Effect of High Temperature on the Behaviour of Geopolymer Modified Asphalt Binders

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Abstract

The asphalt binder is a viscoelastic substance that exhibits both viscous and elastic behaviour. Asphalt binder is an effective adhesive material for use in the pavement, however it is a difficult material to understand and describe due to the wide variety of its behaviour. This research aimed to investigate the impact of polymer modification on non-recoverable creep compliance (J_{nr}). Three modifiers (fly ash (FA), Styrene-Butadiene-Styrene (SBS), and fly ash-based on geopolymer (GF)) were used. Asphalt binders were tested at various temperatures, ranging from 40 to 70 °C with a 3 °C gap, and regression models were developed. The results revealed that 2% SBS modified asphalt binder exhibited elastomeric behaviour at low temperatures, whereas 4% SBS modified asphalt binder exhibited noteworthy elastomeric behaviour at various temperatures. The power-law models most effectively illustrated the correlation between temperature and non-recoverable creep compliance (J_{nr}) at different stresses, 0.1 kPa and 3.2 kPa. The developed models proved to be effective for appropriately selecting the polymer type and amount suitable to minimize the J_{nr}. The hybrid and 4%SBS binders performed best in terms of strain recovery at high temperatures, with J_{nr} values of less than 0.5 being achieved at 58 °C and 3.2 kPa.

Keywords: Asphalt Binder, Rheology, Geopolymer, Rutting, Creep Recovery

1 Introduction

Rutting is a common sign of distress that affects the road network's serviceability and quality. It is a permanent deformation that occurs in the traffic direction because of unrecoverable strain accumulated by repetitive loads applied to the asphalt pavement (Asphalt Institute, 2007). Due to the combined effects of viscoelastic characteristics and shear loads on the HMA layer, asphalt is highly susceptible to rutting. As the temperature increases, the asphalt binder loses the ability to elastically recover from deformation, increasing the sensitivity to permanent deformation. In recent decades, there has been attention to modified asphalt binder using different modifiers to enhance the rutting performance. The viscoelastic properties of asphalt binders can be improved by modifying the asphalt binder using different modifiers. Modification, on the other hand, adds to the complexity of binders' behaviour; thus, substantial laboratory testing is required before field application to establish the best solutions.

The Multiple Stress Creep-Recovery (MSCR) test was developed to measure the binder's nonlinear reaction and to link that response to rutting in asphalt mixtures (D'Angelo, 2009). The MSCR test has long been used to predict how polymer-modified asphalt binders may affect creep recovery (Zoorob, et al., 2012; White, 2017; Aurilio, et al., 2019; Dalhat, et al., 2019; Hamid, et al., 2020). The MSCR test is carried out using a Dynamic Shear Rheometer (DSR) with a constant stress creep of 1.0 s and a zero-stress recovery of 9.0 s. The test is carried out at different stresses of 0.1 kPa and 3.2 kPa, whereby each of the two stress levels has ten cycles. Multiple Stress Creep Recovery (MSCR) tests at PG temperatures are recommended to quantify recovery characteristics such as percent recovery (%R) and non-recoverable creep compliance (J_{nr}) (AASHTO, 2013). The %R indicates the asphalt binder's elastic behaviour, whereas the J_{nr} has been applied to categorize asphalt binders into several traffic levels at the proper service temperature (Al-Adham & Al-Abdul Wahhab, 2018).

Many researchers employed the MSCR test to investigate the rutting behaviour of polymer modified asphalt binders (Dalhat, et al., 2019; Tabatabaee & Tabatabaee, 2010). Nonrecoverable creep compliance has been found to be a good predictor of an asphalt binder's resistance to permanent deformation when subjected to repeated loads (AASHTO, 2013; Dreessen & Gallet, 2012). Chang et al. (Chang, et al., 2021) noted that $J_{nr3.2}$ is a crucial indicator for assessing the effect of binder on rutting resistance in asphalt mixtures and may be used to correlate the rutting resistance of asphalt mixtures. Lei, et al. (Lei, et al., 2016) suggested that the J_{nr} and %R indexes be used to describe high-temperature performance in terms of rutting resistance of asphalt binders modified using various rubbers.

