SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

Effects of Fly Ash Geopolymer Hot Mix Asphalt Additive on the Rheological Properties of Unaged and Short-Term Aged Asphalt Binder

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ARTICLE INFO

Article history:
Received 15 May 2023
Received in revised form 20 July 2023
Accepted 30 July 2023
Available online 9 August 2023

Keywords:
Fly Ash Geopolymer; Hot Mix Additive; Rheological; DSR

ABSTRACT

Asphalt pavement has the advantages of driving comfort and convenient maintenance, which has been widely applied to highway construction. However, due to the continuously increased traffic volume, it is recognized that asphalt binder and mixtures with enhanced characteristics are needed to guarantee the durability of the functional performance of transportation infrastructures. This study was carried to evaluate the effect of fly ash geopolymer additive on the rheological properties of unaged and short-term aged asphalt binder. In the respect, asphalt binder 80/100 and 60/70 penetration grade with 0, 3, 5, 7, 9 and 11% fly ash geopolymer by weight of asphalt binder were prepared. The results indicated that the addition of FAG significantly increases the stiffness (G*) and decreases the phase angle (δ) for both unaged and short-term aged modified asphalt binder compared to the control asphalt binder. This can be proved that presence of FAG significantly improved rutting parameter i.e G*/sin δ compared to control in which capable to resist rutting at higher temperature. In terms of failure temperature, highest failure temperature of 9% FAG modified asphalt binder indicated that the binder is less susceptible to be rutting at high pavement temperature for both unaged and short-term aged, respectively. Overall research conclusions are that 9% of FAG is proposed as the minimal content to be used as an additive in asphalt binder for further mixture evaluations.

1. Introduction

Rheology is the study of the flow and deformation of materials, especially the behavior of non-Newtonian materials. Asphalt binder is a rheological viscoelastic material where its behavior depends on the temperature and rate of loading [1]. In addition, asphalt binder rheological parameters are the viscosity, complex modulus, elastic modulus, viscous modulus, and phase angle. Based on the study conducted by Hamid *et al.,* [2], the authors showed that the additive material

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https://doi.org/10.37934/aram.109.1.4452

such as fly ash geopolymer into the virgin asphalt binder affect the rheological behavior by increasing its failure temperature, complex shear modulus, elasticity, and exhibited better performance in terms of rutting resistance.

In addition, Dayal *et al.,* [3] found that the incorporating of fly ash geopolymer affect the complex shear modulus of asphalt binder. Furthermore, the result showed that the rutting factor on modified asphalt binder also increased compare to virgin asphalt binder. Dayal *et al.,* [3] also stated that the bituminous mixtures containing fly ash geopolymer show better resistance to permanent deformation, which points to their higher potential rutting resistance and longer fatigue life. Thus, the addition of fly ash geopolymer into the asphalt mixture is expected to decrease the rate of rutting due to the increase in softening point [4-5]. There appears to be a gap in the literature to evaluate the used of geopolymer modified asphalt in asphalt mixture incorporating different asphalt binder grade to enhance asphalt mix properties. Thus, the use of geopolymer modified asphalt have become a new improvement to the asphalt binder.

2. Methodology

Rheological properties tests were performed on virgin and binder containing fly-ash geopolymer additive to determine the effect in the viscosity, flow behaviour and chemical compositions of the binder used [6]. Rheology of both unmodified and modified binder were characterized $G*/\sin(\delta)$ as an indicator of rutting susceptibility and $G*\sin(\delta)$ as an indicator of fatigue susceptibility of the binder.

2.1 Dynamic Shear Rheometer

Dynamic Shear Rheometer (DSR) tests was conducted accordance to ASTM D7175 [7]. Other than that, elastic modulus (G') and viscous modulus (G") were obtained from this test, which also discussed as dependent variables that affected by chemical properties as independent variables. Using parallel plate arrangement performed the DSR test. The diameter top plate and bottom plate were 25 mm for high temperature test (46^{o}C - 82^{o}C) and 8 mm for medium temperature test (10^{o}C - 32^{o}C). The gap between top (oscillating plate) and bottom plate (fixed plate) was 1 mm for 25 mm diameter plates, and 2 mm for 8 mm diameter plates. The oscillation speed was set as 10radian/second at 1.59 Hz.

