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АНАЛИЗ НА РОЛЯТА НА ДОБАВКИТЕ ПРИ МОДИФИЦИРАНЕ НА ХАРАКТЕРИСТИКИТЕ НА АСФАЛТОВОТО СВЪРЗВАЩО ВЕЩЕСТВО

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ANALYZING THE ROLE OF ADDITIVES IN MODIFYING THE CHARACTERISTICS OF ASPHALT BINDER

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Abstract:

Bituminous binder is widely incorporated in pavement construction globally, underscoring the importance of adopting practices that augment its properties to meet the necessary performance standards through the incorporation of appropriate additives. The influence of rejuvenators (PX, RB, and WO) on the physical characteristics, fatigue, and rutting performance of virgin binder is investigated in this study. Virgin binder Viscosity Grade (VG40) was blended with rejuvenators at 4%, 6%, and 8% by total weight of the binder. In addition to testing physical parameters such as penetration, softening point and viscosity, Dynamic shear Rheometer (DSR) was used to assess the rutting and fatigue performance of the rejuvenator-modified binder. Findings indicate the incorporation of rejuvenators increased penetration while decreasing the viscosity and softening point of the base binder. According to Indian Standard (IS 73:2013), the addition of 4% and 6% rejuvenators (PX, RB) satisfactorily fulfils the VG20 and VG10 binder properties respectively; however, rejuvenator WO requires higher dosages to meet the criterion. The incorporation of rejuvenators reduced rutting performance while increasing the fatigue resistance of the base binder.

Keywords:
Asphalt, Road, Rheological Properties, Rejuvenators

1. INTRODUCTION

Asphalt binder is a fundamental component of flexible pavement because it binds aggregate particles and contributes to the strength, durability, flexibility, and overall performance of asphalt mixtures [1]. Its behaviour is strongly dependent on temperature and loading conditions, as the binder exhibits both viscous and elastic characteristics [2]. During pavement service, asphalt binder is subjected to oxidation, thermal effects, traffic loading, and environmental exposure, which progressively alter its chemical composition and rheological behaviour [3]. Aging generally increases binder stiffness and viscosity and reduces its flexibility, which can adversely affect pavement performance and contribute to cracking and other forms of

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deterioration. Therefore, maintaining or restoring the functional properties of asphalt binder is an important aspect of pavement preservation and sustainable pavement management.

Rejuvenators have been increasingly investigated as a means of restoring the properties of aged asphalt binders [4]. A rejuvenator is generally intended to compensate for the loss or imbalance of lighter components that occurs during binder aging and thereby restore an appropriate balance between the binder's constituent fractions. Previous studies have reported that rejuvenation can modify the physical, chemical, and rheological characteristics of aged asphalt binders and improve their flexibility and resistance to fatigue-related deterioration [5,6]. The selection of an appropriate rejuvenator is particularly important because excessive softening can adversely influence the high-temperature performance of the binder. Consequently, rejuvenator treatment involves a balance between restoring flexibility and maintaining sufficient resistance to permanent deformation.

A wide range of rejuvenating materials has been investigated, including commercial products, petroleum-derived materials, waste oils, and bio-based oils. Their effectiveness depends on their chemical composition, molecular structure, dosage, and interaction with the binder [7]. Ji et al. [8] reported that vegetable oils can improve the properties of aged asphalt binders by increasing molecular mobility and restoring flexibility. Similarly, studies on waste-derived oils have demonstrated their potential for modifying aged asphalt binder properties and improving selected performance characteristics. However, different rejuvenators do not necessarily produce the same degree of softening or the same balance between high- and intermediate-temperature performance. The dosage of rejuvenator is therefore an important parameter that must be evaluated together with the type of rejuvenating material [9].

