vital role in the selection of the binders.

• In MSCR test, Jnr and %R value depends individual upon the type of oven, aging temperatures, binder types, and also the combination of oven and asphalt binder type in the selection of binders.

• In frequency sweep test, |G*| value depends upon the combination of temperature and oven, whereas, δ depends individually upon the asphalt and oven types in the selection of asphalt binders at 60°C test temperature.

• Finally, in the flow curve test, η value depends upon asphalt binder, oven, temperature type individually, and also with the interaction of temperature and oven type during the selection of asphalt binder.

Acknowledgments

The authors would like to acknowledge the financial support extended by the Department of Science and Technology, Government of India under the scheme 'Fund for Improvement of Science and Technology infrastructure' (No. SR/FST/ETI-356/2013) for the creation of required research facilities at the Advanced Asphalt Characterisation and Rheology Laboratory,

Department of Civil Engineering, National Institute of Technology Karnataka, India.

References

[1] E. H. Fini, S. Hosseinnezhad, D. Oldham, Z. Mclaughlin, Z. Alavi, and J. Harvey, "Bio-modification of rubberised asphalt binder to enhance its performance," Int. J. Pavement Eng., vol. 8436 (April/October 2017):1–10, https://doi.org/10.1080/10298436.2017.1398548

[2]. T. Ma, H. Wang, Y. Zhao, X. Huang, and S. Wang, "Laboratory Investigation of Crumb Rubber Modified Asphalt Binder and Mixtures with Warm-Mix Additives," Int. J. Civ. Eng 15, no. 2 (March/May 2016):185–194, https://doi.org/10.1007/s40999-016-0040-3

[3]. A. M. Rodríguez-Alloza, J. Gallego, and I. Perez, "Study of the effect of four warm mix asphalt additives on bitumen modified with 15% crumb rubber," Constr. Build. Mater 43 (December/February 2013): 300–308, https://doi.org/10.1016/j.conbuildmat.2013.02.025

[4] A. M. Rodríguez-Alloza, J. Gallego, I. Pérez, A. Bonati, and F. Giuliani, "High and low temperature properties of crumb rubber modified binders containing warm mix asphalt additives," Constr. Build. Mater 53 (October/Decemeber 2014): 460–466, https://doi.org/10.1016/j.conbuildmat.2013.12.026

[5] H. Kim, K. D. Jeong, M. S. Lee, and S. J. Lee, "Performance properties of CRM binders with wax warm additives," Constr. Build. Mater 66 (February/April 2014): 356–360, https://doi.org/10.1016/j.conbuildmat.2014.05.052

[6] H. Yu, Z. Leng, F. Xiao, and Z. Gao, "Rheological and chemical characteristics of rubberized binders with non-foaming warm mix additives," Constr. Build. Mater 111(Septmeber/Februray 2016): 671–678, https://doi.org/10.1016/j.conbuildmat.2016.02.066

[7] Y. Wen et al., "The engineering, economic, and environmental performance of terminal blend rubberized asphalt binders with wax-based warm mix additives," J. Clean. Prod

184(October/March 2018):985–1001, https://doi.org/10.1016/j.jclepro.2018.03.011

[8] A. V. Kataware and D. Singh, "Dynamic mechanical analysis of crumb rubber modified asphalt binder containing warm mix additives," Int. J. Pavement Eng 8436(May/September 2017):1–11, https://doi.org/10.1080/10298436.2017.1380806

[9] C. K. Akisetty, S.-J. Lee, and S. N. Amirkhanian, "Effects of Compaction Temperature on Volumetric Properties of Rubberized Mixes Containing Warm-Mix Additives," J. Mater. Civ. Eng 21, no. 8(March/January 2009), 409–415, https://doi.org/10.1061/(ASCE)0899-1561(2009)21:8(409)

[10] C. K. Akisetty, T. Gandhi, S.-J. Lee, and S. N. Amirkhanian, "Analysis of rheological properties of rubberized binders containing warm asphalt additives," Can. J. Civ. Eng 37, no. 5(July/May 2010) 763–771, https://doi.org/10.1139/L10-020

[11] H. Wang, Z. Dang, Z. You, and D. Cao, "High-Temperature Viscosity Performance of Crumb-Rubber-Modified Binder With Warm Mix Asphalt Additives," J. Test. Eval 40, no. 5(March/May 2012), 1–10, https://doi.org/10.1520/JTE20120064