1.1 Objectives

The purpose of this research was to assess the influence of different types of additives on the recovery properties of asphalt binder at high temperatures by looking into the following:

- Evaluate the effects of additives, stresses, and temperatures on the elastomeric behaviour of asphalt binder.

- Investigate the possibility of using the linear viscoelastic properties to predict the recovery properties of asphalt binders.
- Develop crucial models to predict the non-recovery compliance of asphalt binder, considering the impacts of additives and temperatures at different stresses.

2 Methodology

2.1 Materials

2.1.1 Preparation of Geopolymer

During the geopolymer preparation, fly ash (200 g) was employed as an alumino-silicate precursor. The alumino-silicate precursors were activated with a 2:1 mass ratio of sodium hydroxide and sodium silicate. The mixture was mixed for 5 minutes before being transferred to silicone moulds and curing for 6 days at room temperature (23-25 °C) as recommended by (Hamid, et al., 2020) and 24 hours at 65 °C. The geopolymer was next grinded and sieved with sieve No. 100 to remove particles larger than 0.15 mm, which could impact the result's consistency. Figure 1 depicts the steps involved in making geopolymer additives. When an aluminosilicate source combines with an alkaline solution, the tetrahedral silica (SiO_4) and alumina (AlO_4) are linked by oxygen (O_2) in three-dimensional chain networks, forming the geopolymer (Duxson, et al., 2007).

2.1.2 Preparation of Asphalt Binders

The asphalt binder PG 58-28 was heated until it became fluid. The temperature was kept constant at 140 °C ± 5, and the fly ash-based on geopolymer (GF) and fly ash (FA) were added to the neat asphalt binder at different concentrations. The mixture was then blended for 60 minutes with a mechanical shear mixer at a speed of 2000 r/min. The modified asphalt binder with SBS modifiers was prepared using a different approach, which involved using a high shear mixer and a heated mantle at a speed of 2000 r/min for 60 minutes at a temperature of 170 °C ± 5. The crosslinking agent was then added at a rate of 10% and blended for 30 minutes. Finally, a curing period was completed by reducing the high shear mixer speed to 1000 r/min for 60 minutes at 180 °C ± 5.

2.1.3 Aging procedure

Samples for short-term ageing in a rolling thin-film oven (RTFO) were filled in cylindrical glass bottles with 35 ± 0.5 g, following the asphalt binder mixing method. All bottles were placed horizontally in a vertically revolving frame, rotating at a speed of 15 revolutions per minute after cooling for 60 to 180 minutes. Because of the temperature and movement, the sample flows along the glass bottle's wall. During each cycle, which took a few seconds, air was blasted into each glass container once. This procedure took 85 minutes at 163 °C.

2.2 Testing Procedure

The Dynamic Shear Rheometer (DSR) was used to investigate the effects of additives and temperatures on the rheological and elastomeric behaviour of asphalt binders using the frequency sweep test and the MSCR test. The frequency sweep test was used to see how frequencies, temperatures, and modifier content affected the linear viscoelastic behaviour of asphalt binders. The test was carried out with a 25-mm-diameter plate with a 1-mm gap at 0.5% shear strain in the linear range, with frequencies ranging from 0.159 H_z to 15 H_z. The %R and J_{nr} of asphalt binders were determined using the MSCR test. The MSCR test was conducted with a 25 mm diameter plate and a 1 mm gap at varied temperatures (from 46 to 70 °C) and stresses (0.1 kPa and 3.2 kPa). The test consisted of applying creep for one second and then recovering for nine seconds, during which the %R and J_{nr} were calculated.