Conventional physical properties, including penetration, softening point, and viscosity, provide useful information regarding the consistency, temperature susceptibility, and workability of asphalt binders . However, these properties alone do not fully describe binder performance under pavement loading. Rheological characterization using a Dynamic Shear Rheometer (DSR) provides additional information about the response of asphalt binders to temperature and loading conditions [10]. The rutting parameter, ($G^*/\sin\delta$), is commonly used to characterize resistance to permanent deformation at elevated temperatures, whereas the fatigue parameter, ($G^* \sin\delta$), has been used to assess binder behaviour associated with fatigue cracking [11]. Previous research has also emphasized the importance of considering multiple performance indicators when evaluating the effectiveness of rejuvenation treatments, since improvement in one property may be accompanied by a reduction in another [12].

Despite the growing application of rejuvenators, the response of different rejuvenator types and dosages can vary substantially. In particular, comparative evaluation of physical properties together with DSR-based rutting and fatigue indicators is necessary to understand the extent to which rejuvenators modify the performance characteristics of a base asphalt binder. The existing literature has reported the effects of individual rejuvenating materials, but differences in rejuvenator composition and dosage make direct comparison of their effects important for practical selection and application. Furthermore, the reduction in stiffness associated with rejuvenation may improve fatigue-related performance while simultaneously reducing high-temperature rutting resistance. This performance trade-off requires systematic evaluation rather than assessment based on a single physical or rheological parameter.

Therefore, the objective of this study is to investigate the influence of three rejuvenators, namely PX, RB, and waste oil (WO), on the physical and rheological properties of VG40 asphalt binder at dosages of 4%, 6%, and 8% by binder weight. Penetration, softening point, and viscosity were evaluated to characterize changes in the conventional physical properties, while DSR testing was used to evaluate high-temperature rutting behaviour through ($G^*/\sin\delta$) and fatigue-related behaviour through ($G^* \sin\delta$). The study further compares the effects of rejuvenator type and dosage to identify the associated changes and the trade-off between rutting and fatigue

performance. The findings are intended to provide practical guidance for the selection and dosage of rejuvenators in asphalt binder modification and to support their potential application in pavement preservation and recycled asphalt pavement systems.

2. METHODOLOGY

In this research, rejuvenators (PX, RB, and WO) are employed due to their molecular structures closely resembling that of bitumen. Rejuvenators (PX, RB) were provided by the manufacturer, and WO was obtained from the local market in Patiala. To eliminate suspended impurities, WO underwent laboratory filtration through a simple process. The base binder used is VG-40 grade bitumen. It was combined with rejuvenators (PX, RB, WO) at varying dosages of 4%, 6%, and 8% by the weight of the asphalt binder as tabulated in table.1.

Table 1. Samples composition

Sample designation	Components
VB40	Virgin binder VG 40
VPX4	VG 40+4% Rejuvenator PX
VPX6	VG 40+6% Rejuvenator PX
VPX8	VG 40+8% Rejuvenator PX
VRB4	VG 40+4% Rejuvenator RB
VRB6	VG 40+6% Rejuvenator RB
VRB8	VG 40+8% Rejuvenator RB
VWO4	VG 40+4% Rejuvenator WO
VWO6	VG 40+6% Rejuvenator WO
VWO8	VG 40+8% Rejuvenator WO

Preliminary tests, including softening point, penetration, and viscosity of the modified binders, were conducted in the laboratory. Penetration, softening-point, and viscosity tests are fundamental for determining the properties of both base binder and rejuvenated samples in accordance with IS:1203, IS:1205, and IS:1208, respectively [13]. G*/sinδ obtained through the superpave rutting test is further employed to evaluate the failure criteria of the rejuvenated binders. Temperatures corresponding to G*/sinδ values of 1 kPa, represent PG temperatures, as per the superpave specification AASHTO D7175 [14]. G*sinδ is used to measure binder fatigue resistance based on the concept of dissipated energy perception. This implies that reduced energy dissipated per cycle leads to lower accumulated stress. Therefore, a bitumen binder with lower G*sinδ exhibits better fatigue strength. G*sinδ is restricted to a maximum of 5000 kPa, as recommended by SHRP for good fatigue resistance [10]. This test was conducted using DSR with an 8-mm diameter and 2- mm gap setting geometry at a temperature of 25°C. Figure.1 presents flow chart of adopted methodology.