[12] X. Zhou, F. Wang, X. Yuan, M. Kuang, Y. Song, and C. Li, "Usage of slurry oil for the preparation of crumb-rubber-modified asphalt emulsions," Constr. Build. Mater 76 (August/November 2014), 279–285, https://doi.org/10.1016/j.conbuildmat.2014.11.064

[13] D. Nasr and A. H. Pakshir, "Rheology and storage stability of modified binders with waste polymers composites," Road Mater. Pavement Des 20, No.4 (June/December 2017), 1–20, https://doi.org/10.1080/14680629.2017.1417152

[14] B. Vural, M. Yilmaz, and M. Akpolat, "Effect of CR and FT-paraffin versus SBS modification in terms of conventional and rheological properties," Int. J. Pavement Eng 18, No.12 (January/January 2016): 1052-1059, https://doi.org/10.1080/10298436.2016.1149832

[15] H. H. Kim, K.-D. Jeong, M. S. Lee, and S.-J. Lee, "Effect of FT Paraffin Wax Contents on Performance Properties of Crumb Rubber–Modified Asphalt Binders," J. Mater. Civ. Eng 27, No. 11 (March/December 2014): https://doi.org/10.1061/(ASCE)MT.1943-5533.0001267.

[16] R. K. Padhan, A. A. Gupta, C. S. Mohanta, R. P. Badoni, and A. K. Bhatnagar, "Performance improvement of a crumb rubber modified bitumen using polyoctenamer and cross linking agent," Road Mater. Pavement Des 18, No. 4 (March/June 2016), 999–1006, https://doi.org/10.1080/14680629.2016.1208622

[17] R. Schmidt, T. Rolling, and T. C. Oven, "The Rolling Thin-Film Circulating Oven — An Improved Rolling Thin-Film Oven Test," Am. Soc. Test. Mater.,(1973):52–65, https://doi.org/10.1520/STP34737S

[18] J. J.-M. Shiau, M. Tia, B. B. E. Ruth, and G. G. C. Page, "Evaluation of aging characteristics of asphalts by using TFOT and RTFOT at different temperature levels," Transp. Res. Rec 1342, No. 1342 (1992): 58–66.

[19] R. B. McGennis, "Evaluation of Physical Properties of Fine Crumb Rubber-Modified Asphalt Binders," Transp. Res. Rec., No. 1488 (1995): 62–71.

[20] S.-C. Huang, M. Tia, and B. E. Ruth, "laboratory aging methods for simulation of field aging of asphalts," J. Mater. Civ. Eng 8, No. 3(August 1996): 147–152, https://doi.org/10.1061/(ASCE)0899-1561(1996)8:3(147)

[21] X. Lu and U. Isacsson, "Effect of ageing on bitumen chemistry and rheology," Constr. Build. Mater 16, No. 1(October/October 2001): 15–22, https://doi.org/10.1016/S0950-0618(01)00033-2

[22] D. Mastrofin and M. Scarsella, "The application of rheology to the evaluation of bitumen ageing," Fuel 79, No. 9(July/October 1999): 1005–1015, https://doi.org/10.1016/S0016-

2361(99)00244-6

[23] R. Y. Liang and S. Lee, "Short-Term and Long-Term Aging Behavior of Rubber Modified Asphalt Paving Mixture," Transp. Res. Rec 1530, No.1 (January 1996):11–17, https://doi.org/10.1177%2F0361198196153000102

[24] R. P. Biligiri and B. Way, "Comparison of Laboratory and Field Aging Properties of Different Asphalt Binders," Adv. Civ. Eng. Mater 2, No. 1(January/May 2013): 288–306, https://doi.org/10.1520/ACEM20130061

[25] F. M. Nejad, P. Aghajani, A. Modarres, and H. Firoozifar, "Investigating the properties of crumb rubber modified bitumen using classic and SHRP testing methods," Constr. Build. Mater 26, No. 1 (March/June 2011): 481–489, https://doi.org/10.1016/j.conbuildmat.2011.06.048

[26] P. Cong, P. Xun, M. Xing, and S. Chen, "Investigation of asphalt binder containing various crumb rubbers and asphalts," Constr. Build. Mater 40 (September/November 2012): 632–641, https://doi.org/10.1016/j.conbuildmat.2012.11.063

[27] M. R. Nivitha and J. M. Krishnan, "Rheological characterisation of unmodified and modified bitumen in the 90 – 200 ° C temperature regime," Road Mater. Pavement Des 1, No. 18 (July/November 2018), https://doi.org/10.1080/14680629.2018.1552890

