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Performance-Based Evaluation of HDPE and Butonal-Modifies Asphalt Binders

Olagoke B. E.[1, a], Olaomotito P. A.[2, b], Olayanju A. B.[1, c]
[1]*Department of Civil Engineering, Adeseun Ogundoyin Polytechnic, Eruwa*
[2]*Department of Civil Engineering, Lead City University, Nigeria*
** Corresponding author: gmgsolas@gmail.com*

Abstract – *The increasing demand for high-performance and durable road pavements has led to widespread interest in polymer modification of asphalt binders. This study investigates the effect of polymer type and dosage concentration on the rheological properties of asphalt binders using two polymer modifiers: Styrene-Butadiene-Styrene (Butonal) and High-Density Polyethylene (HDPE). The unmodified binder was first characterized for its basic properties, after which it was modified with HDPE and Butonal at varying concentrations (2%, 3%, 4%, and 5% by weight of binder). Key tests carried out include penetration, softening point, ductility, viscosity, and flash and fire point, in accordance with relevant ASTM and AASHTO standards. Statistical analysis, including ANOVA and Tukey's pairwise comparison, was employed to evaluate the influence of polymer type, dosage, and their interaction on the measured properties.*
The results revealed that HDPE significantly enhanced softening point, flash point, and fire point, indicating improved high-temperature performance, especially at 2–3% dosages. Butonal, on the other hand, showed better performance in improving penetration and ductility, demonstrating its effectiveness in enhancing binder flexibility. However, high dosages of Butonal (5%) resulted in decreased thermal stability. Statistical analyses confirmed that both polymer type and dosage concentration had highly significant effects (p < 0.001) on binder rheological properties. The findings support the need for careful selection and optimization of polymer type and dosage based on performance objectives and climatic conditions. This study contributes valuable insights into the formulation of performance-based asphalt binders for sustainable pavement design.
Keywords: *Polymer-modified asphalt, HDPE, Butonal, polymer dosage.*

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I. INTRODUCTION

The performance of asphalt binders plays a pivotal role in the structural integrity, durability, and long-term serviceability of flexible pavements. However, conventional bituminous binders are prone to temperature-related distress mechanisms, such as rutting at high service temperatures, thermal cracking at low temperatures, and progressive oxidation and embrittlement during service life. Asphalt pavements worldwide face increasing demands due to the growth in traffic loads and rising climatic stresses. Flexible pavements, comprising aggregates, filler, and a bituminous binder, are particularly susceptible to common forms of distress such as rutting, fatigue cracking, and thermal cracking, which compromise structural integrity and service life (Ghani *et al.,* 2022). These limitations necessitate the adoption of modification techniques aimed at improving binder rheology, elasticity, and thermal stability. Polymer modification has proven to be one of the most effective strategies for enhancing the functional performance of asphalt binders. Polymer modification has emerged as a viable solution to improve the properties of asphalt binders (Olalekan *et al.,* 2024; Lee *et al.,* 2023; Jwaida *et al.,* 2023). Polymer modification involves incorporating materials like Styrene-Butadiene-Styrene (SBS) and polyethylene into the asphalt binder (Yang *et al.,* 2024). Incorporating polymers into asphalt enhances its stiffness at high temperatures, reducing rutting potential, and increases elasticity at low temperatures, mitigating thermal cracking (Riyad *et al.,* 2024).

Among the various polymers used in modifying asphalt binder, Styrene-Butadiene-Styrene (SBS) is renowned for its effectiveness in enhancing elasticity and strength, while polyethylene (PE) offers a cost-effective alternative with potential benefits (Shan *et al.,* 2020; Mahmood and Kattan, 2023; Jung *et al.,* 2023). SBS, a thermoplastic elastomer, is widely recognized for its ability to improve the elasticity and temperature susceptibility of asphalt, leading to enhanced resistance against deformation and fatigue (Yang *et al.,* 2024; Li *et al.,* 2022). Studies have demonstrated that SBS-modified binders exhibit superior performance across a range of temperatures, contributing to increased pavement lifespan (Dziadosz *et al.,* 2021). Polyethylene, a thermoplastic polymer, is another modifier used to enhance asphalt binder properties (Chen *et al.,* 2021). Research indicates that polyethylene-modified asphalt binders can improve resistance to rutting and fatigue, contributing to better pavement performance (Zeiada *et al.,* 2024). Studies have also shown that the addition polymers to asphalt binders creates a continuous polymeric network, enhancing their rheological and viscoelastic properties (Imanbayev *et al.,* 2021; Rodrigues *et al.,* 2023).

By incorporating polymers, the binder's viscosity, temperature susceptibility, and resistance to deformation can be significantly altered. Polymers such as SBS, EVA, and various plastomers have demonstrated improvements in elasticity, softening point, and resistance to deformation (Ghani *et al.,* 2022). High-Density Polyethylene (HDPE), a thermoplastic polymer with high stiffness and chemical resistance, has demonstrated notable improvements in softening point, rutting resistance, and long-term stability. Its utilization, particularly from recycled sources, also contributes to sustainable pavement engineering by diverting plastic waste from landfills. On the other hand, Butonal, (aqueous Styrene Butadine Styrene), is known for imparting superior elasticity, flexibility, and crack resistance due to its elastomeric characteristics. While both polymers enhance performance in different ways, direct comparative studies under uniform testing protocols remain limited. Leveraging both HDPE and butonal could yield synergistic benefits, potentially balancing stiffness, elasticity, thermal stability, and low-temperature cracking resistance. A key aspect of binder evaluation is understanding how polymer dosage influences fundamental engineering properties. Rheological properties, such as viscosity, penetration, and softening point point are critical indicators of an asphalt binder's performance. These properties help assess the binder's resistance to rutting, fatigue, and thermal cracking, which are essential for predicting pavement durability and performance. Viscosity and penetration tests provide insight into workability and binder stiffness, while softening point measurements assess high-temperature performance. Ductility testing evaluates binder flexibility, and flash/fire point analysis indicates thermal stability and handling safety. Temperature susceptibility, often quantified using the Penetration Index (PI), further characterizes the binder's sensitivity to temperature changes. Evaluating these parameters together allows for a comprehensive assessment of both rheological and thermomechanical behavior.

This study conducts a performance-based evaluation of HDPE- and Butonal-modified asphalt binders across varying polymer dosages. The objectives were to quantify changes in viscosity, softening point, ductility, penetration, flash/fire point, and PI due to polymer modification while establishing performance enhancement trends and identify optimal dosages for each polymer.

II. METHODLOGY

Materials

The experimental procedures used to investigate the effect of polymer type and dosage concentration on the rheological properties of asphalt binders is outlined. This study involves the modification of asphalt binders using aqueous Styrene-Butadiene-Styrene (SBS) (Butonal) and aqueous high-density polyethylene polymers (HDPE), conducting rheological tests, and analyzing the results to evaluate their effects on binder performance.

Base Asphalt Binder

A 100/120 penetration-grade bitumen, commonly used in flexible pavement construction, was sourced from a construction yard within Ibadan. The binder met the requirements of ASTM D946 / AASHTO M20 specifications for penetration grade asphalt.

Modifiers

High-Density Polyethylene (HDPE): Commercial-grade HDPE granules were sourced locally. Prior to melting, the HDPE was shredded into particles ≤2 mm to facilitate uniform dispersion. The shredded HDPE polymers is shown on Figure 1

Butonal: A synthetic latex polymer emulsion (Figure 2) obtained from BSAFE.

Figure 1: Shredded High Density Polyethylene HDPE

Figure 2: Aqueous Styrene-Butadiene-Styrene (SBS) (Butonal)

Polymer Dosages

Based on the empirical evidence, this research adopted polymer dosages within the effective ranges identified in previous studies (Al-Khateeb *et al,* 2020; Šrámek *et al.,* 2023). Both modifiers were incorporated into the base binder at 2%, 3%, 4%, and 5% by weight of bitumen, in addition to the unmodified control sample. These dosages were selected based on preliminary trials and literature-reported ranges for optimum performance.

Preparation of Modified Binders

Polymer modification was carried out in the laboratory in accordance with ASTM D8 definitions and guidelines for asphalt modification:

The unmodified bitumen was heated to 70°C to achieve proper fluidity. Pre-weighed HDPE or Butonal was gradually introduced into the binder while stirring to avoid agglomeration. The addition of the polymer was uniform and at a steady pace to prevent clumping. To guarantee that the polymer and asphalt binder blended properly, the desired temperature was maintained during the mixing procedure. A homogenous and uniform modification was attained after 30 minutes of vigorous stirring of the mixture. The modified binder was mixed and then allowed to gradually cool to room temperature. After that, the altered binder was put into clean, labelled sample containers for additional examination.

Evaluating the Rheological Properties of Bitumen

All tests were performed in triplicate to ensure repeatability. Standard test methods were strictly adhered to as shown on Table 1

Table 1: Standard test methods

Property	Test Method	Purpose
Penetration (25 °C)	ASTM D5	Determines binder hardness.
Softening Point (Ring and Ball)	ASTM D36-2000	Evaluates high-temperature performance.
Ductility (25 °C)	ASTM D113	Measures binder flexibility.
Viscosity (135 °C & 165 °C)	ASTM D4402	Assesses workability and mixing properties.
Flash & Fire Point (Cleveland Open Cup)	ASTM D92	Determines thermal safety limits.
Penetration Index (PI)	Calculated from penetration and softening point results	Assesses temperature susceptibility.

Asphalt Binder Softening Point

The ASTM D36-2000 standard specifications were followed for conducting the asphalt binder softening test (De Medeiros et al., 2024).

The Softening Point apparatus (Figure 3), was used. The softening point apparatus consists of of balls, rings, and a pouring plate. hotplate, thermometer, ring holder assembly, glass beaker, and ball-centering guides.

Distilled water was used as a reagent.

Figure 3: Softening Point Test

Procedures

After being put in a little container, a sample of the asphalt binder was put in an oven that had been prepared to 110 °C. It was left there to melt and become sufficiently fluid to pour. After giving the sample a thorough stir, it was transferred into the rings. The samples in the rings were allowed to cool gradually to ambient temperature. The sample is poured into the rings and levelled with a hot straight edge. All samples developed acceptable fluidity within 60 mins.