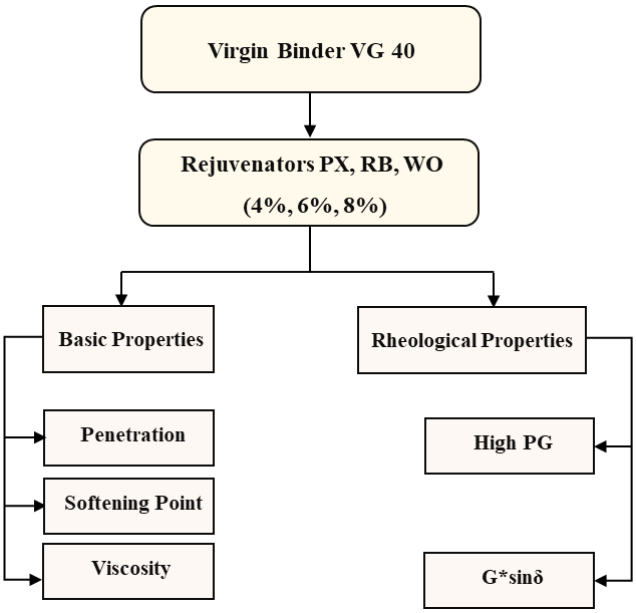

Figure 1. Flow chart of adopted methodology

3. RESULTS AND DISCUSSION

3.1 Physical Properties

The penetration test is an important indicator of binder consistency and stiffness. Figure 2 shows that the penetration value of the virgin binder (VG40) was 51 dmm, indicating a relatively hard binder suitable for high-temperature applications. Upon incorporation of rejuvenators, penetration values increased significantly, demonstrating the softening effect of the additives. The penetration values increased from 51 dmm to 94.1 dmm for PX, 91.6 dmm for RB, and 80.3 dmm for WO at 8% dosage.

Among the rejuvenators, PX exhibited the highest softening efficiency, followed closely by RB, while WO showed comparatively lower effectiveness. The increase in penetration can be attributed to the presence of lighter molecular fractions within the rejuvenators, which restore the maltene content and reduce intermolecular interactions within the binder matrix. This reduction in internal friction allows the needle to penetrate more deeply under standard loading conditions.

The results further indicate a nearly linear relationship between rejuvenator dosage and penetration value. Higher dosages continuously reduced binder stiffness, suggesting that rejuvenators effectively reverse the hardening effects commonly associated with asphalt aging. Similar observations have been reported by Ji et al. and Kumar and Aggarwal, who found that bio-based oils increase the mobility of asphalt molecules and improve binder flexibility.

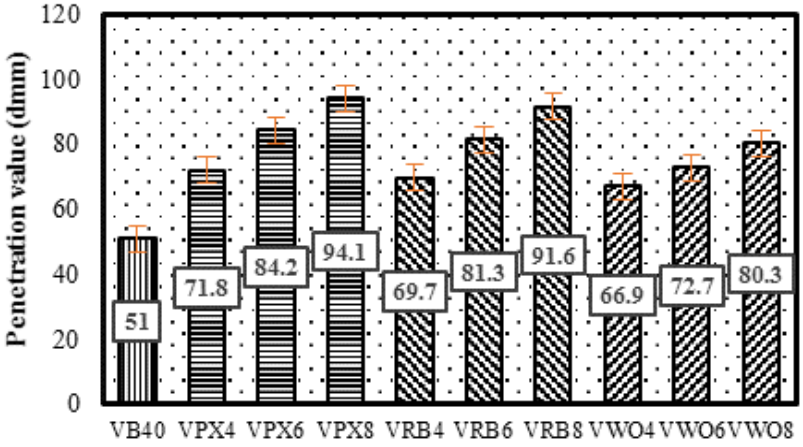

Figure 2. Effect of rejuvenator type and dosage on the penetration of VG40 asphalt binder

