Evaluation of the Rutting Performance of Asphalt Binders and Mixes Modified with Asphaltenes

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ABSTRACT

Asphalt binders' property play a crucial role in enhancing the performance and durability of asphalt pavements, making their properties a subject of continual research and development. Asphaltenes, known for its complex molecular structures, have been identified as key components influencing the performance of asphalt binders. This study explored asphaltenes, sourced from Alberta oil sands, as an additive for modifying asphalt binder, utilizing an asphalt binder derived from crude oil. The objective was to evaluate the rutting resistance property of asphalt binders modified with an optimal concentration of 12 % (by weight of binder) asphaltenes. Multiple stress creep recovery (MSCR) test was used to evaluate the rutting resistance property of both unmodified and asphaltenes-modified binders using a dynamic shear rheometer (DSR). The MSCR results demonstrated that asphaltenes-modified binder had reduced non-recoverable creep compliance (J_{nr}). Lower J_{nr} values suggest an improved resistance to rutting in the binder post-asphaltenes introduction. The J_{nr} values of the asphaltenes-modified binder were consistently below 0.5 kPa^{-1} which is the requirement for extremely heavy traffic conditions. In addition, the reduction in stress sensitivity after asphaltenes modification highlighted the stabilizing influence of asphaltenes. Hamburg wheel-track (HWT) test was also conducted at an extreme high temperature of 60 °C to investigate the rutting and moisture damage resistance of the mixes before and after asphaltenes modification. A 2.8 times lower rut depth was observed for asphaltenes modified mix with a rutting resistance index (RRI) of 16,457. Additionally, asphaltenes-modified mix did not show any sensitivity to the moisture damage with the absence of stripping inflection point (SIP). These findings underscore the promising potential of asphaltenes in sustainable asphalt binder modification. This study contributes to the ongoing efforts to develop sustainable and high-performance asphalt materials, with the potential to extend the service life of asphalt pavements and minimize maintenance costs.

Keywords: Binder Additive, Asphaltenes, Asphalt Binder Modification, Rutting Resistance, Moisture Sensitivity.

1. INTRODUCTION

In the realm of pavement engineering, the quest for durable and resilient asphalt materials remains a persistent search. Asphalt binders, serving as the backbone of asphalt mixes, play a pivotal role in determining the performance and longevity of asphalt pavements. Asphalt pavements are susceptible to various forms of deterioration, and the properties of the asphalt binders largely determine the occurrence of such issues. Rutting, a common pavement distress, refers to the longitudinal depression formed in the wheel path of asphalt pavements. It typically occurs in both asphalt layers and the underlying unbound layers [1-3]. However, approximately 95 % of rutting tends to accumulate within the asphalt layers, representing a significant mode of pavement degradation [4]. This phenomenon becomes particularly critical during the warmer seasons and earlier stages of pavement life, primarily because of the decreased stiffness of the asphalt binder [5]. Rutting not only diminishes the longevity of the pavement but also poses potential safety hazards for highway users [6].

To enhance the durability of asphalt pavements against damage issues like rutting, various additives are incorporated into the asphalt binder to modify its properties. In 2019, Ghanoon and Tanzadeh conducted a study investigating the behavior of asphalt binder in a non-linear viscoelastic state with the addition of nano-silica. They observed a decrease in the sensitivity of the asphalt samples in response to applied stress and a notable improvement in their resistance to rutting following the modification [7]. Notani et al. in 2020, utilized waste toner as a modified to enhance the rutting resistance in the neat asphalt binder at varying percentages. They used the multiple stress creep recovery (MSCR) test for asphalt binder and wheel track test for asphalt mixes to assess the permanent deformation resistance. Their findings indicated a significant improvement in the anti-rutting properties of both asphalt binder and subsequently asphalt mixture with the addition of waste toner [8]. A study on the asphalt rubber binder (ARB) modified with nano-clay was conducted by Amini et al. in 2021, where they highlighted that higher nano-clay content significantly impacts rutting performance, the performance grading (PG) temperature range, and the temperature susceptibility of ARB [9]. Over the years, various modifiers including gilsonite, natural rubber latex, crumb rubber, and asphaltenes have been employed in the modification of asphalt binder to modify their properties and to optimize their utilization in the asphalt pavement industry [10-13].

Asphaltenes is one of the four components of asphalt binder alongside saturates, aromatics and resins. In refineries, asphaltenes is considered to be a by-product with insignificant importance with no other relevant applications in the industry. In 2020, Ghasemirad et al. explored the effects of different concentrations of asphaltenes on a PG 70-22 binder. Their findings revealed that the presence of asphaltenes enhances the stiffness and elasticity of the asphalt binder, leading to a rise in the high PG temperature [13]. In the past, asphaltenes has also been utilized as a modifier in asphalt binders for the development of high-performance asphalt concrete (HPAC), aiming to enhance the performance, particularly under severe climatic conditions [14-17]. Nevertheless, the influence of asphaltenes on the evaluation of rutting performance in both asphalt binder and mix remains largely unexplored. Hence, this study seeks to employ an optimal concentration of asphaltenes in asphalt binder modification to investigate the rutting performance of both asphalt binder and mix.

