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PERFORMANCE EVALUATION OF WOOD-BASED ADDITIVES IN ASPHALT BINDER: A COMPARATIVE STUDY

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ABSTRACT

Asphalt is a non-renewable byproduct of petroleum refining and acts as a binder that holds aggregate particles together during compaction in flexible pavements. Increasing traffic loads, heavy commercial vehicle congestion, and significant temperature variations have led to performance limitations in traditional asphalt binders. To improve durability and sustainability, researchers have explored modifying binders with waste materials to enhance their mechanical and rheological properties. This study investigates the efficacy of wood dust (WD) and wood ash (WA) as alternative binder modifiers. These widely available waste materials promote environmental sustainability by reducing waste disposal problems and have the potential to improve asphalt properties. The modification process involves incorporating WD and WA at a rate of 4% by binder weight. The modified binders are evaluated through rheological tests to assess their stiffness, elasticity, and resistance to deformation under different temperature conditions, along with the control mixture (CS). The findings of this research demonstrated improvement in binder performance, increased resistance to aging and thermal variations, and a more sustainable approach to asphalt pavement construction. By incorporating these natural wastes, this study aims to contribute to the development of cost-effective and environmentally friendly road infrastructure. The findings will provide insights into the feasibility of using biomass-derived waste as a bitumen binder modifier in future pavement applications.

Keywords: *Asphalt Binder; Biomaterials; Performance Evaluation; Sustainable Pavement; Workability; Wood-Based Additives.*

1. INTRODUCTION

Bitumen is an essential binder used in flexible pavements to hold the aggregate skeleton. However, conventional binders are facing sustainability challenges because of issues related to premature aging and environmental concerns. Modifying binder with waste materials such as wood dust (WD) and wood ash (WA) is an environmentally friendly way of addressing sustainability challenges. Wood dust is a waste product produced from

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the timber and woodworking industries that is available in large quantities but often disposed of poorly, creating pollution problems. Using wood by-products to modify binder enhances the mechanical and rheological properties of bitumen and pavement performance by improving elasticity, stiffness, durability, and resistance to temperature-related and traffic stresses, and it decreases maintenance and construction costs. From an environmental perspective, using wood with asphalt decreases reliance on petroleum-based products, contributes to waste management practices, and leverages circular economies in our construction and maintenance practices.

This study examined three important aspects of asphalt pavement engineering: workability, mix design optimization, and the inclusion of bio-waste products. Workability describes the ease of placing and compacting asphalt material as it is constructed and is a function of both the type and proportions of materials incorporated into the mix. Workability affects pavement density and long-term durability. Mix design optimization is critical as it balances the proportion of aggregates, binder, and intended additives to achieve the desired mechanical properties in an asphalt pavement when subjected to traffic and environmental stresses. The inclusion of bio-waste products from wood industry operations addresses increasing sustainable opportunities by reusing potential waste products, limiting the use of virgin bitumen, and decreasing the carbon footprint of new road construction. All three examined elements considered in combination represent a holistic approach to creating environmentally sustainable, high-performance asphalt pavements that satisfy engineering requirements alongside general environmental objectives.

In recent decades, numerous studies have explored enhancing the performance of Hot Mix Asphalt (HMA) through bitumen binder modification using various waste products, including waste plastics (Sharma et al., 2020; Nizamuddin et al., 2020; Mashaan et al., 2022), crumb rubber (Loderer et al., 2018; Navarro et al., 2005; Mashaan et al., 2012), waste engine oil and bio-oils (Penki & Rout, 2023; Abbas et al., 2023; Fernandes et al., 2018; Senevirathne et al., 2024). Plastics and rubber, for instance, enhance the deformation resistance and fatigue crack resistance of asphalt, resulting in longer pavement life (Sharma et al., 2020; Nizamuddin et al., 2020; Mashaan et al., 2022). For example, as concluded by Sharma et al. (2020), the addition of waste polyethylene into bitumen improved rutting resistance and stiffness. Crumb rubber (Loderer et al., 2018; Navarro et al., 2005; Mashaan et al., 2012) is also an effective modifier due to its flexibility, reducing temperature susceptibility, and enhancing asphalt fatigue life. Waste engine oil has also been explored for use to revive aged binders, their workability, and recover them to their original state (Penki & Rout, 2023; Abbas et al., 2023; Fernandes et al., 2018; Senevirathne et al., 2024). Gawande et al. (2012) have also shown that waste cooking oil and natural latex can serve as bio-modifiers to enhance flexibility, water resistance, and make the mix sustainable.