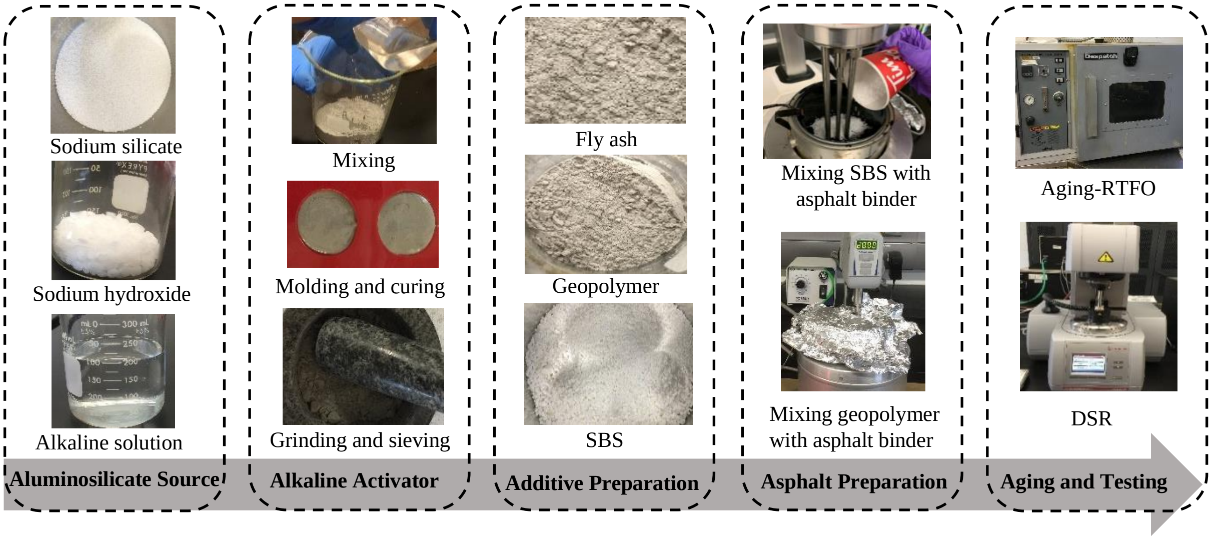

Figure 1. Additives preparation and testing

3 Results and Discussions

3.1 Elastomeric Behaviour of Modified Asphalt Binders

Figure 2 demonstrates the relationship between non-recoverable strain creep compliance (J_{nr}) and percent recovery (%R) for GF, FA, and SBS binders. The modified asphalt binders were tested at high stress (3.2 kPa) and at various temperatures. According to the AASHTO specifications, the elastomeric properties of modified binders can be evaluated by constructing a standard curve using equation (1) and considering the position of data points. If the data point lies above the standard curve, that means the binder has high elastomeric behaviour. Figure 2(a) shows the influence of geopolymer on the elastic behaviour of asphalt binders. At moderate and high temperatures, it was observed that GF binders did not achieve the desired elastomeric behaviour. Figure 2(b) points out that 2%SBS modified asphalt binder reached high elastomeric properties at low temperatures, while 4%SBS modified asphalt binder achieved notable high elastomeric behaviour at different temperatures. This suggests that a small number of polymer molecules is adequate to increase the elastic recovery of asphalt binder, as also concluded by (Al-Adham & Al-Abdul Wahhab, 2018). In contrast, there is no notable sign of enhanced elastomeric behaviour for asphalt binder modified with a hybrid modifier to reach the high elastomeric behaviour.