2. OBJECTIVE

The objective of this study is to use asphaltenes, a by product, in the process of asphalt binder modification with an optimum content to improve the performance in terms of rutting resistance, moisture sensitivity, and stress sensitivity of both asphalt binder and mix. By achieving the objective, the study aims to contribute to the development of sustainable and high-performance asphalt materials, ultimately leading to the extension of asphalt pavement service life and decrease the expenses associated with maintenance.

3. METHODOLOGY

Initially, the asphalt binder was modified with an optimal concentration of 12 % (by weight of binder) asphaltenes [13]. Short-term aging was conducted on the neat and asphaltenes-modified binders prior to the multiple stress creep recovery (MSCR) test using a rolling thin-film oven (RTFO). The MSCR test was conducted with a dynamic shear rheometer (DSR) device as per AASHTO T350 standard [18] and the resulting parameters from the test are average non-recoverable creep compliance (J_{nr}), average percent recovery (R), and stress sensitivity indices ($J_{nr\ diff}$, and $J_{nr\ slope}$). Additionally, the Hamburg wheel-track (HWT) test was performed following AASHTO T324 guidelines [19]. This test evaluates parameters including the stripping inflection point, rut depth, and rutting resistance index (RRI) to assess the performance of the asphalt mixes. Figure 1 shows the methodological steps adopted in this study with a flowchart.

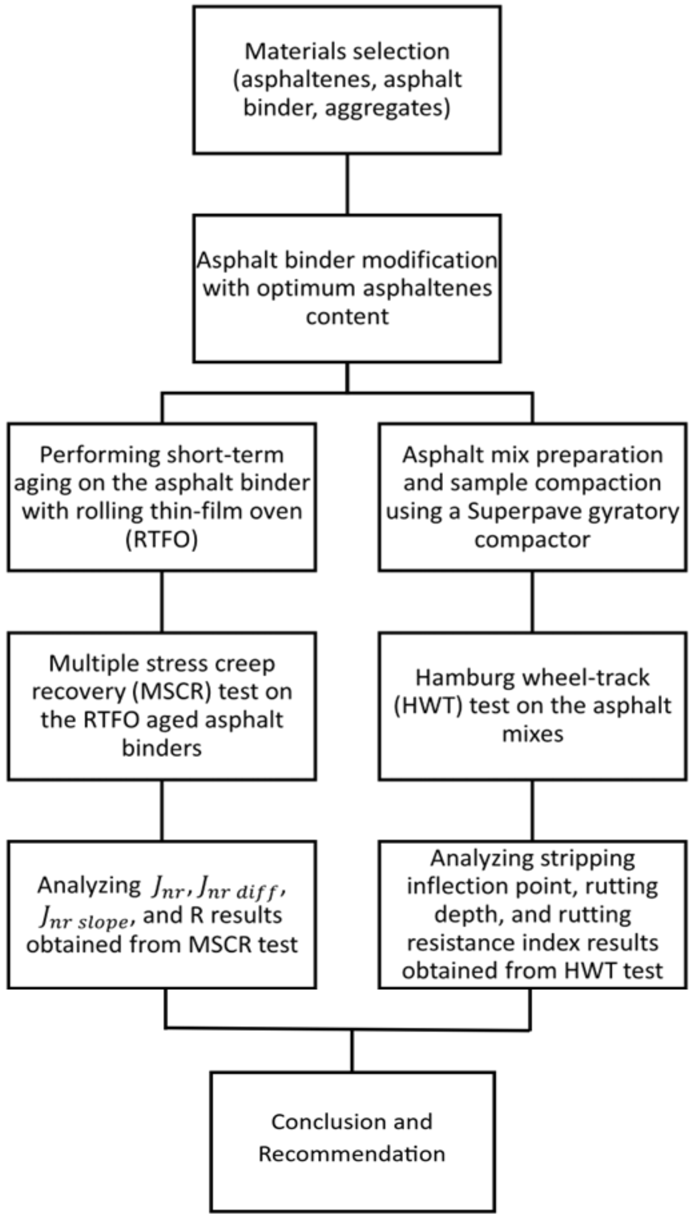

Figure 1: Methodological flowchart

4. MATERIALS AND EXPERIMENTS

4.1 Materials

The asphalt binder used in this study is originated from crude oil, with its detailed specifications outlined in Table 1. The true performance grade (PG) of the unmodified binder is identified as 70.2-25.9.