Other wastes, such as waste wax and refinery sludges (Singh et al., 2020; Vargas & Hanandeh, 2024), have also been explored. The wastes improve the stability of the binder, reduce permanent deformation, and offer an economic method of pavement construction. Singh et al. (2020) explored the use of sulfur as one type of bitumen modifier and found that it increased stiffness and improved performance under different temperatures. This conforms to worldwide sustainability efforts through the transformation of waste into products of value. Wood dust is one such alternative that can improve the quality of roads and assist in waste management. As millions of tons of wood fiber dust are created annually, wood dust in asphalt can address both construction issues and waste issues simultaneously. Not only does it increase the pavement lifespan, but it also supports the building of greener infrastructure. Further research with wood dust-modified bitumen can render roads less expensive, stronger, and more sustainable in the coming years.

Despite the growing body of literature on waste-modified binders, several gaps remain. Studies on waste plastics and crumb rubber have primarily focused on deformation resistance and fatigue performance, with limited attention to the workability implications of modifier addition (Sharma et al., 2020; Loderer et al., 2018). Research on bio-oils and waste engine oil has reported inconsistent outcomes with respect to aging resistance and long-term durability (Penki & Rout, 2023; Fernandes et al., 2018). Critically, no study has simultaneously evaluated wood dust and wood ash as binder modifiers under identical experimental conditions, nor has the Arrhenius-based workability framework been applied to wood-based modified binders. This study addresses these gaps by conducting a unified comparative evaluation of WD and WA modifications, encompassing rheological characterisation, Marshall mix design, and workability analysis within a single experimental programme.

The scope of this research included: (i) evaluating the properties of the additives and modifying the conventional binder; (ii) studying the rheological properties of modified binders along with the control binder; (iii) preparing asphalt mixtures incorporating each modifier along with a control sample; (iv) determining the optimum binder content for each asphalt mixture; and (v) conducting the workability analysis.

2. MATERIAL ANALYSIS AND SAMPLE PREPARATION

The overall experimental framework adopted in this study is illustrated in Figure 1. The programme encompassed binder modification, material characterisation, mix design, and workability analysis, as detailed in the following sections.