The rings holding the samples were arranged in the ring holder as part of the test apparatus. Over the rings were the ball centering guides. The centering guide held the balls in place as they were carefully positioned. The glass beaker was used to hold the setup equipment. To fully submerge the ring and the ball, the liquid bath was poured into the beaker. For the distilled water and glycerin bath samples, the initial temperature was 5 ±1°C and 30 ±1°C, respectively. To attain temperature equilibrium in the samples and equipment, the initial temperature was maintained at that level for 30 minutes prior to the heating procedures.

The beaker holding the two-ringed sample was gradually heated from below at a steady temperature rise after temperature equilibrium. The rate of temperature rise was maintained at 5 ±1°C/min. The softening point is the temperature at which a ball comes into contact with the ring holder's base. When the softening point temperature difference between the two rings is greater than 1°C, the test is repeated. The softening point of a sample was determined by calculating the mean temperature of the two rings.

Asphalt Binder Viscosity Test

Viscosity is expressed in seconds required for a specified volume of liquid to flow through an orifice[3]. The asphalt binder dynamic viscosity test was conducted in accordance with the ASTM D4402 standard specifications (De Medeiros *et al.,* 2024).

Apparatus includes; Rotational Viscometer; Temperature controlled heating bath; Thermometer; Beaker (500ml); Stirring spindle; Stopwatch

Procedures

The dynamic viscosity of the asphalt binders was determined using a rotational viscometer in accordance with the procedures outlined in ASTM D4402. The test was conducted to evaluate the rheological behaviour of the unmodified and polymer-modified binders at elevated temperatures representative of mixing and compaction conditions. Prior to testing, the viscometer was calibrated according to the manufacturer's specifications to ensure measurement accuracy. Samples of both unmodified and modified asphalt binders were prepared by heating them in a thermostatically controlled oven at a temperature not exceeding 163 °C to achieve a fully fluid state without causing thermal degradation. Each binder sample was stirred gently to ensure uniformity and to avoid entraining air bubbles. Approximately the required volume of binder, sufficient to submerge the spindle to the designated immersion depth, was poured into a clean sample chamber. The sample chamber was then mounted in the viscometer, which was fitted with an appropriate spindle size based on the expected viscosity range of the binder. The chamber temperature was maintained at the test temperature (135 °C) using the viscometer's temperature control system, and the binder was allowed to equilibrate for at least ten minutes to ensure uniform temperature distribution throughout the sample. The spindle was rotated at a pre-selected shear rate, and the torque values were recorded once a steady-state reading was achieved. The apparent viscosity was calculated directly from the instrument's output, which took into account both the yield stress and the shear-induced resistance to flow. To determine the yield point, the shear rate was gradually increased from zero until the binder exhibited initial movement, and the corresponding torque value was recorded. The plastic viscosity was derived from the slope of the shear stress versus shear rate plot, excluding the yield stress component.

All measurements were performed in triplicate for each sample to ensure repeatability, and the mean values were reported. Between tests, the spindle and sample chamber were thoroughly cleaned with a suitable solvent to avoid contamination between samples. The obtained apparent viscosity, yield point, and plastic viscosity values were later analysed to assess the effect of polymer type and dosage on the rheological characteristics of the binders.

Asphalt Binder Penetration

The ASTM D5 / AASHTO T49 standard specifications were followed for conducting the asphalt binder penetration test. It was carried out with a needle weighing 100 grammes and a penetration period of 5 seconds at a temperature of 25°C ± 0.1°C.

Apparatus; Penetrometer; Standard needle; Water bath maintained at 25°C; Sample container; Timing device

Procedure

After being heated to a pourable consistency, the asphalt binder sample was poured into the sample container until it reached a minimum depth of 10 mm. After cooling in a controlled setting, the sample was submerged in a water bath set at 25°C for at least an hour. The needle of the penetrometer was positioned such that it barely touched the binder's surface (Figure 4). For the needle assembly, a standard weight of 100g was employed. After that, the needle was allowed to pierce the binder for five seconds. The consistency of the binder was determined by measuring the depth of penetration in tenths of a millimetre.

Figure 4: Penetration Test Apparatus Setup

Asphalt Binder Ductility

Ductility is expressed in centimeters of elongation before rupture (De Medeiros *et al.,* 2024). The asphalt binder ductility test was conducted in accordance with the D113 / AASHTO T51. The test conducted in a water bath at 25°C ± 0.5°C. The extension speed was 5 cm per minute.

Apparatus includes; Ductility testing machine with a water bath maintained at 25°C; Briquette mold; Thermometer; and Sample trimming device

Procedure

The asphalt binder was heated to a pourable state and poured into the briquette mold, which has been pre-coated with a releasing agent. The filled mold was allowed to cool at room temperature and then placed in the water bath at 25°C for 1 hour. After cooling, excess binder was trimmed to ensure a smooth surface flush with the mold. The mold was carefully removed, and the specimen was mounted in the ductility testing machine. The machine elongated the specimen at a constant rate of 5 cm per minute until rupture. The distance at which the specimen breaks was recorded in centimeters, representing the binder's ductility.

Flash and Fire Point of Asphalt Binder

Flash point and fire point temperatures are recorded in °C. The test was conducted in accordance with the ASTM D92 / AASHTO T48 with a heating rate of 5–6°C per minute

Apparatus includes: Cleveland Open Cup apparatus (Figure 5) which consists of the open cup, thermometer; ignition source; and heating device

Procedure

The asphalt binder sample was heated to a fluid state and poured into the Cleveland Open Cup to a specified level. The sample was heated at a controlled rate of approximately 5–6°C per minute. At intervals of 2°C rise, an ignition source was passed over the surface of the sample. The temperature at which a flash (a distinct flame) first appears on the sample's surface was recorded as the flash point. The binder was continually heated and flame was applied until the sample sustains combustion for at least 5 seconds. This temperature is the fire point. The flash point and fire point temperatures were recorded in °C.

Figure 5: Flash and Fire Point Test Apparatus

Data Analysis

The results obtained for the modified asphalt binders was compared to those of the unmodified (base) asphalt binder. Key rheological properties such as viscosity, penetration, ductility, and flash/fire points were examined to determine the extent of improvement achieved through polymer modification. To ensure the reliability of results and identify the optimal conditions for asphalt binder modification, statistical analyses was carried out

Analysis of Variance (ANOVA): ANOVA was used to determine the significance of individual factors (polymer type, and dosage) and their interactions on the rheological properties of asphalt binder. This analysis established which factors have a statistically significant impact on properties such as viscosity, penetration, ductility, and flash/fire point.

III. RESULTS AND DISCUSSION

Properties of the Unmodified Asphalt Binder

To ascertain the basic characteristics of the unmodified binder, tests were conducted (Table 2). Recorded were the flash and fire points, specific gravity, penetration value, and softening point. When comparing these values to those of modified binders, they were used as the baseline. The binder's softening point of 41.5°C indicates that it can withstand high temperatures before becoming soft. It seems to have minimal resistance to thermal deformation at high temperatures, considering its low value. Similarly, the unaltered asphalt binder's high penetration (109.7 pens) suggested that it is extremely soft and prone to rutting under heavy traffic loads. Such high penetration could jeopardise structural integrity in pavement construction, especially in hotter regions. It is not appropriate for hot regions or heavy-load pavements without modification since the softening point and penetration values indicate that the binder is soft and does not resist deformation at high temperatures (Olalekan et al., 2024).

The unaltered bitumen's specific gravity was 1.05, which is in line with the predicted value for bitumen of paving grade. This suggests that the bitumen has enough density and is free of any significant contaminants or compositional anomalies. In addition to reflecting the binder composition—higher values may indicate the existence of denser fractions, which influence stiffness, ageing susceptibility, and thermal cracking resistance—it is also used to determine the volume of bitumen needed in a hot mix asphalt (HMA) design. Since the specific gravity is normal, there may not be any major impurities influencing the bulk composition. The temperature at which the binder may release flammable vapours (flash point) and maintain combustion was found to be 95.1°C, whereas the fire point was found to be 102°C. The relatively low values suggest that care must be used when combining and applying the binder, as it becomes volatile at moderate heating temperatures. According to Huo et al. (2020), the extremely low flash and fire points (230°C to 250°C) are much below normal and suggest oxidation or volatility problems. When combining or applying in the field, this poses major safety risks (Huo et al., 2020).

Finally, the ductility of the unmodified asphalt binder was determined to be rather low at 17.9 cm. This low ductility suggests that the unmodified binder is less flexible and more prone to crack when subjected to mechanical or thermal stress, particularly at low temperatures. The low ductility (17.9 cm vs. >100 cm standard) shows the binder is brittle and susceptible to cracking, especially at low temperatures (Ma *et al.,* 2024). The ASTM D946/AASHTO M20 Standard Specification for Asphalt Cement suggests a penetration grade of 60–70 dmm, a softening point of 45–52 °C, ductility of at least 100 cm, and a flash point of at least 230 °C. These characteristics of the unmodified binder demonstrate that it is not operating at its peak efficiency, which supports the necessity to modify it with HDPE and Butonal polymers to enhance its rheological properties. When characteristics deviate from ideal ranges, studies highlight the necessity of binder modification, particularly for use in high-temperature environments or under repeated loading (Duarte and Faxina, 2021).

Table 2: Properties of Unmodified Binder

S/N	Properties of Bitumen	Average Values
1.	Softening Point	41.5 ℃
2.	Penetration Values	109.7 pens
3.	Specific Gravity	1.05
4.	Flash Point	95.1℃
5.	Fire Point	102℃
6.	Ductility	17.9 cm

Softening Point of Asphalt Binder

One important measure of asphalt binder's resistance to deformation at high temperatures is its softening point. Higher softening point indicates greater rutting resistance and thermal stability, which are advantageous in hotter climates or under high traffic loads. The effects of polymer modification with High-Density Polyethylene (HDPE) and Aqueous Butonal on the thermal behaviour of asphalt binders are shown by the softening point results in Table 3, Table 4 and Figure 6.

It is clear from Table 3 that HDPE, particularly at higher dosages, consistently results in higher softening points than Butonal. The softening point of the control sample (Unmodified asphalt binder) 41.67°C. The softening point values of Butonal, which range from 37.00°C to 40.53°C, fluctuate only slightly when 2% to 5%

polymer is added. On the other hand, HDPE exhibits a consistent upward trend, rising from 38.53°C at 2% dosage to a notably elevated 50.93°C at 5%, indicating a potent hardening and thermal-resistance effect with increasing dosage. All dosages of Butonal have a mean softening point of 39.76°C, while HDPE has a much higher mean of 43.05°C, demonstrating HDPE's superior ability to improve the asphalt binder's high-temperature stability.