2.2 Rolling Thin Film Oven

The rolling thin film oven (RTFO) test was carried out according to ASTM D2872 [8] procedures to simulate short-term aging of the binders. In this test, 35g of binder sample were placed in an eight-glass bottle with a narrow top opening. The bottle glass opening facing a jet of air that followed the bottle's rotation at 15 rpm in an oven at 163 ^{o}C for 85 minutes. The samples bottles were place in the carriage and rotated at the rate of 15 rpm and the airflow was be set at the rate of 4000 ml/min. The method ensures that all the binder is exposed for binder protection. Lastly, the mass change was calculated and the physical properties changes was measured.

3. Results

3.1 Dynamic Shear Rheometer (DSR) Analysis of Unaged

Dynamic Shear Rheometer analysis of unaged asphalt binder was carried out to determine the effect of fly ash geopolymer (FAG) on complex modulus, phase angle and rutting parameter. The details of the findings are discussed in the next sub section.

3.1.1 Effect of FAG content on G and Sin δ of unaged asphalt binder*

The graphs for G* and versus temperature for the unaged specimens of asphalt binder grades 80/100 and 60/70 are shown in Figure 1 and 2. At this point, the linear viscoelastic characteristics of the asphalt binders were determined by measuring the complex modulus (G*) and phase angle (δ) at low shear strain. The average complex shear modulus, G*, and phase angle, were calculated from the DSR test. In general, the trend indicates that the phase angle (δ) rises as stiffness (G*) decreases. As a result, the increases, which enhances the asphalt binders' linear strain limit. The elasticity of the asphalt binder and its stiffness to resist deformation increase as the temperature rises [9-11].

Despite the effect of FAG content on the asphalt binder, the G* increased as the δ decreased, irrespective of the temperature. As shown in Figure 1 and 2 adding 9% FAG to the 80/100 and 60/70 unaged asphalt binder at 46˚C increases the G* by 9.8% and 64.5% respectively. In contrast, the δ decreases by 1.1% and 2.3%, respectively. At 76 ˚C, the G* of asphalt binder grade 80/100 is less than 10 kpa. However, the G* of asphalt binder grade 60/70 has less than 10 kpa at 82 ˚C. Increasing asphalt binder viscosity resulted in increases of asphalt binder stiffness caused by aging condition.

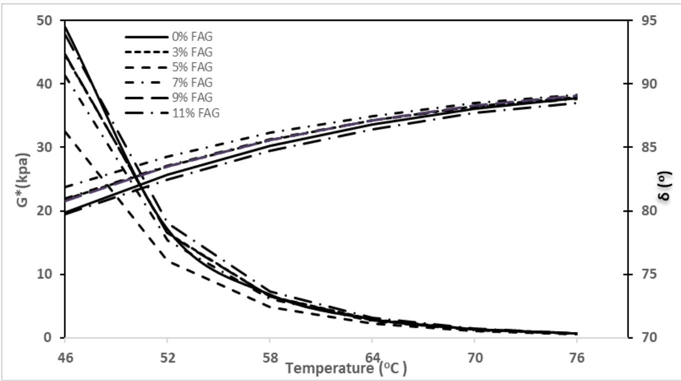

Fig. 1. Effect of FAG content on G* and Sin δ of unaged asphalt binder grade 80/100

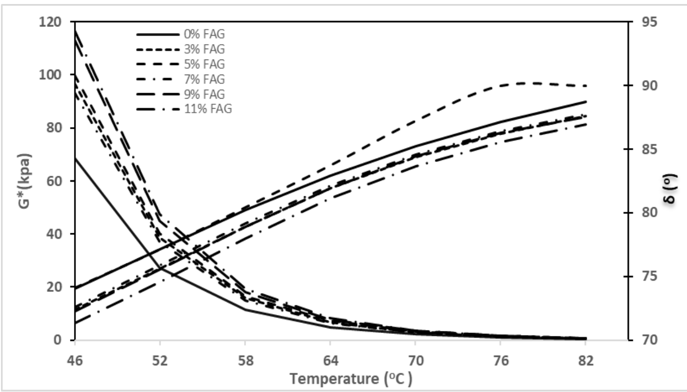

Fig. 2. Effect of FAG content on G* and Sin δ of unaged asphalt binder grade 60/70