Table 1: Asphalt binder specifications [16]

Property	ASTM	Specification		Value
		Minimum	Maximum	
Density @ 15 °C, kg/L	D 70	-	-	1.0341
Penetration @ 25 °C (100 g, 5 s), d_{mm}	D 5	80	100	90
Flash Point (COC), °C	D 92	230	-	276
Ductility @ 25 °C (5cm/min), cm	D 113	100	-	150+
Solubility in trichloroethylene, %	D 2042	99.5	-	99.9
Absolute viscosity @ 60 °C, Pa.s	D 2171	150	-	183
Viscosity @ 135 °C, Pa.s	D 4402	-	3.00	0.42
Mass loss, %	D 1754	-	1.00	0.37

Asphaltenes, obtained as a by-product from Alberta oil sands bitumen, was initially received in solid form, as can be seen in Figure 2 (a). To facilitate its incorporation as a binder additive, the material was processed into a powdered form through grinding and sieving using a No. 100 sieve with a mesh size of 150 µm, as shown in Figure 2 (b). Subsequently, the optimum concentration of 12 % (by weight of binder) powdered asphaltenes was blended with asphalt binder using a high-shear mixer (Figure 2 (c)) [13]. The mixing process was conducted at 140°C for 60 minutes, with the mixer operating at a speed of 2,000 rpm. Following modification, the asphalt binder with incorporated asphaltenes exhibited a true PG of 82.9-21.8.

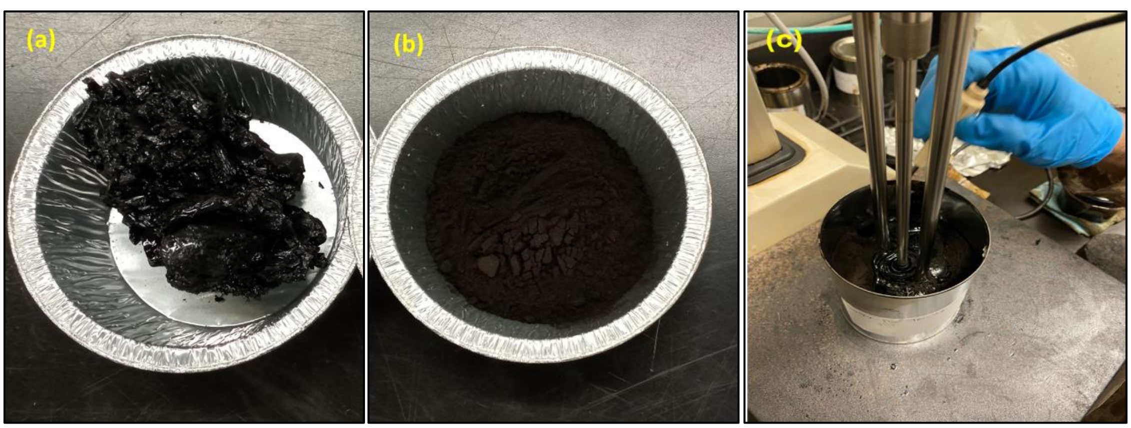

Figure 2: (a) asphaltenes in solid form, (b) asphaltenes in powdered form, and (c) blending process with a high-shear mixer

The properties of both coarse and fine aggregates were assessed through water absorption test and specific gravity test, while Los Angeles abrasion test was used to analyze the coarse aggregate properties only. Based on the results, the aggregate requirements for HPAC preparation are met according to the results provided in Table 2.

Table 2: Aggregate properties [17]

Specific gravity				
	Aggregate portion (%)	Bulk specific gravity	Bulk specific gravity (saturated surface dry)	Apparent specific gravity
Coarse aggregate (≥ 4.75 mm)	39.7	2.618	2.652	2.666
Fine aggregate (< 4.75 mm)	60.3	2.502	2.600	2.617
Water absorption				
	Value obtained (%)		Criterion (%) [20]	
Coarse aggregate (≥ 4.75 mm)	0.3		≤1.0	
Fine aggregate (< 4.75 mm)	0.4		≤1.5	
Los Angeles (LA) abrasion				
	Value obtained (%)		Standard range (%) [21]	
Coarse aggregate (≥ 9.5 mm)	23		10 - 45	

4.2 Rolling Thin-Film Oven (RTFO) Aging

For simulating short-term aging of asphalt binder, the RTFO aging procedure was conducted following the guidelines of AASHTO T240 [22]. Asphalt binder samples, each weighing around 35 g, were filled into specialized glass containers designed for RTFO. These containers were then placed in a rack and allowed to cool for 60 minutes before being transferred to the carriage inside the RTFO. Positioned to face a directed air supply within the oven, each container underwent aging under controlled conditions. The oven maintained a temperature of 163°C, while the carriage rotated at a constant speed of 15 rpm throughout the 85-minutes aging process. The RTFO-aged asphalt binders were then transferred to a container and stored for further testing.