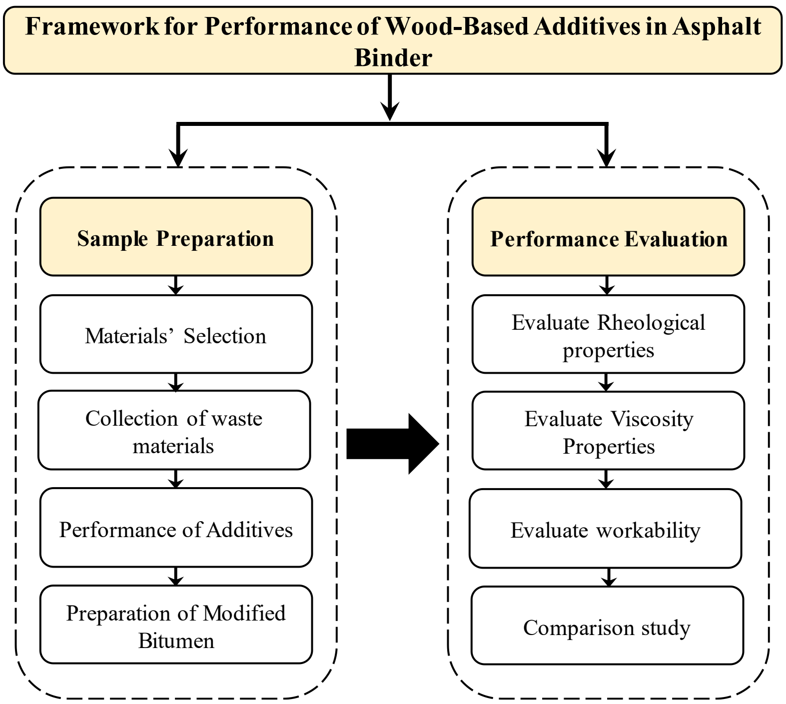


Figure 1: Experimental framework

2.1. BINDER SELECTION AND MODIFICATION

In this study, VG-30 bitumen was selected as the binder for the preparation of hot mix asphalt (HMA) mixtures. Viscosity Grade 30 (VG-30) is widely used for roads with moderate to high traffic loads due to its favorable viscosity and mechanical properties. Two types of modifications were carried out to enhance the characteristics of the conventional binder by incorporating bio-based additives: wood dust (WD) and wood ash (WA). At first, both additives were oven-dried at 50°C and sieved through a 75-micron sieve. The additives were then blended with the VG-30 bitumen at 150°C using a mechanical high-shear mixer. To prevent the formation of air bubbles, the additives were gradually introduced into the binder during mixing, while maintaining a constant shear rate throughout the entire 30-minute mixing process to ensure uniform dispersion. Three types of binder samples were prepared: a control sample (CS) with unmodified VG-30, a sample modified with 4% (by weight) wood dust (WD), and a sample modified with 4% (by weight) wood ash (WA). Rheological property tests were conducted on all binder samples, and the results are presented in Table 1. The objective of these modifications was to improve the binder's resistance to deformation, enhance workability, promote the utilization of sustainable waste materials, and ultimately improve the overall performance of the asphalt mixtures.

Table 1: Rheological properties of the binders.

Properties	CS	WD	WA
Softening point	49 °C	48.5 °C	49 °C
Penetration value (0.1mm)	58	36	40
Elastic recovery	17%	15%	15%
Mixing temperature	155-160 °C	156-162 °C	159-164 °C
Compaction temperature	145-150 °C	148-152 °C	150-154 °C

2.2. AGGREGATE

The aggregate gradation for this study was Bituminous Concrete (BC) 2 (Figure 2) as recommended by the Ministry of Road Transport and Highways (MoRTH, 2013).

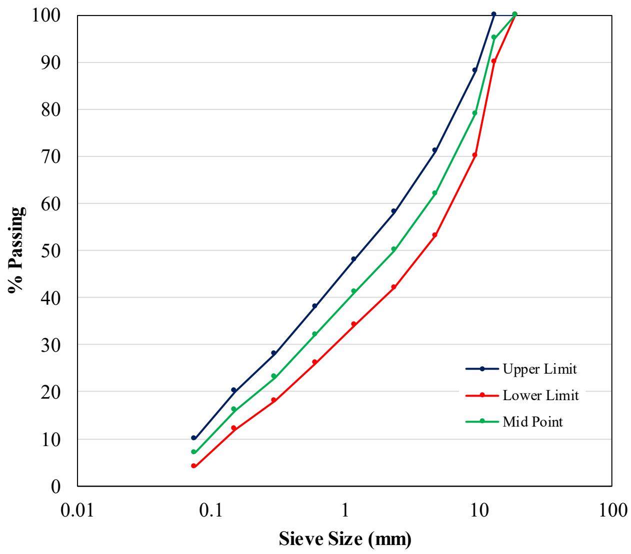


Figure 2: BC-2 Aggregate gradation

Property tests were carried out for aggregates according to the international standards and are mentioned in Table 2.

Table 2: Properties of aggregate

Properties	Values	Test method
Specific gravity (Coarse aggregate)	2.765	ASTM C127
Specific gravity (Fine aggregate)	2.66	ASTM C128
Aggregate crushing value	27.33%	IS: 2386 Part IV
Aggregate impact value	9.17%	IS: 2386 Part IV
Aggregate soundness value	7%	IS: 2386 Part V
Aggregate stripping value	97.90%	IS: 6241-1971

2.3. SAMPLE PREPARATION, TESTING, AND EVALUATION

In this research, three different types of hot mix asphalt (HMA) mixtures were prepared, each utilizing a different binder type: VG-30 bitumen for the control mix (CS), VG-30 modified with wood dust (WD), and VG-30 modified with wood ash (WA). For each HMA mixture, the Marshall stability test was conducted to determine the optimum binder content. Marshall specimens were prepared for each mix using four different binder contents: 4.5%, 5.0%, 5.5%, and 6.0% by weight of the total mix. For each selected binder content, three replicate samples were fabricated, resulting in a total of 12 Marshall specimens for each binder type. The experimental matrix for the study is summarized in Table 3.