3.1.2 Effect of FAG content on rutting resistance for unaged asphalt binder

The G*/sin δ is used as an indicator of pavement rutting resistance, where the higher value of this parameter indicates higher resistance to rutting. To obtains more precise result, three replicates FAG modified asphalt binder for each dosage were tested using dynamic shear binder test at frequency of 1.59 Hz. A higher value of complex modulus, (G*) is favourable as it represents a higher total resistance to deformation. Meanwhile, fatigue parameter is known as G*sin δ. It is used as an indicator for fatigue resistance based on the concept that part of the dissipated energy is spent in generating microscopic damage (cracks) that eventually leads to fatigue.

Taher *et al.,* [12] stated that rutting parameter at the maximum pavement design temperature, the (G*/sin δ) must be greater than 1.0 kPa and 2.2 kPa for unaged and short-term aged asphalt binder, respectively. In this study, the increase of test temperature indicates that the rutting parameter of unaged binder containing FAG has gradually decreased. The effect of temperatures on the rutting parameter (G*/sin δ) of unaged 60/70 FAG modified asphalt binder are shown in Table 1.

Table 1
G*/Sin δ of unaged 60/70 FAG modified asphalt binder

G*/Sin δ (kpa)							
Aging Condition	**T (°C)**	**FAG Content (%)**					
		0	**3**	**5**	**7**	**9**	**11**
Unaged (60/70)	46.0	71.58	101.61	103.98	97.78	123.30	118.80
	52.0	28.09	39.92	41.22	38.14	49.14	46.42
	58.0	11.50	16.12	16.83	15.27	19.70	18.50
	64.0	4.98	6.74	7.29	6.44	8.26	7.74
	70.0	2.29	3.06	3.36	2.90	3.65	3.44
	76.0	1.11	1.45	1.64	1.38	1.71	1.63
	82.0	0.54	0.73	0.86	0.70	0.85	0.81

From Table 1, it clearly seen that the unaged binder 60/70 with 9% of FAG exhibit highest values compared to the control. It can be concluded that the G*/sin δ value of the unaged binder with 9% FAG tested at 46°C and 76°C increase by 72.3% and 54.1%, respectively. Thus, the presence of FAG significantly improves the rutting resistance. It is also noticed that the control asphalt binder 60/70 has less capability to resist the rutting at higher temperatures. Generally, the addition of FAG has stiffened the binder consequently increases the rutting resistance. The rheological results of different FAG contents in asphalt binder showed significance changes in the property of the binders. The increase of the rutting resistance in FAG modified binder could be attributed to the presence of synthetic mineral in powder form of FAG containing around 10% moisture which is chemically and structurally bound. It reduces temperature dependency and increases the elastic property of the binder.

The analysis result of rutting parameter, G*/Sin δ of unaged 80/100 FAG modified asphalt binder also tabulated in Table 2. Similar trend was found for the unaged 80/100 FAG modified asphalt binder which increases of test temperature indicates that the rutting parameter of unaged binder containing FAG has gradually decreased. The addition of FAG significantly decreases binder viscosity and increases binder stiffness resulting increase the G*/sin δ, thus make it potential rutting resistance [13]. All modified asphalt binders meet the Superpave^{TM} specification requirement at selected test temperatures.

Table 2
G*/Sin δ of unaged 80/100 FAG modified asphalt binder

G*/Sin δ (kpa)							
Aging Condition	**T (°C)**	**FAG Content (%)**					
		0	**3**	**5**	**7**	**9**	**11**
Unaged (80/100)	46.00	49.76	45.13	103.98	41.82	48.57	45.19
	52.00	17.25	16.65	41.22	15.37	18.18	16.48
	58.00	6.84	6.59	16.83	6.15	7.28	6.49
	64.00	2.93	2.83	7.29	2.65	3.16	2.77
	70.00	1.36	1.29	3.36	1.23	1.47	1.28
	76.00	0.67	0.64	1.64	0.62	0.74	0.64