Table 3: Effect of Polymer Types and Polymer Dosages on Softening Point of Modified Asphalt Binder

Polymer Types (T)	Significance of the difference between Polymer types (T) and polymer dosages (D)					
	Control	2	3	4	5	**Mean**
Butonal	41.67a (±2.52)	37.00a (±1.41)	39.67a (±1.38)	39.93a (±2.50)	40.53a (±0.93)	**39.76A**
HDPE	41.67bc (±4.16)	38.53c (±0.25)	40.78bc (±1.38)	43.33b (±0.31)	50.93a (±2.04)	**43.05B**
Mean	**41.67B**	**37.77C**	**40.22BC**	**41.63B**	**45.73A**	

Table 4: Analysis of Variance on the Effect of Polymer Types and Polymer Dosages on Softening Point of Modified Asphalt Binder

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Polymer Type	1	81.15	81.148	27.13	0.000
Polymer Dosage	4	200.93	50.233	16.80	0.000
Polymer Type*Polymer Dosage	4	103.82	25.955	8.68	0.000
Error	20	59.82	2.991		
Total	29	445.71			

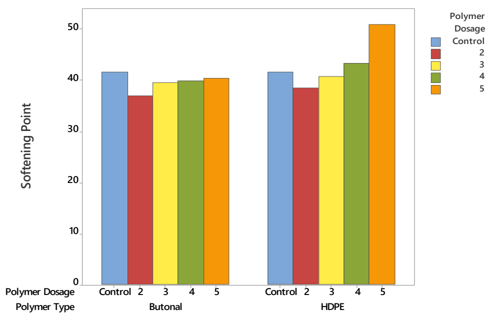

Figure 6: Effect of Polymer Dosage and Type on Softening Point of Asphalt Binder

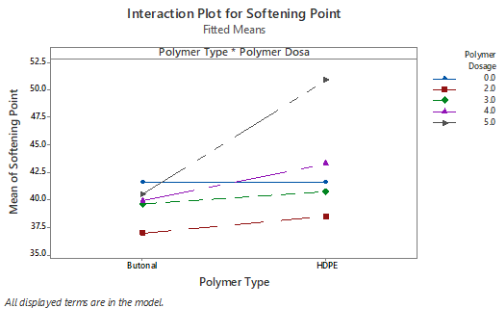

Figure 7: Interaction Plot for Softening Point

At a 95% confidence level ($p \leq 0.05$), the presence of statistically significant differences is indicated by the row-wise lowercase letters and column-wise uppercase letters. All dosage values in the Butonal row have the letter "a," meaning that within this polymer type softening point changes between 2% and 5% are not statistically significant. With HDPE, however, there is a noticeable difference: 5% dosage (50.93°C) is designated "a," which is very different from 2% and 3%, which are designated "c" and "bc," respectively. This indicates that HDPE modification has a high degree of dosage sensitivity. While the lowest average softening point was at 2% (37.77°C, marked "C," the highest average softening point was noted at 5% (45.73°C, marked "A"). This trend highlights that, particularly in the case of HDPE, raising polymer dosage usually increases thermal resistance.

The softening point of HDPE-modified binders clearly increases as the dosage of polymer increases. At 5% HDPE, the softening point increased from 41.5℃ (control) to 50.7℃. This steady rise denotes improved thermal resistance, which makes the binder less prone to softening in hot pavement conditions. The greatest improvement was observed at a dosage of 5%, indicating that this concentration offers the best thermal stability. Increasing HDPE content from 2% to 5% led to a steady increase in softening point from 38.55 °C to 50.7 °C, compared to the control value of 41.5 °C. This aligns strongly with findings from multiple studies. A study reported that incorporating 5% HDPE increased softening point to about 51 °C, indicating improved heat resistance and rutting performance (Khedaywi *et al.,* 2025). Another study observed that HDPE-modified binders exhibit higher softening points than unmodified ones, particularly at 4–6% dosages (Mehta *et al.,* 2024).

Butonal-modified binders, on the other hand, did not show a steady rise. The softening point values stayed below the control sample until the 5% dosage, despite a minor improvement from 37.1℃ at 2% to 40.4℃ at 5%. This may indicate that at lower dosages, Butonal does not significantly enhance the binder's ability to resist heat-induced softening, although it may impart other desirable properties such as improved elasticity or compatibility. This study also showed that Butonal had only a modest effect, with softening point improving slightly from 37.1 °C at 2% to 40.4 °C at 5%, but still below the control value (41.5 °C). This is partially consistent with studies which noted that SBS typically increases softening point at moderate dosages (3–5%), but performance depends on formulation and compatibility with the base binder (Nisar and Mir, 2025). Another study found that SBS-modified binders showed greater improvements in elasticity and recovery properties than thermal softening behavior at low dosagea (Zhang *et al.,* 2025).

Table 4 and Figure 6 shows the ANOVA results of the effect of polymer types and polymer dosages on softening point of modified asphalt. The ANOVA results validate the very significant influences of polymer type, polymer dosage, and their interaction. The softening point is highly influenced by the type of polymer used, as evidenced by the p-value of 0.000 and F-value of 27.13. This supports the distinct difference between HDPE and Butonal that can be seen in Table 4. Polymer dosage factor is also very significant ($F = 16.80$, $p = 0.000$), indicating that the quantity of polymer added is a key factor in altering the thermal characteristics of the binder. The interaction effect plot of polymer type and dosage illustrated on Figure 7 has F-value of 8.68 and a p-value of 0.000, thus the effect of dosage relies on the polymer used. In HDPE, for instance, increasing dosage considerably raises the softening point; however, in Butonal, the effect plateaus or varies slightly.

This analysis unequivocally demonstrates that HDPE is superior to Butonal in raising the asphalt binder's softening point, which makes it more appropriate for uses where high-temperature performance is crucial. The softening point is significantly influenced by HDPE dosage, with 5% exhibiting the greatest improvement. Butonal, on the other hand, is less successful in this performance criterion since it shows little effect on softening point at any dosage. These observations are confirmed statistically by polymer type, dosage, and interaction all showing notable effects on softening point. HDPE was more effective in raising the softening point of asphalt binders, particularly at higher concentrations, making it more suitable for applications requiring enhanced resistance to high service temperatures. Butonal had little effect on heat resistance, indicating that its advantages might be found in other performance domains like workability or flexibility. This could be due to the fact that HDPE possesses a high degree of crystallinity (80–90%) and minimal branching, which results in strong intermolecular forces and a relatively high melting temperature (~130 °C). This crystalline structure acts like rigid reinforcing domains within the bitumen matrix, thereby elevating the binder's thermal resistance and effectively raising the softening point (Lee *et al.,* 2023).

Viscosity of Asphalt Binder

The viscosity properties of asphalt binders such as the plastic viscosity, apparent viscosity, and yield point are crucial markers of the workability of the binder. Table 5 through Table 11 and Figures 8 through 16 show obvious trends in how each polymer - butonal (a styrene-butadiene-based aqueous latex) and High-Density Polyethylene (HDPE) - and dosage concentration influence the flow characteristics of the asphalt binder illustrating how the flow and deformation behaviour of asphalt binders are affected by the addition of HDPE and Butonal polymers at different dosages.

With increasing dosage, HDPE's plastic viscosity consistently decreases, going from 60 cP (control) to 36 cP at 5% dosage. According to this pattern, HDPE may improve workability at mixing and compaction temperatures by lowering internal resistance to flow under shear stress. However, at 5% dosage, the yield point (resistance before flow begins) increases significantly from 25 lb/100 ft² to 68 lb/100 ft², and the apparent viscosity (which takes into account both shear stress and yield stress at a temperature of 135℃ and a shear rate of 1.0 to 10 rpm rotor speed) increases from 42.5 cP (control) to 70 cP. Besides HDPE's improvement of bitumen flow behaviour, these increments in apparent viscosity and yield stress suggest that HDPE also increases the binder's structural resistance under loading. Studies has also shown that HDPE reduces plastic viscosity due to better dispersion and thermoplastic nature at moderate temperatures, facilitating flow at mixing conditions (Ranjbarha *et al.,* 2021; Khumalo *et al.,* 2024). The decrease in plastic viscosity as against increase in apparent viscosity (Table 5), reflects the behavior of a non-Newtonian, viscoplastic fluid (Yang *et al.,* 2024). An increase in apparent viscosity and yield stress at higher HDPE dosages (4–6%) has also been reported in studies, indicating stiffening and improved rutting resistance (Jia *et al.,* 2023).

Both plastic and apparent viscosities for Butonal increase with increment in dosage, peaking at 5% dosage (plastic viscosity: 99 cP, and apparent viscosity: 101.5 cP). This demonstrates that as dosage increases, butonal stiffens the binder more than HDPE. At 3% dosage, the yield point rises dramatically to 146 lb/100ft², and at 5% dosage, it falls to 5 lb/100ft². At higher dosages, Butonal may start to impair binder cohesiveness or cause phase separation beyond the ideal dosage, according to this erratic trend in yield stress. SBS polymers increase viscosity significantly with dosage due to network formation within the asphalt matrix (Liu *et al.,* 2023; Li *et al.,* 2024). However, some studies found that excessive SBS dosage (>4%) can lead to phase separation or agglomeration, reducing homogeneity and causing inconsistent yield strength, which is consistent with the result of this study (Haji *et al.,* 2024).

HDPE improves flowability and decreases plastic viscosity, but it also raises the binder's yield strength, suggesting improved resistance to rutting under stress. However, at moderate dosages, butonal shows high yield strength and significantly increases both viscosities, suggesting improved stiffness and structural integrity. At higher concentrations, however, it may decrease workability and flexibility. HDPE offers a balance between workability and strength enhancement, particularly at higher dosages, whereas Butonal is excellent at increasing the stiffness of the binder but may need to be used at a controlled dosage to prevent adverse effects on flow and processability.