$$\%R = 29.371 {J_{nr}}^{-0.2633} \tag{1}$$

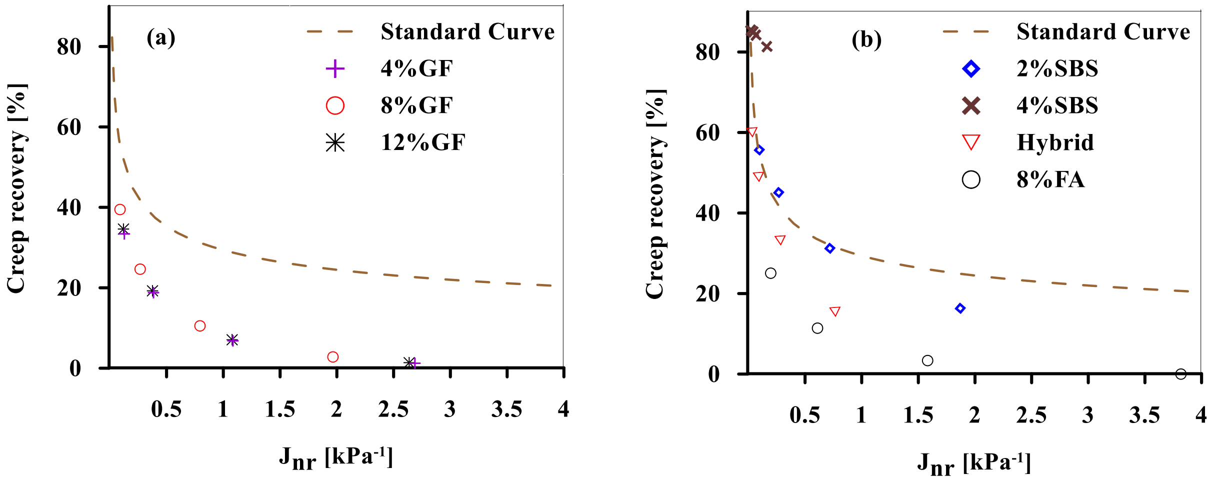

Figure 2. Elastomeric behaviour of (a) GF and (b) SBS and FA binders

3.2 Relationship between G*/sinδ and 1/J_{nr}

Figure 3 (a, b) presents the relationship between G*/sinδ and 1/J_{nr} at different stresses and temperatures. It was noted that there is a good relationship between G*/sinδ and 1/J_{nr} using a power equation with an R^2 of 0.79 and 0.85 for high stress (3.2 kPa) and low stress (0.1 kPa), respectively. While there is no good correlation between G*/sinδ and 1/J_{nr} using linear regression with an R^2 of 0.3 and 0.49 for high stress (3.2 kPa) and low stress (0.1 kPa), respectively.

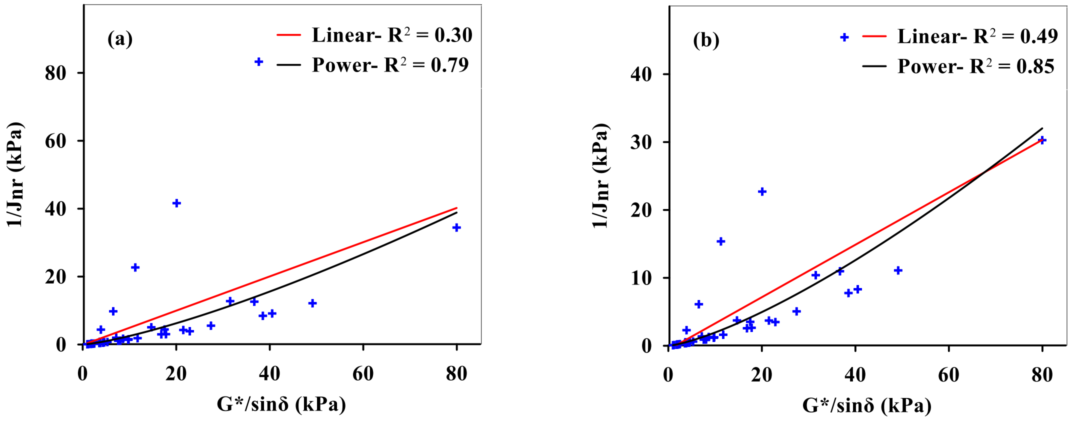

Figure 3. Relationship between G*/sin and (a) 1/$J_{nr0.1}$ and (b) 1/$J_{nr3.2}$

Table 1 summarises the results of the MSCR test at different stresses and temperatures. It was noted that the J_{nr} value of asphalt binders increases dramatically with increasing temperatures, implying that the high-temperature stability of asphalt binders will reduce as the temperature goes up. While the R-value decreases as the temperature increases, showing that the asphalt binder's elastic recovery reduces as temperature increases and its properties become more viscous.