3.1.3 Failure temperature of unaged FAG modified asphalt binder

The failure temperatures of unaged FAG modified binder were obtained at this point of investigation based on data series recorded from DSR test. These failure temperatures were determined directly from DSR equipment, generated through interpolation as the temperatures at which the G*/sin δ value were less than the required value at the testing temperatures. This investigation began with a temperature of each sample was set at 46 °C at the beginning of the test and gradually increased 6 °C to the next PG grade (i.e 52, 58, 64, 70 and 76) until the value of G*/sin δ failed. Figure 3 shows the high failure temperatures of control and modified binders in unaged condition. The failure temperature was recorded in range 76.9 to 80.6 °C and 70.2 to 73.3 °C for modified asphalt binder grade 60/70 and 80/100, respectively.

From the result, it becomes an evident that 9% FAG modified asphalt binder 60/70 and 80/100 exhibit highest failure temperature with te differences between control specimens approximately about 4.8% and 1.0%, respectively. The results showed correlation between the temperature and asphalt binder aging condition is exist [14].

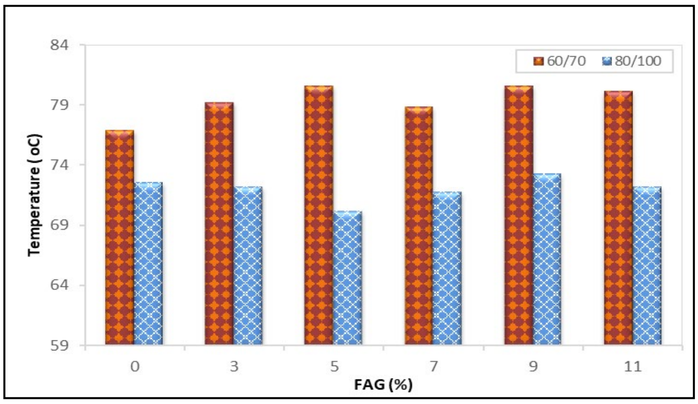

Fig. 3. High failure temperature of unaged modified asphalt binders

According to Motamedi *et al.,* [15], rutting parameter at the maximum pavement design temperature, (G*/sin δ) must be greater than 1.00 kPa for the unaged binders. All in all, it can be concluded that 9% FAG modified asphalt binder has improved rutting parameter. In other words, modified asphalt binder is more resistant to rutting at higher temperature than the control asphalt binder. As so FAG modified asphalt binders are less susceptible to rutting at high pavement temperature.

3.2 Dynamic Shear Rheometer (DSR) Analysis of Short-Term Aged Asphalt Binder

Dynamic Shear Rheometer analysis of unaged asphalt binder was carried out to determine the effect of fly ash geopolymer (FAG) on complex modulus, phase angle and rutting parameter. The HMA binders were aged using rolling thin film oven (RTFO) at 165^{o}C for 85 minutes. The details of the findings are discussed in section 3.2.1.

3.2.1 Effect of FAG content on G* and Sin δ of short-term aged asphalt binder

Figure 4 and 5 show the effect of FAG content G* and Sin δ versus temperature of short-term asphalt binder grade 80/100 and 60/70. In general, the results demonstrates that the addition of FAG asphalt binder has higher complex shear modulus than the control specimens [16]. With the addition of 9% FAG into the 80/100 and 60/70 asphalt binder, the complex shear modulus increases by an average of 16% and 30%, respectively. Modified asphalt binder with 9% FAG after short term aged of 80/100 and 60/70 has shown the highest G* with 16.46% and 28.30% increases from 50.70 kPa to 59.05 kPa and 127.85kPa to 164.03kPa compared to control binder at 46 ˚C. In contrast, the δ decreases by 1.5% and 0.6% of modified asphalt binder 80/100 and 60/70 from 69.33^{o} to 68.29^{o} and 78.43^{o} to 77.97^{o}, respectively. At 76 ˚C, the G* of asphalt binder grade 80/100 is less than 10 kpa. However, the G* of asphalt binder grade 60/70 has less than 10 kpa at 82 ˚C.