Figures 9 and 10, 12 and 13, 15 and 16 show the main and interaction effects of polymer type and dosage on each viscosity parameter. With performance peak around 3–4%, main effect graphs probably show Butonal outperforming HDPE in all three viscosity measurements. Both the type and dosage of polymer used greatly affect the viscosity-related performance of asphalt binders modified with polymer. Especially at 2–3%, butonal greatly increases plastic, apparent viscosity, and yield point; it becomes counterproductive at 5%. Especially at higher dosages (4–5%), HDPE shows more consistent improvements even if its effects are less dramatic.

Comparisons for Yield Point (ib/100ft2)

Yield point specifies the stress level beyond which a material begins to flow. In asphalt mixes, rutting resistance and cohesiveness depend on it. Table 5 shows that butonal at 3% had the highest yield point, 145.67 lb/100 ft²; but, butonal at 5% dropped drastically to 5.00 lb/100 ft². With 5% HDPE reaching a maximum of 67.67 lb/100 ft², the third-highest value overall, HDPE displayed a more progressive increase. The ANOVA on Table 6 validates on yield point values the strong statistical significance of polymer type (F = 994.42), dosage (F = 907.31), and interaction (F = 1726.27). Table 7's Tukey groupings help to highlight the sharp differences even more. Butonal 5% and HDPE 2% formed the lowest tier (G), so indicating a loss of cohesive strength; the top groups were Butonal 3% and 2%.

Table 5: Effect of Polymer Types and Polymer Dosages on Viscosity of Modified Asphalt Binder

Polymer Types (T)	Polymer Dosages (D)	Plastic Viscosity (cp)	Apparent Viscosity (cp)	Yield Point (ib/100ft^2)
Butonal	Control	60.00d (±2.65)	42.50d (±1.44)	25.00d (±2.00)
	2	67.00c (±1.73)	104.67bc (±2.08)	76.00b (±2.65)
	3	72.00c (±1.73)	145.00a (±2.65)	145.67a (±2.08)
	4	87.00b (±2.61)	110.00b (±3.00)	45.67c (±2.09)
	5	99.33a (±3.06)	101.50c (±1.80)	5.00e (±1.00)
HDPE	Control	60.00a (±2.65)	42.50c (±1.44)	25.00d (±2.00)
	2	50.67b (±2.08)	56.50b (±2.78)	10.67e (±1.16)
	3	50.33b (±2.08)	66.50a (±1.80)	33.00c (±2.65)
	4	43.67c (±0.58)	66.69a (±2.09)	46.33b (±1.53)
	5	35.68d (±1.51)	70.33a (±2.08)	67.67a (±2.08)
	T	***	***	***
	D	***	***	***
	T × D	***	***	***

Means that do not share a letter in the same column are significantly different. *** = $p \leq 0.001$; ** = $p \leq 0.01$; * = $p \leq 0.05$ ns = not significant. The number after the ± symbol in parenthesis represents the standard deviation of the mean.

Table 6: Analysis of Variance for Yield Point

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Polymer Type	1	3944.5	3944.53	994.42	0.000
Polymer Dosage	4	14396.0	3599.00	907.31	0.000
Polymer Type*Polymer Dosage	4	27390.1	6847.53	1726.27	0.000
Error	20	79.3	3.97		
Total	29	45810.0			

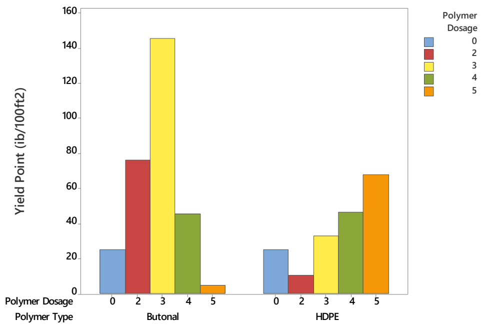

Figure 8: Effect of Polymer Dosage and Type Against Yield Point of Asphalt Binder

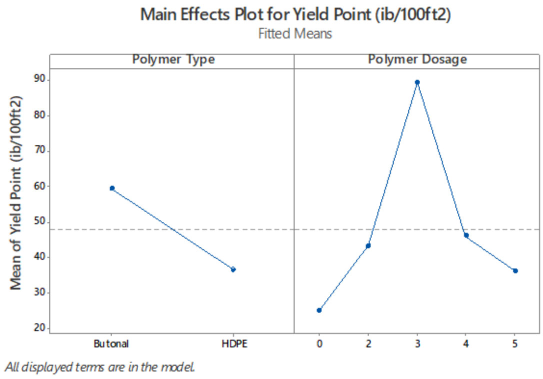

Figure 9: Main Effects Plots for Yield Point of Asphalt Binders

Table 7: Grouping Information Using the Tukey Method and 95% Confidence for Yield Point

Polymer Type*Polymer Dosage	N	Mean	Grouping
Butonal 3	3	145.667	A
Butonal 2	3	76.000	B
HDPE 5	3	67.667	C
HDPE 4	3	46.333	D
Butonal 4	3	45.667	D
HDPE 3	3	33.000	E
HDPE 0	3	25.000	F
Butonal 0	3	25.000	F
HDPE 2	3	10.667	G
Butonal 5	3	5.000	G

Means that do not share a letter are significantly different.

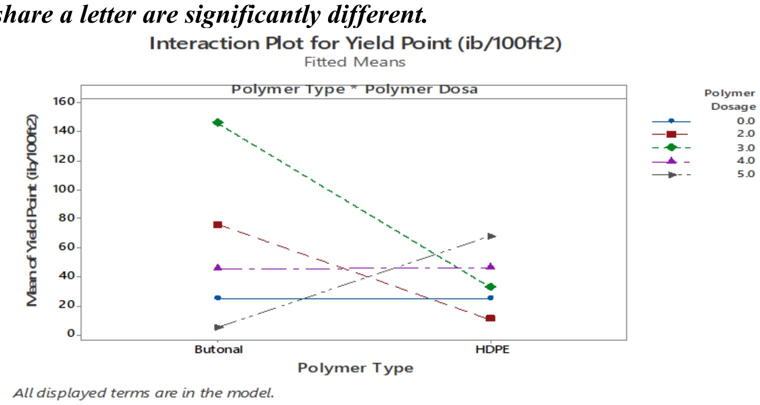

Figure 10: Interaction Plot for Yield Point of Asphalt Binders

Although butonal at 2–3% provides the best structural reinforcement in terms of yield strength, overdosage at 5% results in significant decrease maybe due to binder destabilisation. HDPE might be more suited for uses when consistent performance is desired since it shows more slow and steady improvement in yield stress.

Comparisons for Apparent Viscosity

Apparent viscosity combines plastic and dynamic components and accounts for total resistance to flow. It helps determine the binder's performance during compaction and mixing. From Table 5, Butonal at 3% yielded the highest apparent viscosity—145.00 cp. Consistently having lower values, HDPE-modified samples peaked at

70.33 cp at 5%, still less than half of Butonal' peak. According to the ANOVA (Table 8 and Figure 11), Polymer type, dosage, and interaction effects are all quite highly significant (p = 0.000). With Butonal 3% in the top group (A), Tukey's analysis (Table 9 and Figure 12) clearly shows a separation in groupings; HDPE 2% and Butonal 5% ranked lowest (G), so indicating rather low flow resistance at these points.

Figure 13 shows the interaction plot for apparent viscosity, showing that Butonal improves binder resistance to deformation more successfully than HDPE. But the notable drop at 5%. This trend of apparent viscosity confirms the results of plastic viscosity. Butonal suggests an oversaturation effect, maybe leading to phase separation or incompatibility and so compromising the structural integrity of the mix.

Table 8: Analysis of Variance for Apparent Viscosity

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Polymer Type	1	12140.4	12140.4	2560.73	0.000
Polymer Dosage	4	13033.2	3258.3	687.26	0.000
Polymer Type*Polymer Dosage	4	4856.7	1214.2	256.10	0.000
Error	20	94.8	4.7		
Total	29	30125.2			

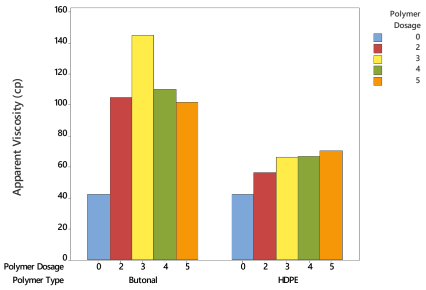

Figure 11: Effect of Polymer Dosage and Type Against Apparent Viscosity of Asphalt Binder

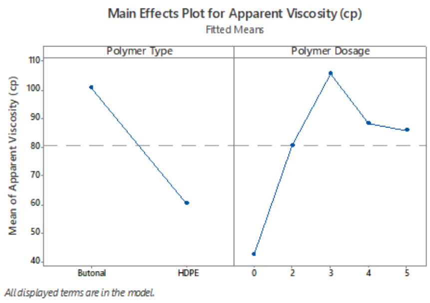

Figure 12: Main Effects Plot for Apparent Viscosity

Table 9: **Grouping Information Using the Tukey Method and 95% Confidence for Apparent Viscosity**

Polymer Type*Polymer Dosage	N	Mean	Grouping
Butonal 3	3	145.667	A
Butonal 2	3	76.000	B
HDPE 5	3	67.667	C
HDPE 4	3	46.333	D
Butonal 4	3	45.667	D
HDPE 3	3	33.000	E
HDPE 0	3	25.000	F
Butonal 0	3	25.000	F
HDPE 2	3	10.667	G
Butonal 5	3	5.000	G

Means that do not share a letter are significantly different.

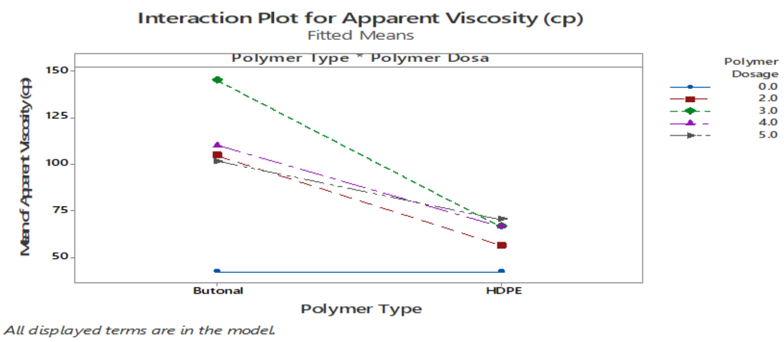

Figure 13: Interaction Plot for Apparent Viscosity

Comparisons for Plastic Viscosity

Plastic viscosity is the binder's resistance to flow following overcoming of yield stress. It is absolutely important for deciding the binder's pumpability and application behaviour at high temperatures.