Table 1. G*/sin and MSCR test results at different temperatures

binders	**Temp. (°C)**	**G*/sin δ (kPa)**	**$J_{nr0.1}$ (kPa^{-1})**	**$J_{nr3.2}$ (kPa^{-1})**	**$R_{0.1}$ (%)**	**$R_{3.2}$ (%)**
Neat	46	22.900	0.254	0.285	28.385	21.165
	52	9.730	0.705	0.841	19.160	8.715
	58	4.380	1.790	2.210	11.475	1.980
	64	2.050	4.180	5.130	5.415	0.000
	70	1.001	8.860	10.750	1.425	0.000
4%GF	46	38.530	0.118	0.1285	39.195	33.430
	52	16.820	0.331	0.385	28.410	18.830
	58	7.580	0.867	1.085	19.445	6.835
	64	3.560	2.100	2.688	10.955	1.255
	70	1.730	4.756	6.039	5.040	0.000
8%GF	46	49.148	0.082	0.090	44.925	39.500
	52	21.517	0.232	0.268	33.835	24.665
	58	9.811	0.633	0.795	24.315	10.565
	64	4.625	1.512	1.966	14.745	2.840
	70	2.276	3.481	4.564	7.810	0.000
12%GF	46	40.508	0.109	0.120	40.765	34.640
	52	17.813	0.324	0.376	28.860	19.280
	58	8.075	0.847	1.078	20.475	7.110
	64	3.808	2.082	2.637	10.635	1.410
	70	1.877	4.626	5.832	5.100	0.000
8%FA	46	27.432	0.179	0.197	31.370	25.090
	52	11.739	0.524	0.610	20.855	11.435
	58	5.297	1.295	1.582	13.345	3.390
	64	2.484	3.126	3.818	6.515	0.030
	70	1.209	6.883	8.255	2.030	0.000
2%SBS	46	31.524	0.078	0.096	63.68	55.715
	52	14.681	0.196	0.267	57.455	45.135
	58	7.166	0.492	0.719	48.890	31.280
	64	3.642	1.223	1.870	37.055	16.375
	70	1.904	2.916	4.594	25.575	4.825
4%SBS	46	37.673	0.012	0.022	91.845	85.465
	52	20.094	0.024	0.044	91.470	85.040
	58	11.255	0.044	0.065	91.195	84.215
	64	6.533	0.102	0.163	88.065	81.370
	70	3.896	0.226	0.432	83.980	70.370
Hybrid	46	79.955	0.029	0.033	64.860	60.055
	52	36.705	0.079	0.091	55.715	48.970
	58	17.509	0.224	0.283	46.325	33.205
	64	8.631	0.575	0.766	32.540	15.465
	70	4.398	1.373	1.962	21.960	4.560

3.3 Correlation between Temperatures and J_{nr}

The neat and modified asphalt binders were tested using the MSCR test at low and high stresses (0.1 kPa and 3.2 kPa) and at various temperatures ranging from 46 °C to 70 °C using 3 °C as an interval; whereby two replicates of each asphalt binder were prepared for each temperature and the average was recognised as the test result. Then, the relationship between J_{nr} and temperature was developed, and regression models were constructed. Figure 4 and Figure 5 demonstrate the results of neat and modified binders that were tested at different temperatures and stresses of 0.1 kPa and 3.2 kPa, respectively.