4.3 Mix Design

4.3.1 Aggregate gradation and volumetric properties

An extensive examination of established standards and literature from various countries such as Australia, France, South Africa, and the United Kingdom was undertaken to determine the most appropriate mixture design approach [20,23-25]. Drawing insights from these references, a final gradation envelope was chosen to optimize dynamic stiffness. The chosen gradation envelope, which adheres to European specifications and draws from French envelopes, maximum density curves, and relevant literature, includes a nominal maximum aggregate size (NMAS) of 19 mm. Studies have shown that when paired with a hard grade binder, this gradation exhibits superior performance in terms of dynamic modulus values compared to other alternatives [26]. Figure 3 visually depicts this gradation aligns within the boundaries set by the French envelope except for one size [23].

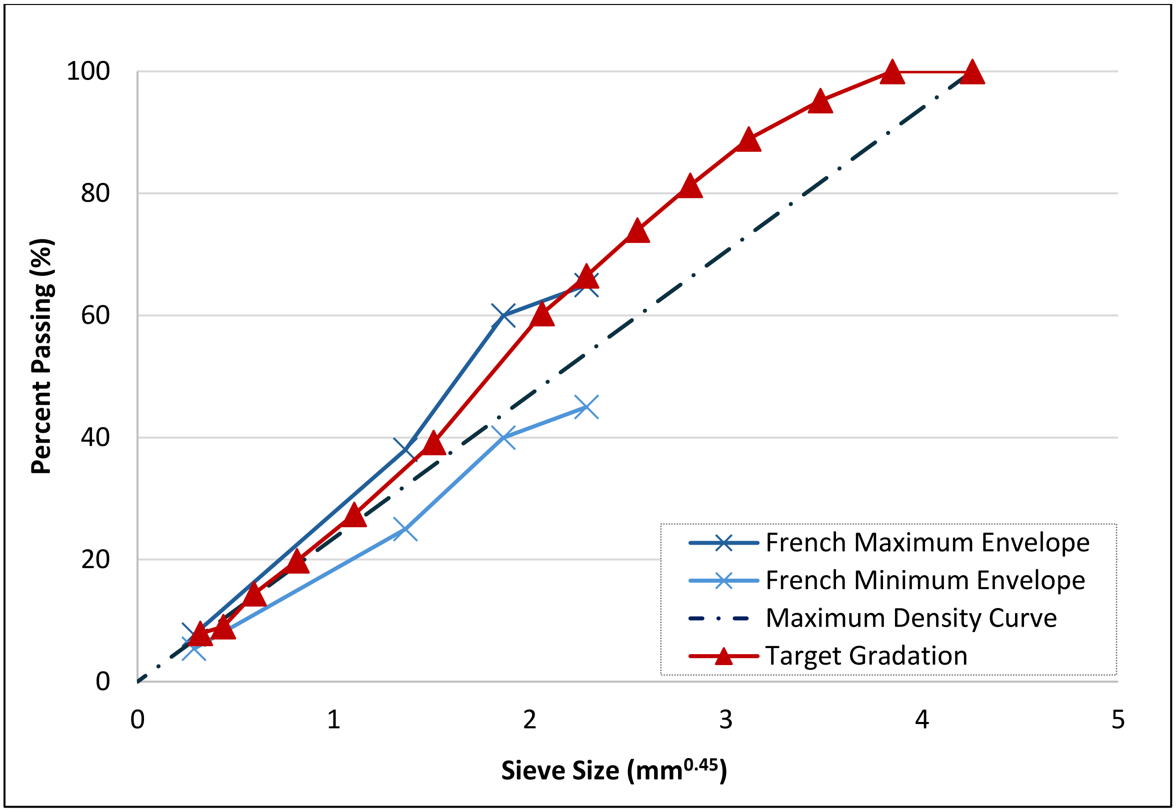

Figure 3: Selected aggregate grain size distribution [17]

Table 3 presents the volumetric properties used for the asphalt mixes in this study, adopted from a study on high modulus asphalt concrete [27].

Table 2: Volumetric properties of the asphalt mixes [27]

Property	Value
Design air voids (%)	1.5 ± 0.5
Voids in the mineral aggregate (VMA) (%)	15
Voids filled with asphalt (VFA) (%)	90
Effective binder content by volume (%)	13.5 ± 0.5

4.3.2 Asphalt binder content

In this study, the required binder content for the asphalt mixes was determined following an approach developed by Denneman et al. for high modulus asphalt [20]. This method involves considering the richness modulus (K), which reflects the thickness of the binder film surrounding the aggregate, along with the type and gradation of the aggregate to calculate the binder content for the mixture design. The optimum binder content was determined to be 5.6 % by total weight of the mixture, as described in Equation 1.

$$TL_{est} = K\alpha\sqrt[5]{\Sigma} \qquad (1)$$

where,

TL_{est} = percent binder by mass of mixture (%),

K = richness factor,
α = correction coefficient for relative density of aggregates, and
Σ = specific surface area of aggregates (m^2/kg).