Table 5, Figure 14 and the matching ANOVA (Table 10) show that, overall dosages, butonal considerably increases plastic viscosity relative to HDPE. From Table 5, butonal-modified binders showed a consistent rise in plastic viscosity with increasing dosage, peaked at 99.33 cP at 5%, while HDPE at the same dosage recorded the lowest value of 35.67 cp, showing an inverse relationship. This points to increased stiffness and possible rutting resistance by suggesting increased resistance to flow. HDPE-modified binders showed a declining trend, with viscosity dropping from 60.00 cP (control) to 35.67 cP at 5%, which would suggest either insufficient dispersion at higher dosages or lower resistance to flow. With F-values of 1269.97, 16.45, and 185.92, respectively, statistical analysis (Table 10) found that polymer type, dosage, and their interaction were all highly significant (p = 0.000). The grouping of Tukey (Table 11) verified the predominance of Butonal 5%, which created a special group (A), much higher than all others. By displaying different lines for Butonal and HDPE, the interaction plot (Fig. 16) supports this and hence confirms the existence of strong interaction effects. These results imply that Butonal is more efficient in raising plastic viscosity, which is preferred for binders applied in high loads. Butonal's capacity to dramatically increase plastic viscosity points to its possibility to improve binder stiffness and load-bearing capacity. Higher viscosity, however, might compromise workability during mixing and compaction, thus a balance between stiffness and constructability is needed.

Table 10: Analysis of Variance for Plastic Viscosity

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Polymer Type	1	6307.5	6307.50	1269.97	0.000
Polymer Dosage	4	326.9	81.72	16.45	0.000
Polymer Type*Polymer Dosage	4	3693.7	923.42	185.92	0.000
Error	20	99.3	4.97		
Total	29	10427.4			

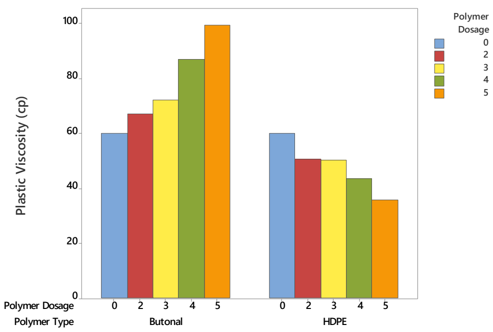

Figure 14: Effect of Polymer Dosage and Type Against Plastic Viscosity of Asphalt Binder

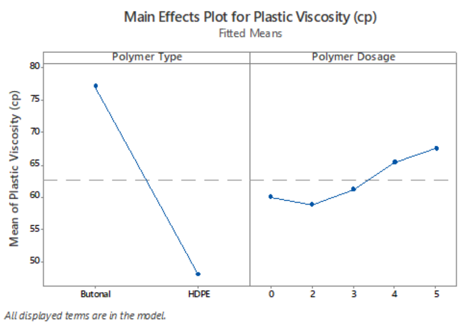

Figure 15: Main Effects Plot for Plastic Viscosity

Table 11: Grouping Information Using the Tukey Method and 95% Confidence for Plastic Viscosity

Polymer Type*Polymer Dosage	N	Mean	Grouping
Butonal 5	3	99.3333	A
Butonal 4	3	87.0000	B
Butonal 3	3	72.0000	C
Butonal 2	3	67.0000	C
Butonal 0	3	60.0000	D
HDPE 0	3	60.0000	D
HDPE 2	3	50.6667	E
HDPE 3	3	50.3333	E
HDPE 4	3	43.6667	F
HDPE 5	3	35.6667	G

Means that do not share a letter are significantly different.

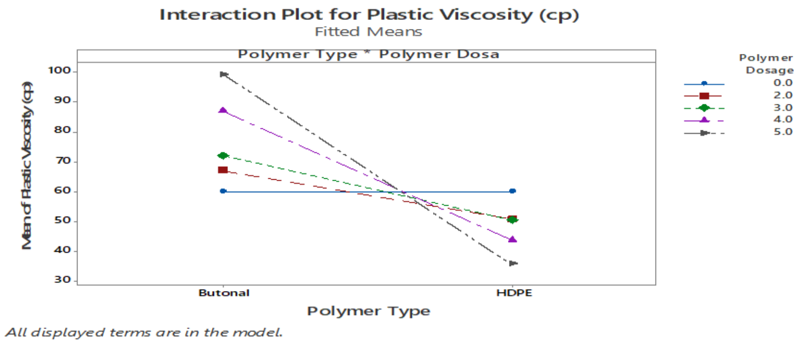

Figure 16: Interaction Plot for Plastic Viscosity

Penetration Values

Penetration value is an indicator of asphalt binder softness or hardness. A higher penetration value signifies a softer binder, whereas a lower value indicates a stiffer binder. The results reveal contrasting trends in how HDPE and Butonal affect penetration at varying dosages. Based on the penetration values provided for both HDPE and Butonal, Table 12, Table 13 and Figure 17 shows how polymer type and dosage concentration affect the hardness and consistency of asphalt binders.

The unmodified binder had a penetration value of 109.67 pens. At 2% and 3%, butonal exhibited noticeably greater penetration values (157.3 and 154.0 pens), suggesting a softening effect, particularly at lower dosages. However, the 4% HDPE dosage produced an unusually high value (132.67 pens), which may have been caused by incomplete blending or phase separation. In contrast, HDPE demonstrated a stiffening effect at 3% (86.33 pens) and 5% (47.33 pens).

Comparing rows within the same polymer (effects of dosage), For Butonal, 2% and 3% are significantly higher than the others ('b'), but not significantly different from one another ('a'). For HDPE, values show significant variation from 'a' to 'd', indicating dosage-sensitive behaviour. Looking at the effect of polymer type (column-wise), Butonal generally produces softer binders, as evidenced by the fact that its mean penetration (117.40A) is much higher than HDPE's (94.07B). The overall effect of dosage reveals that there is a noticeable stiffening effect at higher modifier contents, as evidenced by the fact that the dosage of 5% (60.50B) is much lower than all others (A group).

According to the Analysis of Variance (ANOVA) revealed in Table 13, polymer type ($p \leq 0.000$) is very important, as penetration is greatly influenced by the type of polymer. The polymer dosage ($p \leq 0.000$) is also a very important factor, as penetration depends on the quantity of polymer added, i.e. penetration is sensitive to the polymer concentration. The interaction of polymer type and dosage ($p \leq 0.000$) (Figure 18) is also quite significant, demonstrating that the type of polymer affects dosage and vice versa, i.e. the type of polymer determines the effect of dosage.

Table 12: Effect of Polymer Types and Polymer Dosages on Penetration of Modified Asphalt Binder

Polymer Types (T)	**Significance of the difference between Polymer types (T) and polymer dosages (D)**					
	Control	2	3	4	5	**Mean**
Butonal	109.67b (±4.16)	157.3a (±25.1)	154.0a (±4.16)	92.33b (±10.94)	73.67b (±4.16)	**117.40A**
HDPE	109.67b (±4.16)	94.33bc (±8.33)	86.33c (±2.52)	132.67a (±6.03)	47.33d (±10.97)	**94.07B**
Mean	**109.67A**	**125.83A**	**120.17A**	**112.50A**	**60.50B**	

Row-wise different lower-case letters indicated significant differences at $p \leq 0.05$ among different polymer concentrations under the same polymer type; Row-wise different upper-case letters indicated significant differences at $p \leq 0.05$ among different polymer concentrations for mean of both polymer types; Column-wise different upper-case letters indicated significant differences at $p \leq 0.05$ among different polymer types. The number after the ± symbol in parenthesis represents the standard deviation of the mean.

Table 13: Analysis of Variance on the Effect of Polymer Types and Polymer Dosages on Penetration of Modified Asphalt Binder

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Polymer Type	1	4083	4083.3	29.15	0.000
Polymer Dosage	4	16318	4079.5	29.12	0.000
Polymer Type*Polymer Dosage	4	12219	3054.7	21.80	0.000
Error	20	2802	140.1		
Total	29	35422			

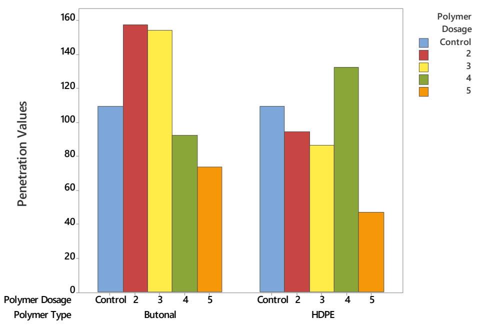

Figure 17: Effect of Polymer Dosage and Type on Penetration Value of Asphalt Binder

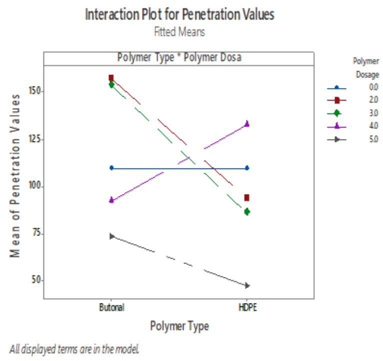

Figure 18: Interaction Plot for Penetration Values

The type of polymer and dosage have a major impact on asphalt binders' penetration properties. Butonal softens the binder at low dosages, whereas HDPE typically produces stiffer binders (lower penetration). According to the statistically significant interaction, each polymer has a specific ideal dosage, above which performance may deteriorate or even reverse. This suggests that for temperature-sensitive pavements to perform as intended, careful polymer selection and dosage are essential

For HDPE, penetration increased at 4% concentration (average: 132 pens), suggesting a softening effect at this dosage. However, at both 2% and 3% concentrations, penetration values remained within a close range (85 and 86 pens respectively), indicating moderate stiffening. At 5%, the penetration sharply decreased (average: 47 pens), implying a significant increase in binder stiffness. This suggests that higher HDPE dosage tends to harden the binder substantially.