Table 3: Experimental matrix

Aggregate				
Experiment	**Samples**			
Specific gravity (Coarse, Fine & Filler)	3			
Aggregate crushing value	2			
Aggregate impact value	2			
Aggregate soundness value	2			
Aggregate stripping value (CM)	2			
Total Samples	11			
Binders				
Experiment	**CS**	**WD**	**WA**	**Samples**
Softening point	3	3	3	9
Penetration test	3	3	3	9
Elastic recovery	3	3	3	9
Brookfield Viscosity test	1	1	1	3
Total Samples				30
Asphalt Mixture				
Experiment	**CS**	**WD**	**WA**	**Samples**
Mix design	12	12	12	36
Total Samples				36
Grand Total				**77**

Figure 3 illustrates the sequential experimental steps followed for the Marshall mix design procedure. Marshall samples were compacted according to specifications for high traffic volume conditions, and the Marshall stability and flow values were measured to evaluate the improvements in mix design properties achieved through the use of the modified binders.

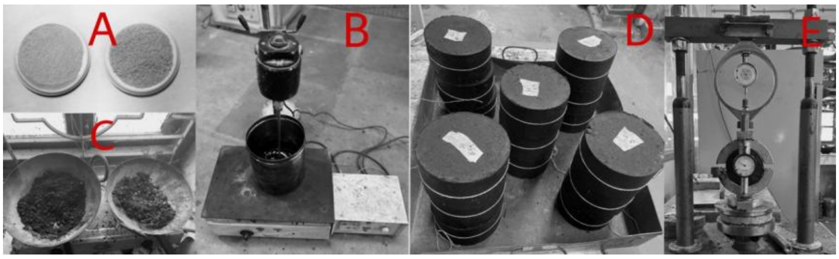


Figure 3: Sequential experimental steps

3. RESULTS AND DISCUSSION

3.1. RHEOLOGICAL PROPERTIES

When comparing the softening point values across all mixtures, it was observed that they exhibited similar softening points. However, the modified binders showed lower penetration values compared to the control mix. Lower penetration values at low temperatures indicate that the modified binders are stiffer and harder, providing greater resistance to deformation under loading conditions, which is advantageous for pavements in high-temperature regions. However, a potential drawback is that increased stiffness can lead to brittleness at low temperatures, increasing the risk of thermal cracking in colder climates.

3.2. VISCOSITY ANALYSIS

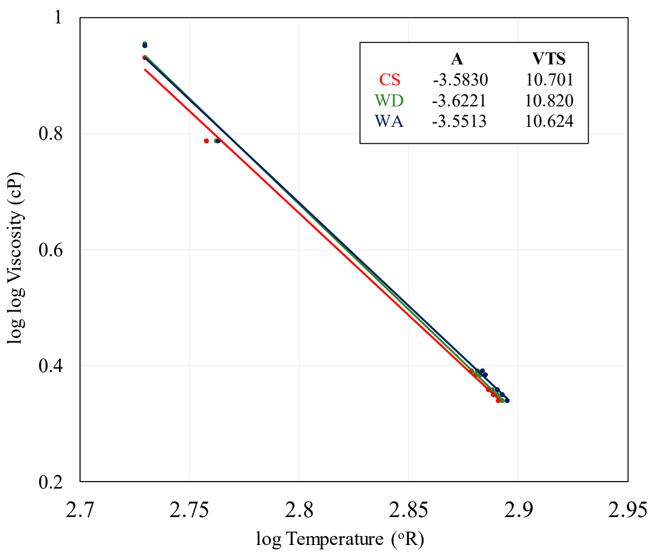


Figure 4: A_i-VTS_i Graph

The observed viscosity data, along with penetration and softening point data, were used to generate an A_i-VTS_i curve (Figure 4) for each binder. Upon examining the A_i-VTS_i