4.4 Asphalt Mix Preparation

Initially, the materials were heated in the oven at specific temperatures before mixing. A laboratory bucket mixer was then utilized to blend the aggregates and asphalt binders. Subsequently, the asphalt mixture was evenly distributed into flat aluminum trays and subjected to conditioning in an oven at 135°C for four hours following AASHTO R30 guideline [28]. The compaction temperatures chosen for mixes with unmodified and asphaltenes-modified binders were 145°C and 160°C, respectively, based on the viscosity-temperature relationship established using a rotational viscometer. Following this, a Superpave gyratory compactor was employed to compact both the unmodified and asphaltenes-modified samples.

4.5 Multiple Stress Creep Recovery (MSCR) Test

The MSCR test is identified as the most effective method for evaluating the susceptibility of asphalt binders to rutting [29,30]. In this research, both neat and asphaltenes-modified binders underwent MSCR testing to determine their average non-recoverable creep compliance and percent recovery. This test was conducted using a DSR device (Figure 4) following the protocols outlined in AASHTO T350 [18]. The test involves subjecting the RTFO-aged residue to specified temperatures and applying stress levels of 0.1 kPa and 3.2 kPa over ten cycles of creep stress and recovery. The testing temperature selected for this study was 64 °C, closely resembling the field temperature range where rutting occurs [31,32]. A 25-mm plate geometry with a 1-mm gap setting was employed for testing.

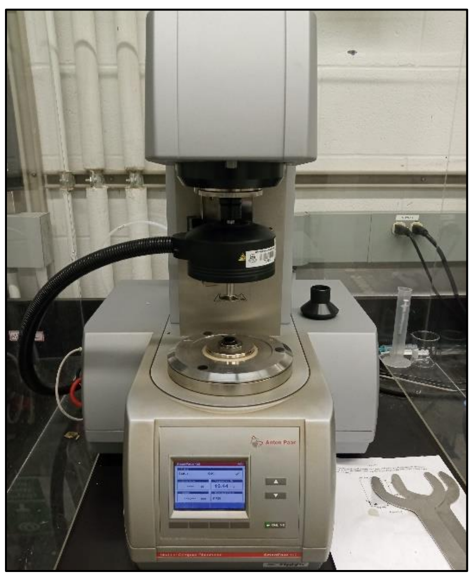

Figure 4: MSCR test using a DSR device

The average non-recoverable creep compliance (J_{nr}) values were calculated using Equations 2 and 3, at stress levels of 0.1 and 3.2 kPa, respectively.

At 0.1 kPa:

$$J_{nr_{0.1}} = \frac{SUM[J_{nr}(0.1,N)]}{10} \text{ for N = 11 to 20} \tag{2}$$

where,

$J_{nr_{0.1}} =$ Average non-recoverable creep compliance at 0.1 kPa (kPa^{-1}), and
N = Number of cycles.

At 3.2 kPa:

$$J_{nr_{3.2}} = \frac{SUM[J_{nr}(3.2,N)]}{10} \text{ for N = 1 to 10} \tag{3}$$

where,

$J_{nr_{3.2}} =$ Average non-recoverable creep compliance at 3.2 kPa (kPa^{-1}).

Furthermore, Equations 4 and 5 were used to evaluate the average percent recovery (R) results at 0.1 and 3.2 kPa stress levels, respectively.

At 0.1 kPa:

$$R_{0.1} = \frac{SUM[\epsilon_r(0.1,N)]}{10} \text{ for N = 11 to 20} \tag{4}$$

where,

$R_{0.1} =$ Average percent recovery at 0.1 kPa (%), and
ϵ_r = The strain value at the end of the recovery portion.

At 3.2 kPa:

$$R_{3.2} = \frac{SUM[\epsilon_r(3.2,N)]}{10} \text{ for N = 1 to 10} \tag{5}$$

where,

$R_{3.2} =$ Average percent recovery at 3.2 kPa (%).