In contrast, Butonal-modified binders showed high penetration at 2% (average: 157 pens) and 3% (average: 154 pens), indicating a very soft binder at low dosages. However, penetration drastically dropped at 4% and 5% concentrations (92 and 73 pens respectively), indicating a transition to a stiffer material. The significant drop in penetration between 3% and 5% suggests that Butonal becomes more effective at hardening the binder beyond a certain threshold concentration. Butonal showed a distinct pattern. It starts with a higher softening effect and exhibits a sharper transition to stiffness as the concentration increases. The aqueous nature of Butonal may have contributed to the softening of the binder, as evidenced by the initial increase in penetration values to 157 pens at 2%. As the dosage is increased, this value progressively drops: 154 pens at 3%, 92 pens at 4%, and 73 pens at 5%. This behaviour suggests that while higher dosages of Butonal start to increase stiffness as concentration rises and water content decreases or evaporates during blending, lower dosages of Butonal soften the binder. This could be because of stronger interactions between the polymer and bitumen. HDPE, on the other hand, shows more gradual changes, with an anomalous softening at 4% before stiffening significantly at 5%. These results highlight the importance of dosage optimization in polymer modification of binders, as both under- and over-dosage can lead to suboptimal rheological properties depending on the polymer type used.

The penetration test results reveal distinct behavioral patterns in asphalt binder modification depending on polymer type and dosage. Butonal (SBS) initially softens the binder at lower dosages (2%–3%), as evidenced by the very high penetration values, but contributes significantly to binder stiffening at higher concentrations (4%–5%). This suggests that Butonal has a threshold beyond which its effect transitions from softening to stiffening, offering flexibility in performance tuning based on desired application. At low dosages, butonal acts as a softening agent; at higher dosages, however, it becomes a stiffening modifier.

HDPE improves binder stiffness more effectively at all tested dosages, while Butonal's effect is highly dose-dependent, changing from softening to hardening as the concentration of the polymer rises. The substantial hardening caused by high concentrations may be advantageous for high-temperature performance but may compromise low-temperature flexibility, as evidenced by the sharp decline in penetration for both polymers at 5%. A study found that HDPE-modified binders exhibit a steady decrease in penetration values as dosage increases, particularly from 2% to 6%, signifying increased stiffness (Nunes-Ramos *et al.,* 2024). Another study also observed lower penetration values at higher HDPE concentrations, concluding HDPE enhances rutting resistance in warm climates (da Silva *et al.,* 2024). This is consistent with findings from studies highlighting that SBS at low concentrations tends to soften asphalt, especially if water-based latex (such as Butonal) is used, due to moisture-induced softening during blending (Sun *et al.,* 2024). Studies also confirmed that higher SBS concentrations (4–6%) create stronger cross-linked networks, reducing penetration and improving stiffness (Li *et al.,* 2024b). The transition from softening to stiffening observed in this study is consistent with SBS behavior described by authors who found SBS exhibits dual-phase behavior, depending on polymer dispersion and concentration (Yuan *et al.,* 2022).

Penetration Index

The Penetration Index (PI) is a measure used to indicate the temperature susceptibility of bitumen, indicating how its consistency changes with temperature. It is a fundamental rheological characteristic reflecting asphalt binders' temperature sensitivity. A higher PI value suggests lower temperature susceptibility, which is desirable for pavement performance. This means that, while a positive PI indicates reduced sensitivity and better resistance to deformation under heat, a negative PI indicates great temperature sensitivity (i.e the binder softens easily with temperature) (Olalekan *et al.,* 2024). the penetration index is presented in Table 14 and Figure 19.

The unaltered binder's PI of -0.89 indicated that it was moderately susceptible to temperature changes, which is a common feature of bitumen used for conventional paving. At 2% HDPE, PI dropped to -1.13, suggesting heightened sensitivity to temperature in contrast to the control. At 3% HDPE, PI rose to -0.78, indicating a marginal improvement over the control, suggesting improved thermal performance at this dosage. At 4% HDPE, PI decreased once more to -0.91, which is irregular and could be related to the atypically high penetration value at this dosage, which could be brought on by problems with polymer dispersion. And at 5% HDPE, PI jumped to 0.43, the only positive PI, indicating that HDPE considerably increases the binder's thermal stability at 5% by lessening its vulnerability to softening at high temperatures. This shows that HDPE has a dosage-dependent effect. It performs best at 5%, when the binder has the greatest resistance to deformation brought on by temperature.

Table 14: Penetration Index of Asphalt Binder

Dosage	Softening Point	Penetration Value	Penetration Index
Control	41.5	109.7	-0.89
		HDPE	
2%	38.55	94	-1.13
3%	40.87	86	-0.78
4%	43.3	132	-0.91
5%	50.7	47	0.43
		Butonal	
2%	37.1	157	-1.57
3%	39.4	154	-1.31
4%	40	92	-1.31
5%	40.4	73	-0.83

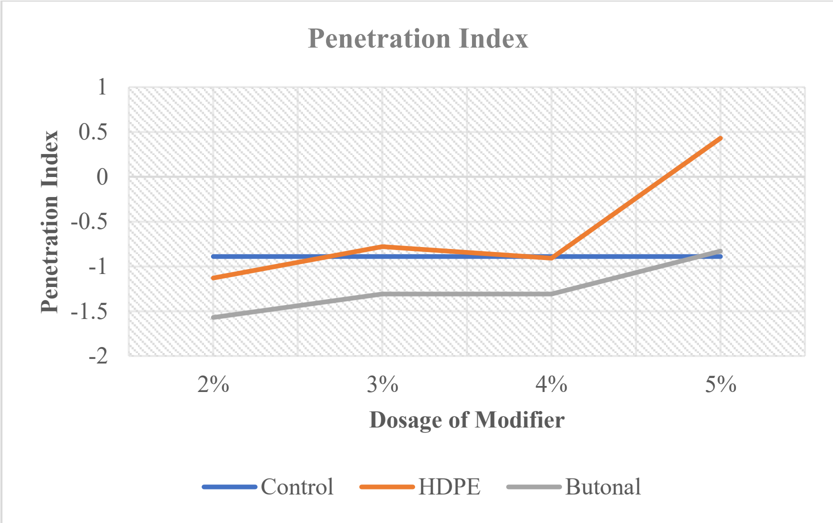

Figure 19: Penetration Index of Asphalt Binder

Similarly, at 2% and 3% Butonal, the asphalt binders showed high thermal susceptibility with extremely low PIs (-1.57 and -1.31, respectively) which may be due to the softening effect of the aqueous Butonal at low concentrations. However, at 5% Butonal, PI increased to -0.83, indicating that while a higher dosage starts to provide some thermal resistance, HDPE is still more effective. Studies reported PI improvements when HDPE content increased from 4–6%, while noting reduction in binder susceptibility to rutting and cracking under temperature fluctuations (Mohammed *et al.,* 2023). Studies also note that SBS-modified binders improve PI when thermoplastic networks are fully formed, typically at 4–6% dosage (Li *et al.,* 2022). However, Butonal (aqueous SBS latex) at low dosages often results in water retention, leading to temporary softening and low PI values (Li *et al.,* 2024c).

Butonal-modified binders show poor temperature stability, particularly at lower concentrations. Butonal falls short of HDPE's thermal performance level, even at 5%. Although Butonal is a functional modifier, at low to moderate dosages it tends to increase temperature susceptibility; therefore, higher content or blend optimisation are needed for improved performance. Increasing the dosage of HDPE improves the temperature susceptibility of the bitumen, while Butonal requires higher dosages to achieve similar improvements.

Ductility of Asphalt Binder

Ductility is a measure of the ability of asphalt binder to stretch without breaking, and this is a crucial parameter in ensuring flexibility and resistance to cracking under temperature changes and traffic loads. It is a is a major determinant of flexibility and resistance to cracking, particularly in cold conditions or dynamic loading. It reflects the ability of the material to stretch without breaking. Higher ductility values mean better performance in terms of resistance to fatigue cracking and thermal contraction. The effects of two polymer types (HDPE and Butonal) at different dosages (2–5%) on the ductility of modified asphalt binder are examined in Tables 15 and 16 and Figure 20. Strong performance differences between polymers are shown, as well as clear interactions between polymer type and dosage. The ductility of the unmodified asphalt binder was 17.90cm, while the ductility values of the modified asphalt binder varied significantly with the addition of polymers, though not uniformly at all dosages.

Table 15: Effect of Polymer Types and Polymer Dosages on Ductility of Modified Asphalt Binder

Polymer Types (T)	Significance of the difference between Polymer types (T) and polymer dosages (D)					
	Control	2	3	4	5	**Mean**
Butonal	17.90c (±0.56)	42.40a (±1.51)	13.90d (±0.56)	33.40b (±0.99)	18.40c (±0.50)	**25.20A**
HDPE	17.90c (±0.56)	38.380a (±0.20)	21.60b (±0.80)	16.00c (±1.73)	22.40b (±0.79)	**23.34B**
Mean	**17.90D**	**40.60A**	**17.75D**	**24.70B**	**20.40C**	

At 2% HDPE, the ductility of asphalt binder showed a notable rise to 38.3 cm, so indicating great resistance to cracking and great flexibility. At 3% HDPE, the ductility of the modified asphalt binder, dropped to

21.6 cm, and at 4% HDPE, there was a further drop in the ductility (16 cm). However, at 5% HDPE, the ductility of the modified asphalt binder rose to 22.4 cm, indicating performance and suggests that larger dosage could help to restore ductility advantages. The ductility response to HDPE is non-linear; while 2% and 5% dosages enhance ductility significantly, the 4% dosage may lead to phase separation or poor dispersion, affecting flexibility.

Upon modifying with 2% Butonal, the asphalt binder showed great flexibility and outstanding resistance to fatigue and heat cracking, having a ductility of 42.4 cm. At 4% Butonal, there was a drop in ductility 33.4 cm, and at 5% Butonal, the ductility of the asphalt binder further dropped to 18.4 cm. Butonal greatly increases ductility at 2% and 4%, but at 3% and 5%, it may cause inconsistent behaviour, perhaps as a result of chemical imbalance between the modifier and base binder or problems with dispersion. For Butonal, the ductility peaked at 2% dosage (42.40 cm), dropped sharply to 13.90 cm at 3%, recovered slightly to 33.40 cm at 4%, and then dropped once more to 18.40 cm at 5%. This erratic pattern implies that the influence of the Butonal polymer on ductility is non-linear, maybe due to interaction with the base asphalt or saturation effects at particular concentrations. For HDPE, ductility also raised significantly at 2% dosage (38.38 cm) but generally stayed moderate at higher dosages, with values between 16.00–22.40 cm. Compared to Butonal beyond the 2% dose, HDPE displayed a more constant, but lower, ductility profile.