curve for the CS, WD, and WA, it was found that all three binders exhibit similar temperature susceptibility, as their slopes and intercepts are nearly identical. However, the slope for the CS binder is slightly lower than that of the modified binders, indicating that CS is less sensitive to changes in viscosity with temperature fluctuations. In contrast, both modified binders exhibit higher viscosities at higher temperatures, suggesting a higher susceptibility to rutting under high-temperature conditions. Modified binders also imply a higher susceptibility to thermal cracking at low temperatures compared to the control sample.

3.3. MARSHALL MIX DESIGN

The optimum binder content for all mixtures was determined using the Marshall mix design method. During the process, the Marshall stability and flow values were measured for each specimen to obtain the necessary data. Additionally, the theoretical maximum specific gravity (Gmm) was determined for each mixture. After identifying the optimum binder content, volumetric analysis was conducted on the samples prepared with the corresponding binder content. Table 4 presents the optimum binder content and the theoretical maximum specific gravity (Gmm) values for all the mixtures.

Table 4: Optimum binder content and Gmm values of mixtures

Mix	OBC (%)	Gmm
CS	4.9	2.475
WD	4.7	2.532
WA	4.9	2.603

The air voids (Pa), voids filled with asphalt (VFA), voids in the mineral aggregate (VMA), and bulk density were calculated for each set of test specimens. The variations of these properties with binder content, ranging from 4.5% to 6.0%, were analyzed. Furthermore, the changes in Marshall stability and flow values with varying binder content were also examined. All these results are presented in Figure 5. It was observed that modification of the binder led to a reduction in the optimum binder content (OBC), with WD exhibiting the lowest OBC among the mixtures. Although WA showed a similar OBC to the CS, it contained a lower amount of pure bitumen due to the inclusion of 4% wood ash by weight. A lower binder content offers several benefits. First, it directly reduces the amount of bitumen required, leading to significant cost savings in material expenses. Additionally, since bitumen production is associated with carbon emissions, reduced binder usage contributes to lowering the environmental footprint, supporting sustainable construction practices. From a performance perspective, lower binder content enhances the mixture's stiffness, which improves resistance to permanent deformation (rutting) under high traffic loads. Furthermore, it reduces the risk of asphalt bleeding, a phenomenon where excess binder rises to the surface, potentially creating dangerously slippery road conditions.