The stress sensitivity of asphalt binders can be assessed using Equation 6 according to the guidelines provided in AASHTO T350 [18],

Where, $J_{nr\,diff}$ is the difference between the J_{nr} values at two different stress levels of 3.2 kPa and 0.1 kPa. Additionally, Equation 7 was utilized to calculate a modified stress sensitivity evaluation index ($J_{nr\,slope}$) as proposed by Stempihar et al. [33].

$$J_{nr\,diff} = \left(\frac{J_{nr_{3.2}} - J_{nr_{0.1}}}{J_{nr_{0.1}}}\right) \times 100\% \tag{6}$$

$$J_{nr\,slope} = \left(\frac{J_{nr_{3.2}} - J_{nr_{0.1}}}{3.1}\right) \times 100\% \tag{7}$$

4.6 Hamburg Wheel-track Test

The Hamburg wheel-track test (Figure 5) conducted in this study followed the guidelines outlined in AASHTO T324 standard [19]. It involved utilizing a pair of Superpave gyratory compacted samples measuring 150 mm in diameter and 60 mm in thickness. Preparation of the test specimens involved cutting them with a diamond saw blade along a secant line to ensure that the gap between the sample molds did not exceed 7.5 mm. Prior to testing, the specimens underwent preconditioning in a water bath at an elevated temperature of 60°C for 45-minutes. During the test, a load of 703$\pm$4.5 N was applied to the samples submerged in water using a steel wheel, with a speed of 0.305 m/s and a frequency of 52 passes per minute. Loading continued until either 20,000 passes were completed or a deformation of 12.5 mm was observed in the samples.

Figure 5: HWT test setup [16]

5. RESULTS AND DISCUSSION

5.1 Multiple Stress Creep Recovery (MSCR) Test Results

The MSCR test can assess the rutting characteristics of both unmodified and modified binders, offering a notably improved correlation to mixture rutting compared to the Superpave binder criteria [34]. As illustrated in Figure 6, for the asphalt binder, the average non-recoverable creep compliance (J_{nr}) value decreased by 87.8 % after asphaltenes modification at a stress level of 0.1 kPa, and by 88.5 % at the 3.2 kPa stress level. A decrease in the J_{nr} value signifies a slower rate of deformation, indicating enhanced resistance to rutting [35].

The neat binder met the criteria for the standard traffic 'S' grade (as 2 kPa^{-1} $< J_{nr_{3.2}} \leq$ 4.5 kPa^{-1}), whereas the asphaltenes-modified binder fulfilled the specifications for the extremely heavy traffic 'E' grade (as $J_{nr_{3.2}} \leq$ 0.5 kPa^{-1}), as specified in AASHTO M332 standard [36]. The 'S' grade classification typically applies to traffic volumes of less than 10 million equivalent single axle loads (ESALs) and traffic speeds exceeding 70 km/h. Conversely, the 'E' grade designation is typically for traffic volumes exceeding 30 million ESALs and standing traffic with speeds below 20 km/h.

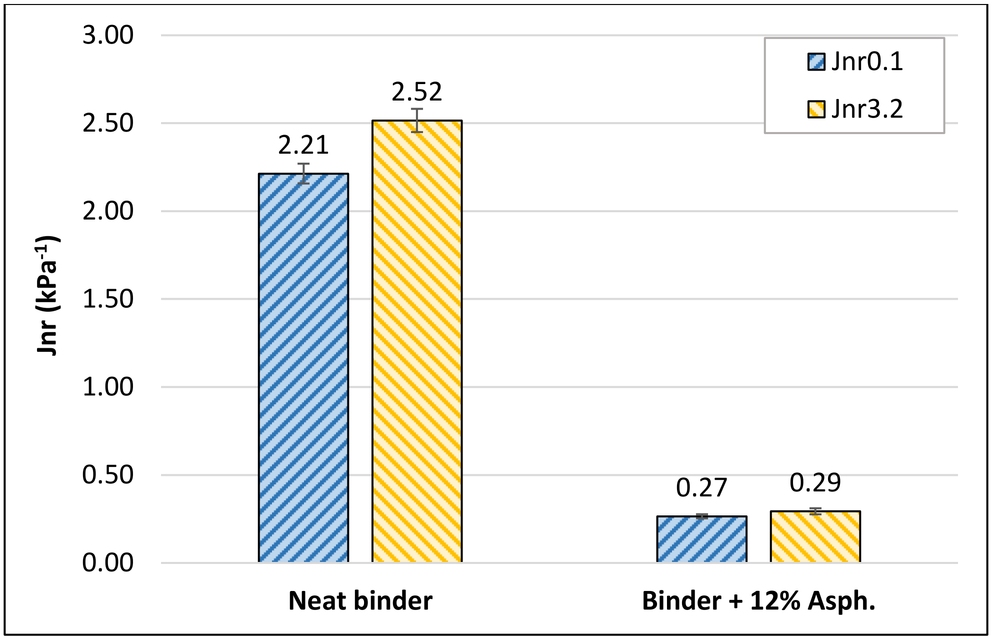

Figure 6: Comparison of J_{nr} results at 0.1 kPa and 3.2 kPa

Observations from Figure 7 indicate that both neat and asphaltenes-modified binders had $J_{nr\ diff}$ values below 75%, meeting the stress sensitivity requirement outlined in AASHTO M332 [36]. Additionally, it is evident that the asphalt binder, when modified with asphaltenes, exhibited reduced stress sensitivity. However, previous studies have noted a lack of significant correlation between $J_{nr\ diff}$ and rutting test results, suggesting that a modified stress sensitivity evaluation index, $J_{nr\ slope}$, may offer a more accurate depiction of the relationship between non-recoverable creep compliance and rutting [33,37,38]. Following asphaltenes modification, the binder exhibited a considerable 90.6 % reduction in $J_{nr\ slope}$. Notably, lower $J_{nr\ slope}$ values are indicative of reduced stress sensitivity. This implies that the introduction of asphaltenes allows the modified binders to retain their stiffness and viscosity even under high-stress conditions, ultimately enhancing mixture stability.