Table 16's superscripts indicate differences that are statistically significant ($p \leq 0.05$). The 2% dosage in the Butonal row designated "a," produced the highest and most distinct ductility, whereas the 3% and 5% dosages are designated "d" and "c," respectively, indicating significantly lower performance. The highest ductility for HDPE was also observed at 2% (designated as "a"), whereas statistically significant decreases in ductility were observed at other dosages (designated as "b" or "c"). This is further supported by the column-wise means, which show that the 2% dosage had the highest average ductility (40.60 cm), whereas the 3% and control samples had the lowest (17.75 cm and 17.90 cm, respectively). This makes it abundantly evident that, regardless of the type of polymer, a dosage of 2% is ideal for enhancing ductility. Among the polymers, Butonal' mean ductility (25.20 cm) was marginally greater than HDPE's (23.34 cm), indicating that Butonal might provide superior ductility enhancement, particularly at lower dosages.

The ANOVA results shown of Table 16 shows that ductility was much affected by the type of polymer used given an F-value of 29.69 and a p-value of 0.000. This is consistent with earlier findings showing Butonal generally had more ductility than HDPE. Polymer dosage having F-value of 626.29 ($p = 0.000$), also very strongly influences the ductility of the bitumen. Furthermore, from Figure 21, the interaction of polymer and dosage had an F-value of 160.35 ($p = 0.000$). This implies that the effect of a given dosage level on ductility is different for every polymer; for example, 2% greatly increases ductility in both polymers, but 3% works better in HDPE than in Butonal. The observed variations in ductility are not the result of chance, as confirmed by the extremely low error value (Mean Square Error = 0.874) and high significance levels for all factors.

Both polymer type and dosage have a significant impact on the ductility of asphalt binders, according to the data from Tables 16 and 15. 2% seems to be the ideal dosage for maximising ductility, especially for Butonal, which had the highest ductility value overall.

Table 16: Analysis of Variance on the Effect of Polymer Types and Polymer Dosages on Ductility of Modified Asphalt Binder

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Polymer Type	1	25.95	25.947	29.69	0.000
Polymer Dosage	4	2189.51	547.377	626.29	0.000
Polymer Type*Polymer Dosage	4	560.57	140.142	160.35	0.000
Error	20	17.48	0.874		
Total	29				

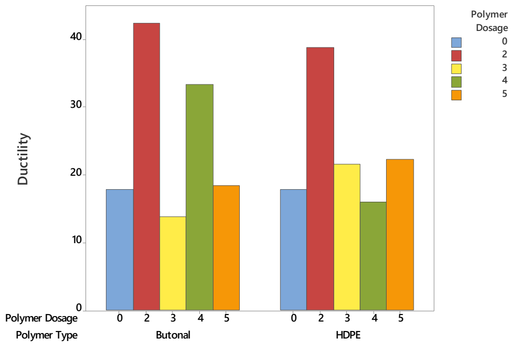

Figure 20: Effect of Polymer Dosage and Type Against Ductility of Asphalt Binder

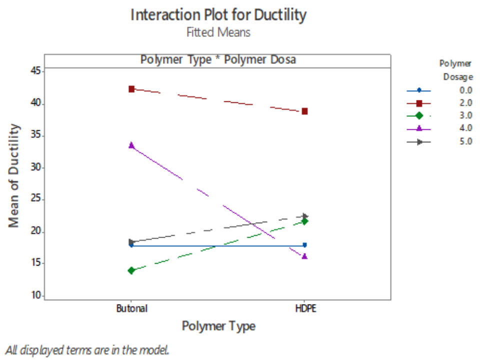

Figure 21: Interaction Plot for Ductility

Beyond this threshold, however, dosage increases may result in decreased ductility, most likely as a result of polymer saturation or decreased compatibility with the asphalt matrix. Butonal demonstrated a greater potential for ductility improvement than HDPE, which makes it more appropriate for uses where binder flexibility is essential, like in cold climates or on roads that experience high tensile stress. However, a thorough multi-property evaluation would be required for more balanced performance across several criteria (such as stiffness, rutting resistance, and thermal susceptibility).

A study reported that 2–3% HDPE increased ductility due to plasticizing effects, but higher percentages (above 4%) sometimes reduced ductility due to stiffness and poor dispersion (Savini and Oréfice, 2020). Another study found that ductility improved up to a dosage of **3%**, then declined due to polymer agglomeration and lack of flexibility in the matrix (Roja *et al.,* 2021). This is consistent with the findings of this study, showing that HDPE enhances ductility at low dosages but declines at 4%, with slight recovery at 5%. Studies has also shown that SBS significantly enhances ductility, especially at low dosages (2–3%) due to the elastomeric network formed between polymer and bitumen (Xue and Xu, 2023). This result is consistent with the findings of this study which revealed that Butonal at 2% gave the highest ductility (42.4 cm).

Although both HDPE and butonal can improve ductility, dosage greatly affects how they work. The greatest ductility improvements were obtained with 2% Butonal and 2% HDPE, indicating great potential for flexible pavement applications. Mid-range dosages (3%–4%) for both modifiers could indicate the need of either optimal mixing techniques or the use of compatibilizers since they could result in either inconsistent or decreased ductility. 2% Butonal or 2% HDPE seem to be the most advantageous for applications needing high flexibility and crack resistance

Flash and Fire Point of Asphalt Binder

The flash and fire points of asphalt binders are paramount safety and performance factors when dealing with asphalt binders. The flash and fire point of an asphalt binder shows the temperature at which the binder can vaporise and ignite under an open flame (flash point) and the temperature at which steady combustion takes place (fire point). They provide information about the thermal ability and volatility of the asphalt binder by indicating the temperature at which vapour ignites from the binder (flash point) and continue to burn (fire point). The flash and fire point are given on Table 17 and illustrated in Figure 22 and Figure 25 respectively.

From Table 17, the flash point of the control sample was 95.17°C, so indicating the baseline volatility of the unmodified binder. But significant variations arose upon polymer modification. The highest flash point (172.80°C) came from HDPE at 2% followed by HDPE at 3% (137.27°C), so clearly improving the thermal resistance of the binder. By contrast, butonal-modified binders showed erratic performance, with a modest rise at 2% (97.13°C) followed by a dramatic fall at higher dosages — most notably falling to 48.90°C at 5%. This points to possible Butonal degradation or instability at high dosages. The ANOVA (Table 18) verified statistically significant variances for Polymer type ($F = 2722.03$, $p < 0.001$), Polymer dosage ($F = 1376.74$, $p < 0.001$) and $F = 499.04$, $p = 0.001$; polymer type × dosage interaction. Further clarity came from Tukey pairwise comparisons (Table 19), which showed that while Butonal 5% falls in the lowest group (H), HDPE 2% and 3% fall in the highest grouping (A and B). These findings support the conclusion that, given its non-volatility and high melting temperature, HDPE is a better moderator for enhancing flash point; but, at higher dosages, Butonal may cause fire hazards because of its declining stability and increasing volatility.

The fire point is the temperature at which the binder continues to burn after ignition. The fire point trends closely mirrored the flash point data, with HDPE 3% and 2% again producing the highest values: 228.0°C and 224.0°C, respectively. In contrast, Butonal at 5% recorded a much lower fire point of 126.57°C, only marginally better than the control sample (102.0°C). The ANOVA table for fire point (Table 20) shows very high F-values: Polymer Type (F = 457.99), Dosage (F = 2242.21), and Interaction (F = 282.57) — all with p-values less than 0.001.

Table 17: Effect of Polymer Types and Polymer Dosages on Flash and Fire Point of Modified Asphalt Binder

Polymer Types (T)	Polymer Dosages (D)	Flash Point	Fire Point
Butonal	Control	95.17a (±1.26)	102.00d (±2.65)
	2	97.13a (±1.21)	183.20a (±0.72)
	3	83.30b (±2.10)	172.23b (±1.96)
	4	80.00b (±1.73)	174.80b (±2.66)
	5	48.90c (±1.71)	126.57c (±2.35)
HDPE	Control	95.17c (±1.26)	102.00d (±2.65)
	2	172.80a (±1.38)	224.00a (±2.65)
	3	137.27b (±2.73)	228.00a (±1.32)
	4	91.60c (±1.23)	153.50b (±1.66)
	5	81.73d (±1.97)	139.50c (±2.91)
	T	***	***
	D	***	***
	T × D	***	***

Means that do not share a letter in the same column are significantly different. *** = $p \leq 0.001$; ** = $p \leq 0.01$; * = $p \leq 0.05$ ns = not significant. The number after the ± symbol in parenthesis represents the standard deviation of the mean.

Table 18: Analysis of Variance for Flash Point

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Polymer Type	1	8075.4	8075.36	2722.03	0.000
Polymer Dosage	4	16337.3	4084.32	1376.74	0.000
Polymer Type*Polymer Dosage	4	5921.9	1480.47	499.04	0.000
Error	20	59.3	2.97		
Total	29	30393.9			

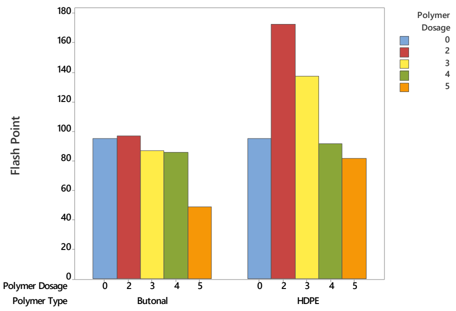

Figure 22: Effect of Polymer Dosage and Type Against Flash Point of Asphalt Binder

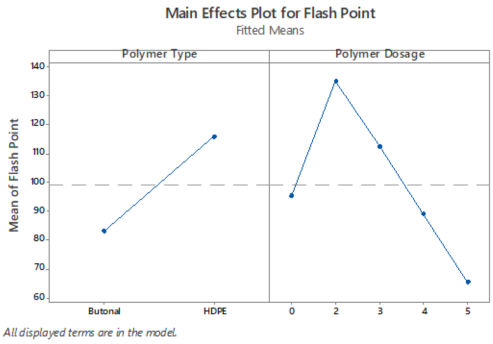

Figure 23: Main Effects Plot for Flash Point

Table 19: Grouping Information Using the Tukey Method and 95% Confidence for flash Point

Polymer Type*Polymer Dosage	N	Mean	Grouping
HDPE 2	3	172.800	A
HDPE 3	3	137.267	B
Butonal 2	3	97.133	C
HDPE 0	3	95.167	C D

Butonal 0	3	95.167	C D
HDPE 4	3	91.600	D E
Butonal 3	3	87.300	E F
Butonal 4	3	86.000	F G
HDPE 5	3	81.733	G
Butonal 5	3	48.900	H

Means that do not share a letter are significantly different.