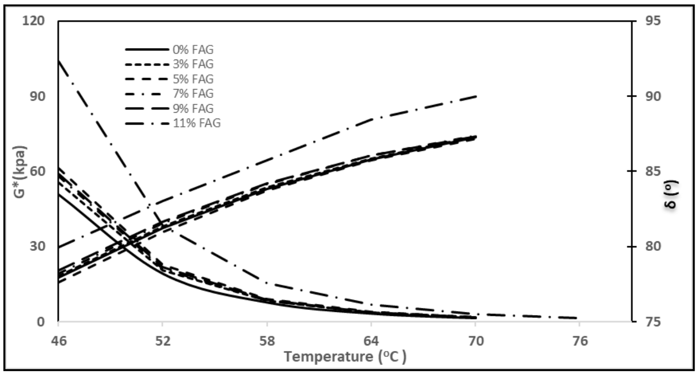

Fig. 4. Effect of FAG content on G* and Sin δ of short-term asphalt binder grade 80/100

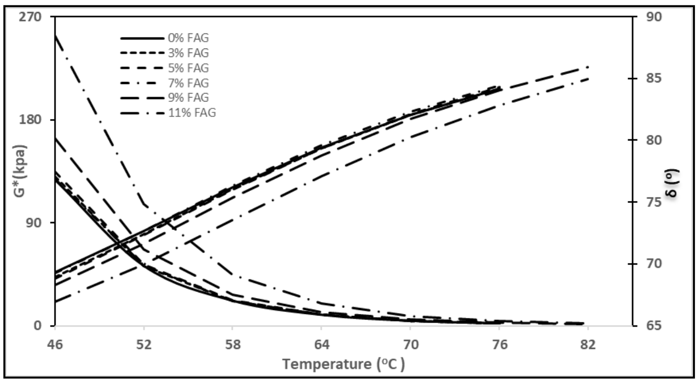

Fig. 5. Effect of FAG content on G* and Sin δ of short-term asphalt binder grade 60/70

3.2.2 Effect of FAG content on rutting resistance for short-term aged asphalt binder

The DSR test has been used to assess the rheological properties of asphalt binder. This test can be performed at various temperatures, strain and stress levels and frequencies. Rutting and fatigue characteristic of asphalt binder were obtained rather than empirical properties such as penetration or softening point values. According to Superpave^{TM} specifications, the testing temperature for PG64 is 64^{o}C for virgin and RTFO aged binders. The specification defines requirements on a rutting parameter, G*/sin δ which represents the high temperature viscous component of overall binder stiffness. G*/sin δ must be at least 2.20kPa after aging in the RTFO test.

Generally, the trend of the data shows rising in the test temperature results decreases the G*/Sin δ for short-term aged binders containing FAG. Interestingly, it can be seen that the rutting resistance of STA 80/100 and 60/70 asphalt binder is higher than control, as shown in Table 3 and Table 4. From the result, the short term aged asphalt binder 80/100 and 60/70 incorporating 9% of FAG exhibit highest rutting resistance.

It also noticed that the G*/Sin δ of the short term aged 80/100 and 60/70 asphalt binder with 9% of FAG tested at 46°C increase by 106% and 102% from 51.84 kPa to 106.83kPa and 136.64 kPa to 276.05 kPa compared to control binder, respectively. Thus, FAG has improved G*/Sin δ value of the rutting resistance. The rutting of STA binder at different FAG contents has significant changed in the properties of the binder [17-18]. This situation gives insight from the studied percentages (3, 5, 7, 9 and 11), where 9% seems the optimum content of FAG when considering rutting.