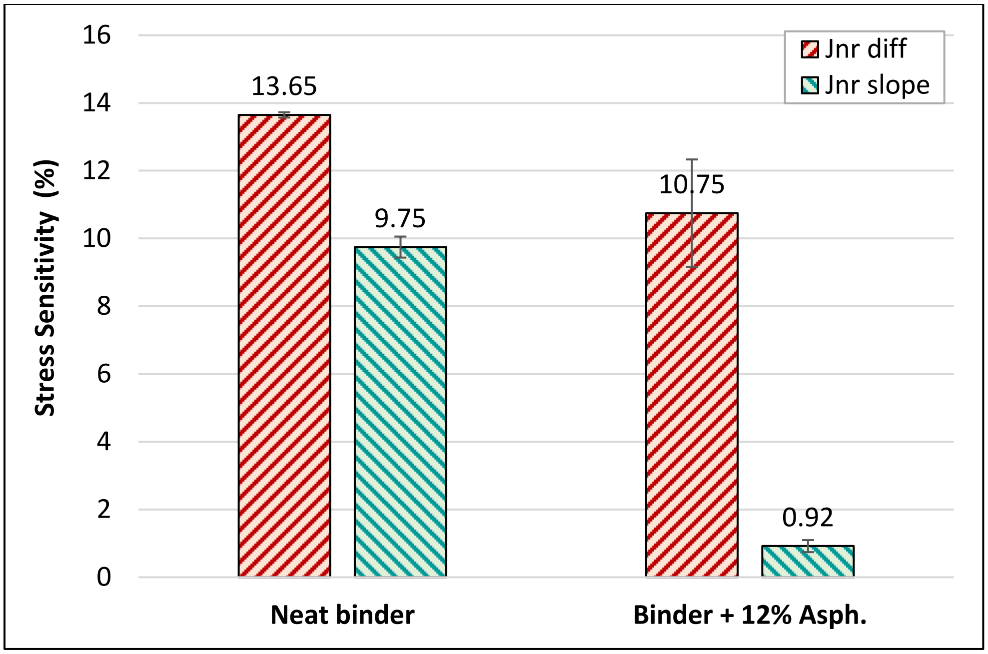

Figure 7: Stress sensitivity comparison between neat and asphaltenes-modified binders

Based on the average percent recovery (R) results, the asphaltenes-modified binder showed substantially higher values compared to the neat binder. Specifically, at 0.1 and 3.2 kPa stress levels, the average percent recovery for the asphaltenes-modified binder was 22.46 % and 16.28 %, respectively. In contrast, the neat binder exhibited lower average percent recovery values of 4.18 % at 0.1 kPa and 0.1 % at 3.2 kPa. This indicates an enhancement in the elastic recovery of the asphalt binder post-asphaltenes modification.

5.2 Hamburg Wheel-Track (HWT) Test Results

The inflection point where the concavity of the graph changes, known as the stripping inflection point (SIP), marks the onset of moisture damage. Typically, if the SIP occurs at a load pass less than 10,000, it suggests susceptibility to moisture damage, leading to increased maintenance requirements before reaching the intended lifespan [39]. In Figure 8, it is evident that the unmodified mix reached a maximum rutting of 12.5 mm after 6,278 passes, indicating a SIP point and hence higher sensitivity to moisture damage. Conversely, the asphaltenes-modified mix did not exhibit a SIP point and only had a 4.5 mm of rutting even after 20,000 passes, suggesting enhanced resistance to moisture damage.