The softening point test provides an indication of the temperature susceptibility of asphalt binders. The virgin binder exhibited a softening point of 53°C, whereas rejuvenated binders showed a gradual reduction in softening point with increasing rejuvenator dosage. The lowest softening point values were recorded for PX8 (38.2°C), RB8 (41.5°C), and WO8 (43.9°C).

The reduction in softening point confirms that rejuvenators effectively soften the asphalt binder by restoring lighter fractions lost during oxidation. A lower softening point generally reflects improved flexibility at intermediate and low temperatures but may adversely affect resistance to permanent deformation under high-temperature service conditions.

PX demonstrated the greatest reduction in softening point, indicating stronger rejuvenating capability. RB showed moderate effectiveness, whereas WO produced the least reduction. Based on IS 73:2013 grading requirements, PX and RB were capable of transforming the VG40 binder toward VG30, VG20, and VG10 categories at suitable dosages. In contrast, WO required higher concentrations to achieve similar effects, suggesting comparatively lower rejuvenation efficiency.

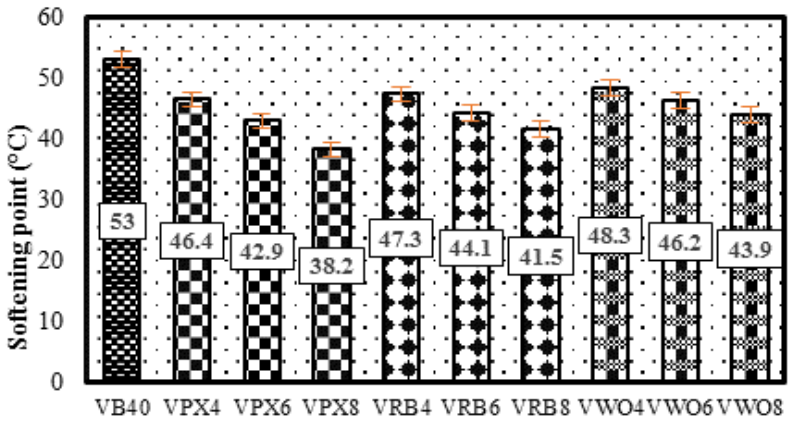

Figure 3. Effect of rejuvenator type and dosage on the softening point of VG40 asphalt binder

Viscosity represents the resistance of asphalt binder to flow and directly influences mixing, compaction, and field workability. The virgin VG40 binder exhibited the highest viscosity of 730 mPa.s at 135°C. The incorporation of rejuvenators caused a substantial reduction in viscosity, with values decreasing to 385 mPa.s, 415 mPa.s, and 490 mPa.s for PX8, RB8, and WO8, respectively.

The reduction in viscosity indicates improved workability and lower energy requirements during asphalt production and construction. The observed trend can be explained by the dilution effect caused by the rejuvenators, which lower the concentration of high molecular weight asphaltenes and increase the relative proportion of maltenes.

PX again demonstrated the strongest effect, reducing viscosity by approximately 47% relative to the virgin binder. RB exhibited a reduction of approximately 43%, while WO achieved a reduction of approximately 33%. These findings suggest that PX and RB are more effective in restoring the flow characteristics of aged binders and may facilitate easier mixing and compaction in asphalt mixtures containing recycled materials.