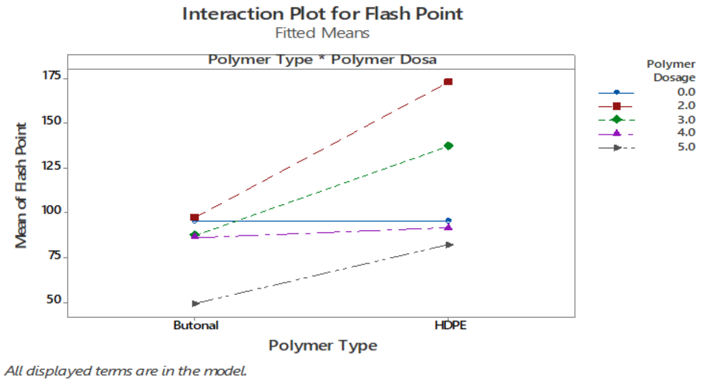

Figure 24: Interaction Plot for Flash Point

Tukey comparisons (Table 21) also place HDPE 2% and 3% in Group A (highest fire resistance), with Butonal 5% and the unmodified binders in the lowest groups (F and G, respectively). This grouping pattern reveals that increasing Butonal content beyond 2% not only reduces rheological stability but also compromises fire safety, making it a less desirable option under high-heat or open-flame construction conditions. Butonal, although useful for enhancing certain rheological properties (e.g., ductility and viscosity), exhibited inferior thermal stability, particularly at 4–5% dosages. The rapid decline in both flash and fire points at these dosages indicates that Butonal-modified binders may pose safety risks at higher temperatures, likely due to the volatility or decomposition of polymer chains when thermally stressed. The main effects plots (Figures 23 and 26) most certainly show that with dose up to 3%, HDPE greatly increases flash and fire points, while Butonal, especially in flash point, shows a peak at 2% then a drop. The statistical analysis confirms that HDPE is the more thermally stable polymer modifier, effectively increasing both flash and fire points at appropriate dosages. In contrast, Butonal-modified binders demonstrate declining thermal safety at higher dosages

Table 20: Analysis of Variance: Fire Point

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Polymer Type	1	2333.8	2333.8	457.99	0.000
Polymer Dosage	4	45702.3	11425.6	2242.21	0.000
Polymer Type*Polymer Dosage	4	5759.5	1439.9	282.57	0.000
Error	20	101.9	5.1		
Total	29	53897.5			

Table 21: Grouping Information Using the Tukey Method and 95% Confidence for Fire Point

Polymer Type*Polymer Dosage	N	Mean	Grouping
HDPE 3	3	228.000	A
HDPE 2	3	224.000	A
Butonal 2	3	183.200	B
Butonal 4	3	174.800	C
Butonal 3	3	172.233	C
HDPE 4	3	153.500	D
HDPE 5	3	139.500	E
Butonal 5	3	126.567	F
HDPE 0	3	102.000	G
Butonal 0	3	102.000	G

Means that do not share a letter are significantly different.

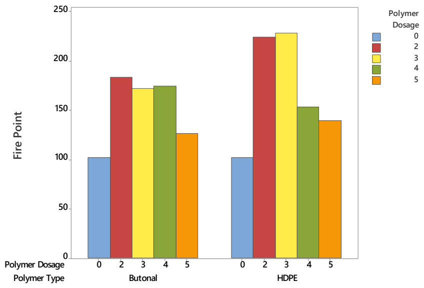

Figure 25: Effect of Polymer Dosage and Type Against Fire Point of Asphalt Binder

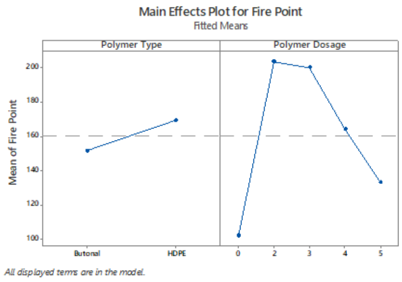

Figure 26: Main Effects Plot for Fire Point

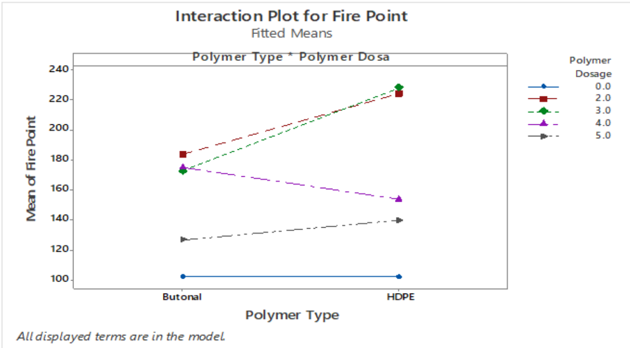

Figure 27: Interaction Plot for Fire Point

Looking at the results of the HDPE-modified asphalt binder, the greatest improvement in thermal stability was noted at 2%, having a flash point of 172.8℃ and a fire point of 224℃. At 3%, HDPE, the flash point was 137.3℃ and the fire point was 228℃, which still suggest outstanding ignition resistance as the flash and fire point is still quire high. At 4% HDPE, the flash point dropped to 91.6℃, but the fire point was at 153.5℃. And at 5%, HDPE, there was a drop in both the flash point and fire point, with the asphalt binder having a flash point of 81.7℃, and a fire point of 139.5℃.

It can be also noted from the results gotten for the Butonal-modified asphalt binder, (Figure 20 and Figure 22), that 2% Butonal also had the highest flash and fire point in this regard, having a flash point of 97.1℃ and a fire point of 183.2℃. At 3% Butonal, the flash and fire point dropped to 87.3 ℃ and 172.2 ℃ respectively. At 4% Butonal, a further drop in the flash (below control) and fire point was noted, as the flash point was 86.0 ℃ and fire point was 174.8 ℃. Furthermore, at 5% Butonal a notable decrease up to 48.9 ℃ (flash point) and 126.6 (fire point) was observed. While butonal moderately raises fire point between 2 and 4%, a higher dosage of 5% causes a significant drop in flash point, indicating either a decreased ability to withstand fire or a higher risk of an early ignition.

Studies using Cleveland open cup methods report that HDPE-modified binders achieve flash points between 170–200 °C at 2–3%, aligning closely with your 172.8 °C. Polyethylene's lower melting point (around 132 °C) means that higher dosages may reduce fire point, a phenomenon confirmed in studies with waste PE and PVC (Kumar and Kumar, 2024). This is consistent with the observed decreases at 4–5% HDPE. For SBS/Butonal modifiers, studies found flash points remain near control values or slightly increase at optimal dosages. But performance declines at >5%, consistent with your drop at high Butonal levels (Wang *et al.,* 2024). With flash/fire points significantly higher than the control, HDPE at 2–3% offers the most notable thermal stability. Butonal fire point improves moderately and steadily, but at higher dosages, it becomes less stable. For both modifiers, going over the recommended dosage (3% for HDPE and Butonal) may result in a reduction in or negative impact on fire and flash properties. This suggests that when designing a modified asphalt binder, careful dosage selection is essential to striking a balance between performance improvement and safety concerns.

IV. CONCLUSION

The study concludes that HDPE is better suited for improving high-temperature properties like softening point and rutting resistance, whereas Butonal is more appropriate for uses requiring high ductility and flexibility at lower temperatures. Climate, anticipated traffic volumes, and particular pavement performance requirements should all be taken into consideration when choosing between the two. Thorough statistical validation backs up these conclusions, and the distinct patterns found in all tests offer a solid foundation for well-informed binder design decisions.

Based on the findings from this study, the following conclusions are drawn.

i. Polymer modification significantly influences the rheological and thermal properties of asphalt binders. Both High-Density Polyethylene (HDPE) and Butonal (SBS-latex) showed improvements in binder characteristics, but with different performance trends.

ii. HDPE proved most effective at enhancing softening point, flash point, and fire point. This indicates superior thermal stability and resistance to high-temperature deformation, especially at 2–3% dosage levels.

iii. Butonal performed better in improving ductility, penetration, and viscosity, especially at 2–3% concentrations, highlighting its suitability for enhancing binder flexibility and resistance to cracking under low temperatures.

iv. The study revealed that excessive polymer dosages (particularly 5%) can reduce performance, notably with Butonal, which showed significant reductions in flash point and yield strength due to possible phase separation or instability.

v. Statistical analyses (ANOVA, Tukey comparisons, interaction plots) confirmed that polymer type, dosage, and their interaction all had highly significant effects ($p < 0.001$) on the measured properties, reinforcing the need for precise formulation and optimization.

Recommendations

Based on the results from this study, the following recommendations are given.

i. Use HDPE at 2%–3% for high-temperature regions or where improved thermal resistance and rutting performance are required. It significantly improves softening point, flash/fire points, and yield strength.

ii. Apply Butonal at 2%–3% for flexible pavement design, especially in low-temperature environments where higher penetration and ductility are beneficial. Avoid higher dosages to prevent binder instability.

iii. Consider environmental conditions, traffic load, and performance goals when selecting polymer type and dosage for binder modification.

Suggested Areas for Future Research

i. Further research should explore dual modification (HDPE + Butonal) to assess synergy and balance between flexibility and stiffness.

ii. Optimization techniques such as Response Surface Methodology (RSM) or regression modeling is recommended to be used in future work to define optimal dosage-temperature-performance windows.

iii. Long-term aging and field validation studies are recommended to confirm laboratory results under real-world conditions.

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