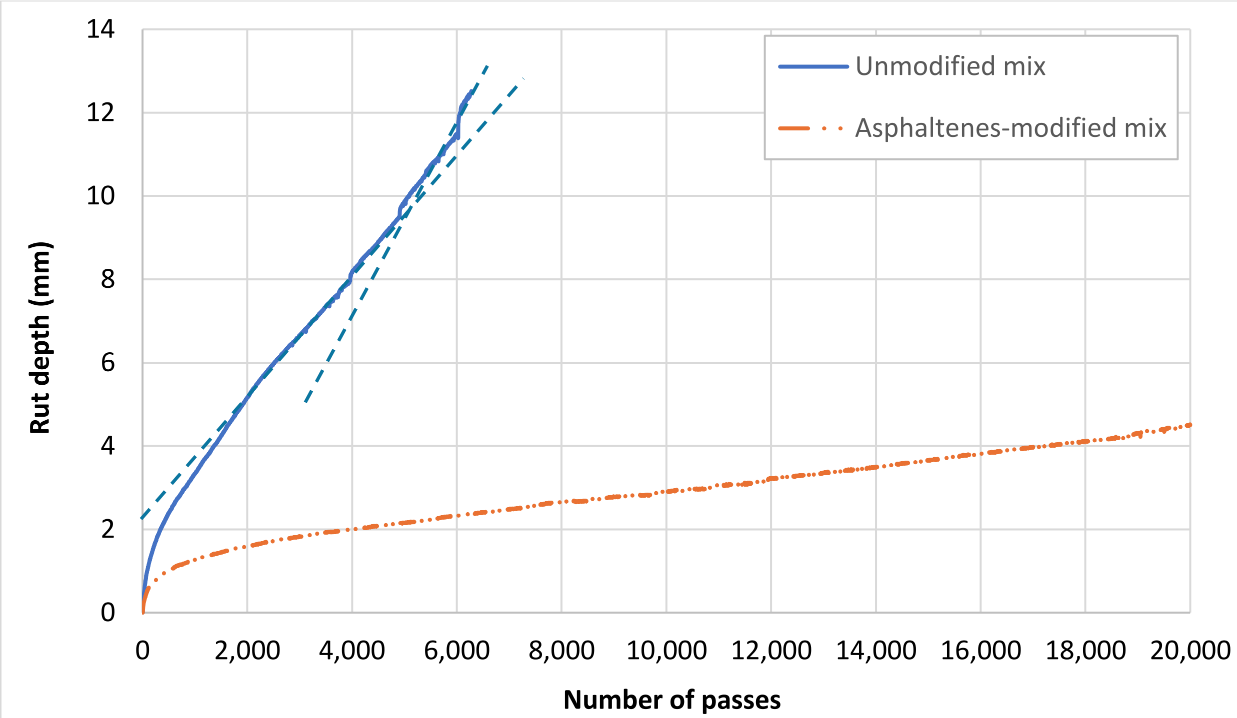

Figure 8: HWT rutting depth for unmodified and asphaltenes-modified mixes

Table 4 displays the results of the HWT test for the asphalt mixes, including the calculation of the rutting resistance index (RRI) using Equation 8 [40]. A higher RRI value suggests greater resistance to rutting. As the results show, the asphaltenes-modified mix had 5 times higher RRI in comparison with the unmodified mix, indicating considerable improvement in the rutting resistance property of the asphalt mix containing asphaltenes-modified binder.

$$RRI = N \times (1 - RD) \tag{8}$$

where,

RRI = rutting resistance index,

N = number of cycles at test completion, and

RD = rut depth at test completion (in.).

Table 4: Hamburg wheel-track test results

Sample	**Passes at stripping inflection point**	**Final rutting (mm)**	**Number of passes at completion**	**Rutting resistance index**
Unmodified mix	5,064	12.5	6,278	3,188
Asphaltenes-modified mix	n/a	4.5	20,000	16,457

6. CONCLUSIONS

This study investigated the potential of utilizing asphaltenes sourced from Alberta oil sands as an additive for modifying asphalt binders, with a focus on evaluating rutting resistance and moisture damage sensitivity of both asphalt binders and mixes utilizing multiple stress creep recovery (MSCR) and Hamburg wheel-track (HWT) tests. The following conclusions can be drawn from the study:

- The asphaltenes-modified binder exhibited superior resistance to rutting, characterized by a reduced average non-recoverable creep compliance (J_{nr}). Specifically, at the highest stress level of 3.2 kPa, the J_{nr} value for the modified binder was 0.29 kPa^{-1}.
- Both unmodified and modified binders fulfilled the stress sensitivity criterion, as indicated by $J_{nr\ diff}$ values below 75%. Nevertheless, the introduction of asphaltenes resulted in a notable reduction in stress sensitivity within the binder, as evidenced by a 90.6 % lower $J_{nr\ slope}$ value for the modified binder compared to the unmodified counterpart.
- In the case of the asphaltenes-modified mix, the presence of a stripping inflection point (SIP) was notably absent, suggesting reduced susceptibility to moisture damage.
- The modified mix exhibited a considerable enhancement in rutting resistance, as indicated by a fivefold increase in the rutting resistance index (RRI) compared to the unmodified mix.

In the future, laboratory testing such as the indirect tensile (IDT) test, the thermal stress restrained specimen test (TSRST) can be carried out to see the impact of asphaltenes in the lower temperature performance of the asphalt mixes.

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