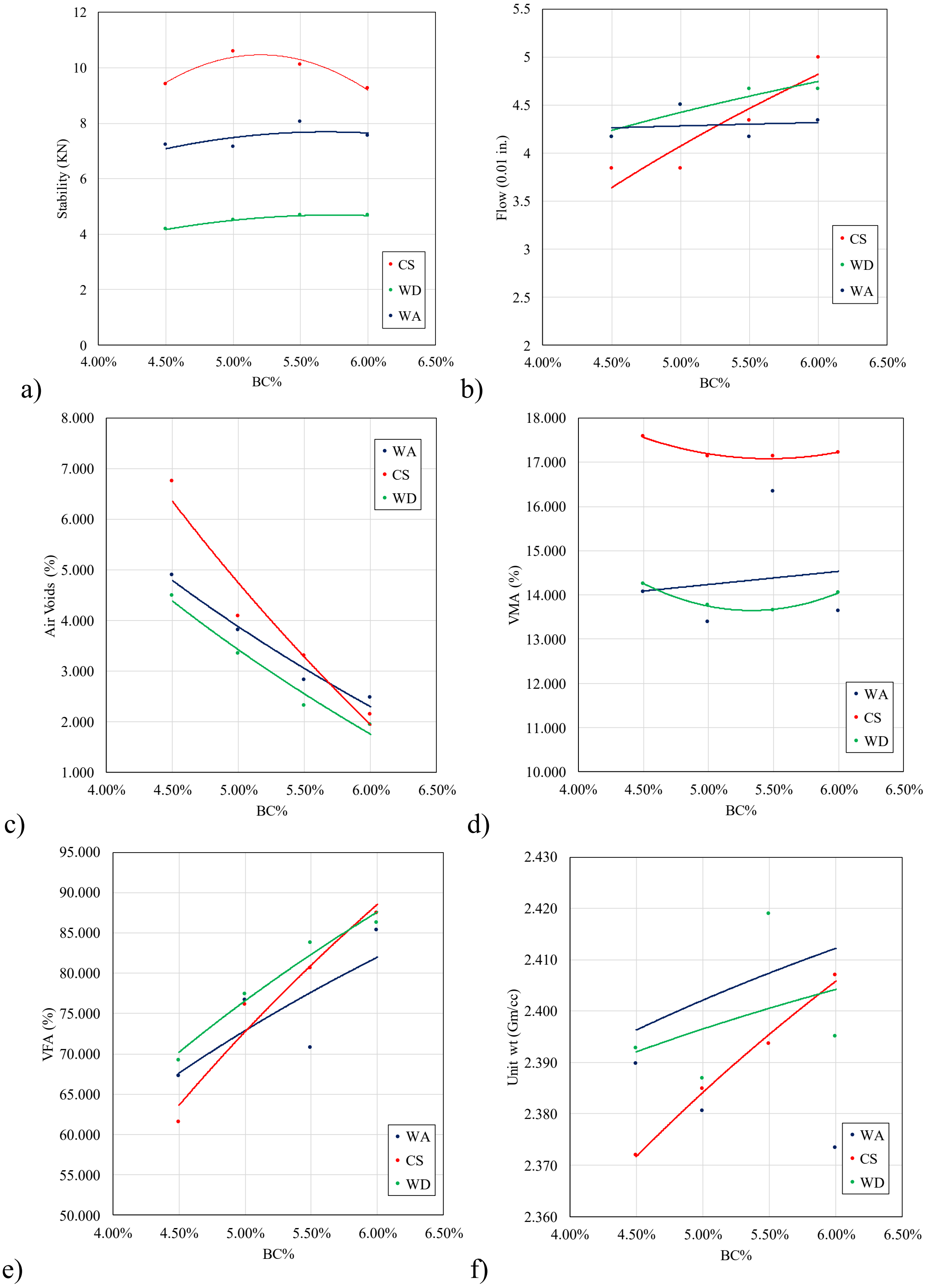


Figure 5: Marshall mix design plots: (a) Stability vs. Binder content, (b) Flow value vs. Binder content, (c) Air void percentage vs. Binder content, (d) VMA vs. Binder content, (e) VFA vs. Binder content, and (f) Unit weight vs. Binder content

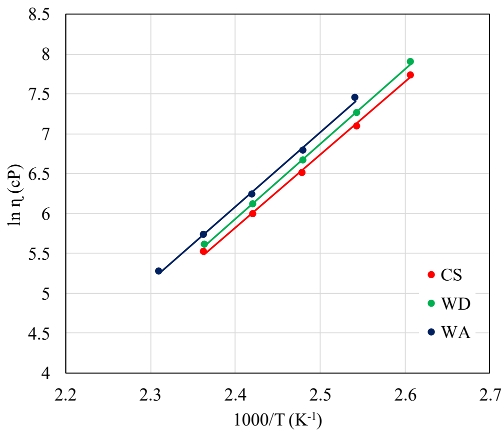
3.4. WORKABILITY ANALYSIS

The workability of asphalt mixtures is crucial during the compaction process. Therefore, a workability analysis was conducted for the binders using the Arrhenius equation. Following the approach suggested by Akhil et al. (2023), the viscosity of the binders was measured as a function of temperature. As shown in Figure 6(a), the temperature dependency of viscosity was evaluated through a plot of ln(η) versus 1000/T. Although the Arrhenius plot traditionally assumes that temperature is not dependent on a dynamic property, in this case, the analysis was approached based on a molecular interpretation of the macroscopic properties. The linear trend observed in the Arrhenius plot indicates that the binders follow Arrhenius behavior within the studied temperature range, allowing the calculation of activation energies (Ea) and pre-exponential factors (As) according to the Arrhenius relationship.