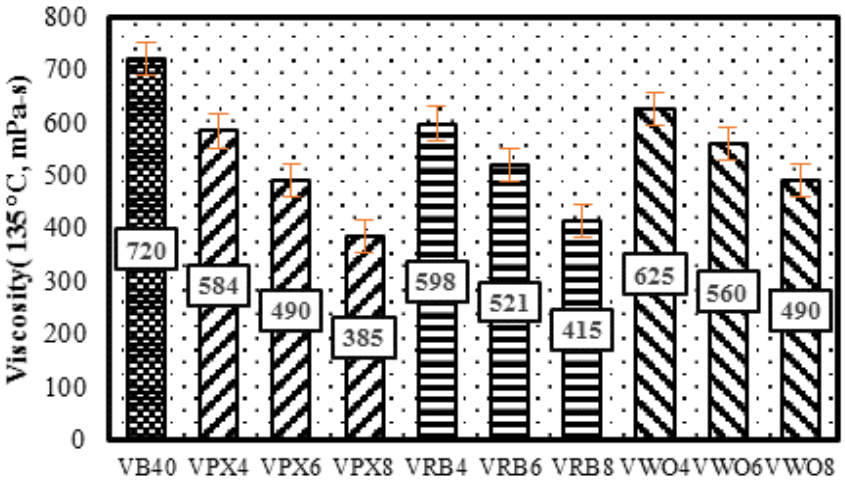

Figure 4. Effect of rejuvenator type and dosage on the viscosity of VG40 asphalt binder at 135°C

3.2 Rheological Properties

The rutting parameter (G*/sinδ) obtained from DSR testing is widely used to evaluate the resistance of asphalt binders to permanent deformation at high temperatures. The corresponding performance grade (PG) temperatures obtained from the study are presented in Figure 5. The virgin VG40 binder exhibited the highest critical temperature of 82°C, indicating superior rutting resistance.

As rejuvenator dosage increased, the PG temperature progressively decreased. The critical temperatures declined to 63.8°C for PX8, 64.9°C for RB8, and 68.4°C for WO8. This reduction demonstrates that rejuvenators soften the binder and lower its ability to resist deformation under heavy traffic loads and elevated temperatures.

Among all rejuvenators, PX caused the largest reduction in PG temperature, indicating the greatest influence on binder stiffness. RB exhibited a similar trend, whereas WO maintained relatively higher PG temperatures, suggesting better retention of rutting resistance. Therefore, from a rutting perspective, WO appears to be the most suitable rejuvenator among the three evaluated materials.

The decrease in rutting resistance is expected because rejuvenators restore lighter molecular components and reduce the concentration of stiff oxidized fractions. Although this improves flexibility, excessive softening may increase susceptibility to rutting in regions experiencing high pavement temperatures.

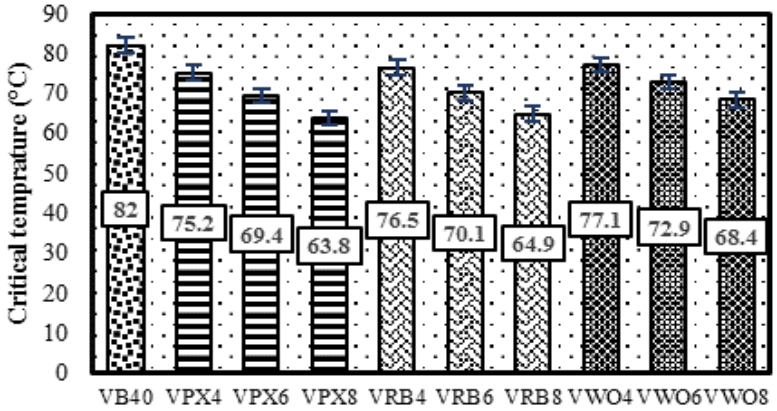

Figure 5. Effect of rejuvenator type and dosage on the critical temperature obtained from the DSR rutting parameter

The fatigue parameter (Gsinδ) is used to evaluate binder resistance to cracking under repeated traffic loading. Lower values of Gsinδ correspond to improved fatigue performance. The virgin binder exhibited the highest G*sinδ value of 4106 kPa, indicating lower resistance to fatigue cracking compared with rejuvenated samples.