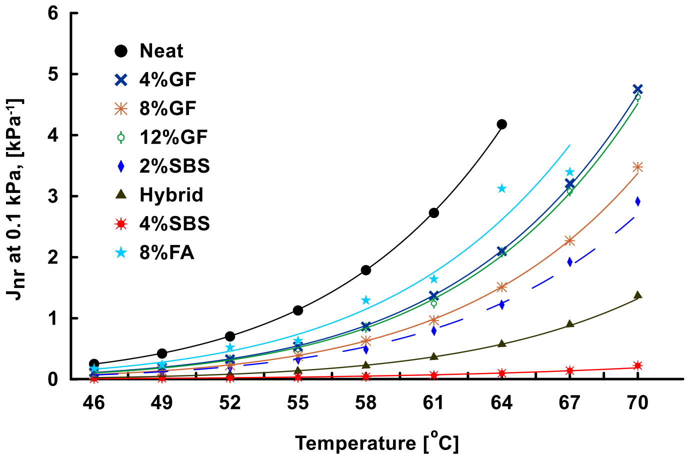

Figure 4. Correlation between temperature and $J_{nr0.1}$

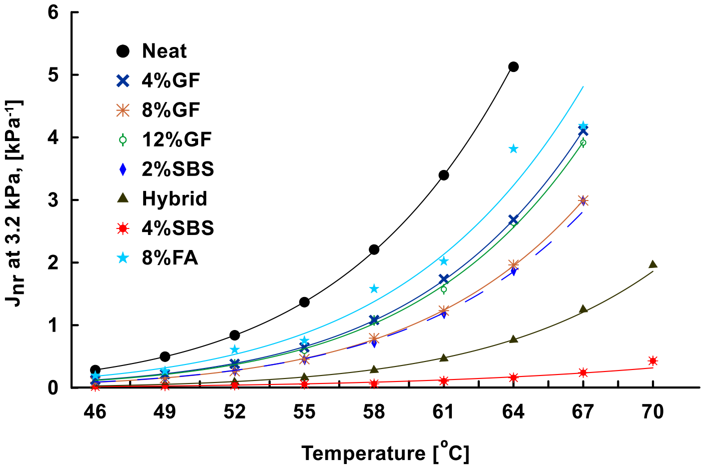

Figure 5. Correlation between temperature and $J_{nr3.2}$

Temperature, polymer amount, and polymer type were found to have significant effects on MSCR results. The results showed that the 4%SBS binder achieved the J_{nr} values less than 0.5 at different temperatures and stresses, while the hybrid binder had J_{nr} values less than 0.5 at 46 °C, 52 °C, and 64 °C and various stresses, as shown in Figure 4 and Figure 5. Also, adding the geopolymer additives has a significant influence on the recovery behaviour of asphalt binder. The power law is used to identify an appropriate link between temperature and J_{nr}, which contains the following equation:

$$J_{nr} = \alpha T^{\beta} \tag{2}$$

J_{nr} is the average of non-recoverable compliance during ten cycles of stress testing, T is the temperature, $\boldsymbol{\beta}$ is the power law exponent, and $\boldsymbol{\alpha}$ is constant.

Table 2 summarises the model components for the power-law correlation between temperature and J_{nr}.

Table 2. Correlation between temperature and J_{nr} using power-law

Additive Type	**J_{nr} model at 0.1 kPa**			**J_{nr} model at 0.1 kPa**		
	β	**α**	**R^2**	**β**	**α**	**R^2**
Neat	8.486	1.943E-15	0.999	8.766	7.599E-16	0.999
4%GF	8.869	2.013E-16	0.999	9.296	4.351E-17	0.999
8%GF	8.933	1.114E-16	0.999	9.401	2.037E-17	0.999
12%GF	8.948	1.395E-16	0.999	9.315	3.826E-17	0.999
2%SBS	8.639	3.109E-16	0.997	9.135	5.868E-17	0.998
4%SBS	6.789	5.614E-14	0.986	6.737	1.178E-13	0.966
Hybrid	9.272	1.032E-17	0.999	9.864	1.174E-18	0.998
8%FA	8.356	2.112E-15	0.984	8.675	6.937E-16	0.985

4 Conclusions

Assessing the creep recovery behaviour of modified asphalt binders at various temperatures is crucial, as is developing models that can be used to accurately pick the polymer type and amount appropriate for the region of concern, as well as in the design of pavement structures. Based on the findings, the following conclusions can be drawn:

- Geopolymer additives have a significant effect on the recovery behaviour of asphalt binder.
- The 4%SBS binders achieved the highest creep recovery resistance at different temperatures and stresses compared with the other modifiers.
- At different temperatures and stresses, the 4%SBS binder had J_{nr} values less than 0.5, whereas the hybrid binder had J_{nr} values less than 0.5 at 46 °C, 52 °C, and 64 °C at different stresses.
- There is a good relationship between $G^*/\sin\delta$ and $1/J_{nr}$ using a power equation with an R^2 of 0.79 and 0.85 at 3.2 kPa and 0.1 kPa stresses, respectively.
- The power-law models most effectively illustrated the correlation between temperature and J_{nr} at different stresses with R^2 of more than 95%.

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