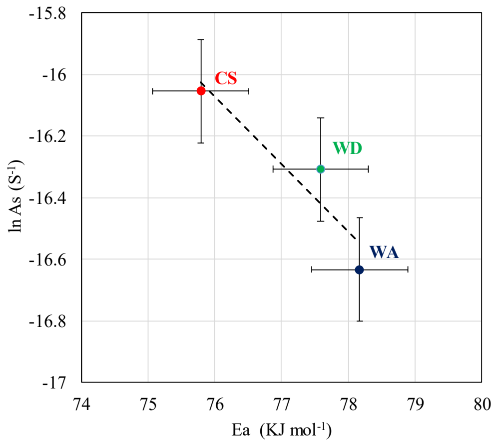
$$ln\eta(T) = lnAs + \frac{Ea}{R} \times \frac{1000}{T} \qquad (01)$$

According to the Arrhenius relationship, E_a represents the activation energy, lnA is the pre-exponential factor, T is the temperature, η is the viscosity, and R is the universal gas constant ($R = 8.314\ J\cdot mol^{-1}\cdot K^{-1}$).

Figure 6(b) illustrates the correlation between Ea and ln(As) for all the binders. The Arrhenius model is based on Transition State Theory (TST), which is commonly used in chemical kinetics to describe reaction rates based on the transition of molecules to an activated state. According to TST, a negative value of ln(As) indicates a negative entropy of formation for the activated state during flow. The results show that the modified samples have the highest activation energy compared to the control binder, suggesting that more energy is required to initiate flow. Furthermore, the lower ln(As) values observed for the modified binders imply that fewer molecular collisions are necessary for the flow process.



a)



b)

Figure 6: (a) Arrhenius plot, and (b) Correlation between the pre-exponential factor (ln As) and the activation energy (Ea)

4. CONCLUSIONS

The objectives of this research were to enhance asphalt binders using wood-based additives. Two modified binders incorporating wood dust (WD) and wood ash (WA) were compared to a standard control binder (CS). A number of tests were conducted to evaluate rheological behavior, viscosity, Marshall mix design properties, and workability of the binders. In addition, the environmental aspects of reusing waste materials were assessed. The key outcomes support the use of wood-based additives in developing stronger, more durable, and sustainable asphalt pavements, and the major findings are summarized below.

With respect to rheological properties and viscosity, the modified binders (WD and WA) exhibited lower penetration values than the control, indicating increased stiffness and improved resistance to deformation under load. Softening points were similar across all binders, confirming that high-temperature softening behavior was not adversely affected by the modifications. Viscosity analysis revealed that the modified binders had higher temperature susceptibility, which may improve rutting resistance at high temperatures but could increase the risk of thermally induced cracking in cold climates. The Ai-VTS curves further confirmed that WD and WA binders have slightly higher viscosity susceptibility than CS, consistent with their potential suitability for high-temperature pavement applications.

Regarding Marshall mix design, the optimum binder content (OBC) was reduced for the WD mixture (4.7%) compared to both CS (4.9%) and WA (4.9%), resulting in cost savings and a reduced environmental impact through lower bitumen consumption. Volumetric properties, including air voids (Pa), VMA, and VFA, were within acceptable limits for all mixtures, confirming structural durability. The reduced binder demand of the WD-modified mixture also contributes to improved stiffness and lower susceptibility to rutting and asphalt bleeding.

In terms of workability, the Arrhenius model established that the modified binders required higher activation energies (E_a) for flow, indicating greater thermal stability at elevated temperatures. Despite the increased stiffness, both modified binders retained acceptable workability, allowing adequate compaction during construction.

From a sustainability perspective, the use of wood-based waste materials supports the principles of a circular economy by converting industrial by-products into value-added construction materials. Reduced bitumen consumption directly decreases reliance on petroleum-based products, lowering the overall carbon footprint of pavement construction. Furthermore, incorporating these waste materials into asphalt mixtures contributes to reduced pollution and improved waste management practices, supporting a more environmentally responsible approach to road infrastructure development.

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