The addition of rejuvenators substantially reduced G*sinδ values. At 8% dosage, PX, RB, and WO reduced the fatigue parameter to 3120 kPa, 3180 kPa, and 3409 kPa, respectively. These reductions correspond to improvements of approximately 24%, 23%, and 17% compared with the virgin binder.

The enhanced fatigue performance can be attributed to increased binder flexibility and improved stress relaxation capability. Softer binders dissipate less energy during repeated loading cycles, thereby delaying crack initiation and propagation. PX exhibited the greatest improvement in fatigue resistance, closely followed by RB, whereas WO showed comparatively lower effectiveness.

The results reveal a clear trade-off between rutting and fatigue performance. While higher rejuvenator dosages improve fatigue resistance, they simultaneously reduce rutting resistance. Therefore, an optimum dosage must be selected to balance both distress mechanisms.

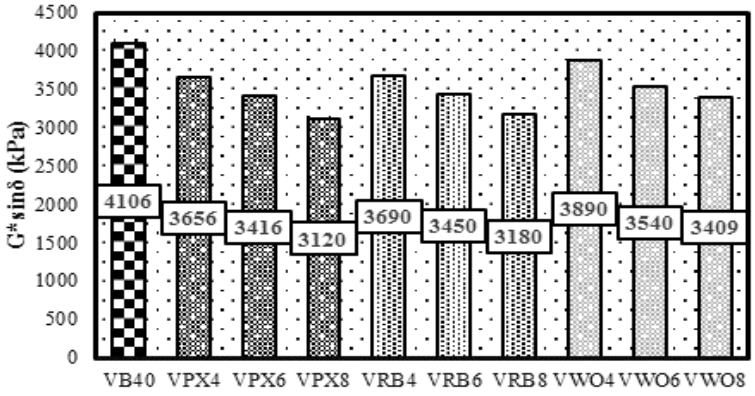

Figure 6. Effect of rejuvenator type and dosage on the fatigue parameter (G*sinδ) of VG40 asphalt binder

4. CONCLUSION

This experimental investigation assesses the potential of PX, RB, and WO as rejuvenators when utilized with an aged binder and compares the performance of rejuvenators by analyzing their physical and rheological properties. The precise conclusions are outlined below:

1. The penetration of base binder rise with higher proportions of rejuvenators. Additionally, the softening temperature, and kinematic viscosity decreases, show an exponential pattern as the doses of both rejuvenators increase within the tested range.
2. The examination of physical properties and viscosity test outcomes indicates that at an ideal dosage of 6% and 8%, rejuvenators (PX, RB) closely match the VG 20 and VG 10 respectively, whereas WO required more dosages to fulfill the criteria.
3. The base binder (VG 40) sample exhibits maximum rutting resistance because of its hardness. This resistance diminishes as the proportions of rejuvenators increase, attributed to the softening of rejuvenated binders. However, the addition of rejuvenators renders the base binder softer and

more prone to rutting. Consequently, considering rutting as a concern, the utilization of VG 40 in conjunction with rejuvenators might not be suitable in regions where rutting is the predominant distress type.

4. The outcomes of the superpave fatigue parameter (G*sinδ) conducted on rejuvenated samples, distinctly demonstrate an enhanced fatigue performance. In comparison to rejuvenator (WO), rejuvenators (PX and RB) show a greater capability to improve the fatigue resistance of the base binder.

5. Future studies should investigate the effectiveness of PX, RB, and WO using aged and RAP-derived binders under short- and long-term aging conditions. Further rheological, chemical, and microstructural characterization can provide deeper insight into the rejuvenation mechanisms and help optimize rejuvenator dosage. Evaluation at the asphalt mixture level, together with life-cycle, economic, and field assessments, would further establish the practical and sustainable applicability of rejuvenator-modified binders in pavement preservation and recycled asphalt applications.

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