[28] G. Liu, Y. Liang, H. Chen, H. Wang, J. Komacka, and X. Gu, "Influence of the chemical composition and the morphology of crumb rubbers on the rheological and self-healing properties of bitumen," Constr. Build. Mate 210 (August/March 2019): 555–563, https://doi.org/10.1016/j.conbuildmat.2019.03.205

[29] B. V. Kok and H. Colak, "Laboratory comparison of the crumb-rubber and SBS modified bitumen and hot mix asphalt," Constr. Build. Mater 25, No. 8 (November/March 2011): 3204–3212, https://doi.org/10.1016/j.conbuildmat.2011.03.005

[30] H. U. Bahia and R. Davies, "Effect of crumb rubber modifiers (CRM) on performance related properties of asphalt binders," Asph. paving Technol. 63 (March 1994): 414

[31] S. Lee, S. N. Amirkhanian, B. J. Putman, and K. W. Kim, "Laboratory Study of the Effects of Compaction on the Volumetric and Rutting Properties of CRM Asphalt Mixtures," J. Mate- rials Civ. Eng 19, No. 12 (December/March 2007):1079–1089, https://doi.org/10.1061/(ASCE)0899-1561(2007)19:12(1079)

[32] A. Mittal, K. Arora, G. Kumar, and P. K. Jain, "Comparative Studies on Performance of Bituminous Mixes Containing Laboratory Developed Hard Grade Bitumen," Adv. Civ. Eng. Mater 7, No. 2(March/September 2017): 92–104, https://doi.org/10.1520/ACEM20170039

[33] R. Dongre, J. D. Angelo, and G. Reinke, "New Criterion for Superpave High-Temperature Binder Specification," J. Transp. Res. Board, 1875, No. 1(January 2004): 22–32, https://doi.org/10.3141%2F1875-04

[34] S. Biro, T. Gandhi, S. Amirkhanian, and M. Asce, "Midrange Temperature Rheological Properties of Warm Asphalt Binders," J. Mater. Civ. Eng 21, No. 7 (July/January 2009): 316–323, https://doi.org/10.1061/(ASCE)0899-1561(2009)21:7(316)

[35] *Indian Standard for Paving Bitumen*, IS73:2013 (2018)—Fourth Revision (Bureau of Indian Standards, approved April, 2013). Doc No.: PCD 6 (2634)

[36] *Indian Standard for Polymer and Rubber Modified Bitumen*, IS15462:2004 (2004), (Bureau of Indian Standards, approved February, 2004). Doc: No. PCD 6 (1862)

[37] *Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test),* ASTM D2872-12e1 (West Conshohocken, PA: ASTM International, February, 2012). https://doi.org/10.1520/D2872-12E01

[38] *Standard Test Method for Effects of Heat and Air on Asphaltic Materials (Thin-Film*

Oven Test), ASTM D1754/D1754M-09, (West Conshohocken, PA: ASTM International, June 1, 2014). https://doi.org/10.1520/D1754_D1754M-09R14

[39] *Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer,* ASTM D7175-15, (West Conshohocken, PA, ASTM International, July 1, 2015), https://doi.org/10.1520/D7175-15

[40] *Standard Specification for Performance Graded Asphalt Binder*, ASTM D6373-16, (West Conshohocken, PA: ASTM International, Sept. 2016), https://doi.org/10.1520/D6373-16

[41] *Standard Test Method for Multiple Stress Creep and Recovery (MSCR) of Asphalt Binder Using a Dynamic Shear Rheometer*, ASTM D7405-15, (West Conshohocken, PA: ASTM International, Dec. 2015), https://doi.org/10.1520/D7405-15

[42] R. Zhang, H. Wang, X. Jiang, Z. You, X. Yang, and M. Ye, "Thermal Storage stability of bio-oil modified asphalt," J. Mater. Civ. Eng 30, No. 4 (July/October 2018): 1–9, https://doi.org/10.1061/(ASCE)MT.1943-5533.0002237

[43] AASHTO, "Standard method of test for determining the rheological properties of asphalt binder using a dynamic shear rheometer (DSR)," AASHTO T315-10, p. Washington, DC., 2013.

[44] Highway Materials Engineering Course (HMEC), Participant workbook laboratory manual, (U.S. Department of Transporation Federal Highway Admistration, 2017).