Table 3
G*/Sin δ of STA 80/100 FAG modified asphalt binder

G*/Sin δ (kpa)							
Aging Condition	**T (°C)**	**FAG Content (%)**					
		0	**3**	**5**	**7**	**9**	**11**
Short Term Aged (80/100)	46.0	51.84	56.65	62.67	59.25	106.83	60.27
	52.0	19.48	20.78	23.11	21.47	39.04	22.18
	58.0	7.86	8.52	9.18	8.53	15.71	8.83
	64.0	3.41	3.72	3.90	3.70	6.77	3.84
	70.0	1.57	1.70	1.79	1.70	3.07	1.86
	76.0	0.73	0.81	0.89	0.80	1.49	0.93

Table 4
G*/Sin δ of STA 60/70 FAG modified asphalt binder

G*/Sin δ (kpa)							
Aging Condition	**T (°C)**	**FAG Content (%)**					
		0	**3**	**5**	**7**	**9**	**11**
Short Term Aged (60/70)	46.0	136.64	139.94	144.28	137.92	276.05	176.55
	52.0	55.01	55.07	56.55	55.43	113.25	70.21
	58.0	22.69	22.46	23.01	22.50	46.46	28.35
	64.0	9.86	9.63	9.88	9.74	19.79	12.02
	70.0	4.42	4.39	4.50	4.43	8.79	5.37
	76.0	2.19	2.10	2.14	2.13	4.11	2.53
	82.0	1.03	1.22	1.28	1.26	2.02	1.25

3.2.3 Failure temperature of short-term aged FAG modified asphalt binder

Once the rutting of short-term aged (STA) asphalt binder results from the DSR test was obtained, the next characteristic of failure temperature of STA FAG modified asphalt binder has been determined at which the G*/sin δ value is less than the required value at the testing temperature. Similar with earlier discussion of unaged samples in sub-section 3.1.3, the temperature of each sample was set at 46°C at the beginning of the test and gradually increased 6 °C to the next PG grade (i.e., 52, 58, 64, 70 and 76) until the value of G*/sin δ failed. The DSR test was conducted on samples with three replicates for every dosage of FAG content under short term aged (STA) in order to get the more precise results [19].

Figure 6 shows the failure temperature of short-term aged asphalt binder at different FAG contents. The modified binders are considered failed after the value of G*/sin δ is below 2.20 kPa for RTFO asphalt binders. From the results, the modified asphalt binder with 9% FAG 60/70 and 80/100 has the highest failure temperature which is prove that the FAG additive improves the rutting characteristics approximately 8.01% and 7.1% compared to the control asphalt binder.

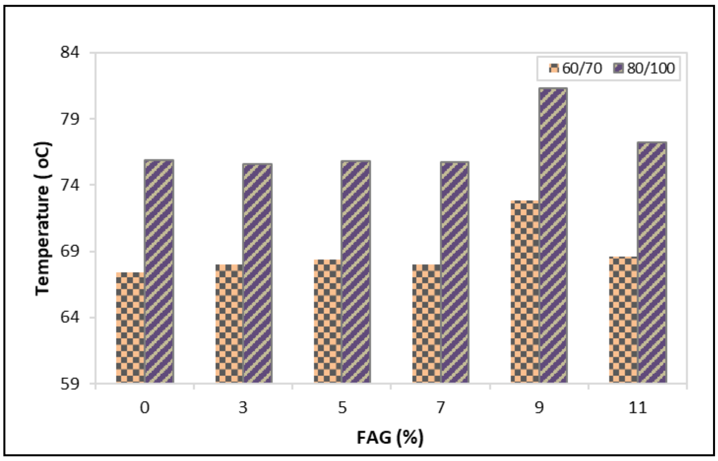

Fig. 6. High failure temperature of short term aged modified asphalt binders

4. Conclusions

This study determined the addition of FAG significantly increases the stiffness, G* and decreases the phase angle, δ for both unaged and short-term aged modified asphalt binder compared to the control asphalt binder. This can be proved that presence of FAG significantly improved rutting parameter i.e G*/sin δ compared to control in which capable to resist rutting at higher temperature [20]. In terms of failure temperature, highest failure temperature of 9% FAG modified asphalt binder indicated that the binder is less susceptible to be rutting at high pavement temperature for both unaged and short-term aged, respectively. Therefore, 9% of FAG is proposed as the minimal content to be used as an additive in asphalt binder for further mixture evaluations.

Acknowledgement
This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 (vot Q141). Communication of this research is made possible through monetary assistance by Universiti Tun Hussein Onn Malaysia and the UTHM Publisher's Office via Publication Fund E15216 and through Postgraduate Research Grant (GPPS) Vot H616.

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