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RHEOLOGICAL PERFORMANCE OF RECLAIMED ASPHALT PAVEMENT MIXTURES MODIFIED WITH SUGARCANE BAGASSE BIO-ASPHALT

*Indah Handayasari[1], Leksmono S. Putranto[2], Bambang Sugeng Subagio [3] and Najid[4]

[1,2,4] Faculty of Engineering, Tarumanagara University, Indonesia; [3] Faculty of Civil and Environmental Engineering, Bandung Institute of Technology, Indonesia

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ABSTRACT: The growing demand for sustainable pavement materials has intensified the use of Reclaimed Asphalt Pavement (RAP) to reduce consumption of virgin aggregates and petroleum-based binders. However, oxidative aging of RAP binders leads to excessive stiffness, reduced elasticity, and increased susceptibility to cracking, limiting its broader application. This study evaluates the effectiveness of sugarcane bagasse–derived bio-asphalt as a bio-based rejuvenator to restore and enhance the rheological performance of aged asphalt binders. Dynamic Shear Rheometer (DSR) tests were conducted under original, short-term aging (RTFOT), and long-term aging (PAV) conditions to assess complex modulus (G*) and phase angle (δ). The results demonstrate that the incorporation of bio-asphalt improves viscoelastic balance by reducing phase angle and stabilizing stiffness across a wide temperature range. Compared with virgin asphalt, the rejuvenated binder exhibited enhanced resistance to permanent deformation at medium to high service temperatures and improved durability against aging-induced hardening. These findings confirm that sugarcane bagasse bio-asphalt is a promising sustainable rejuvenator capable of restoring aged binder properties, mitigating aging effects, and supporting environmentally responsible pavement technologies.

Keywords: Reclaimed Asphalt Pavement, Rejuvenator, Rheological Properties, Sugarcane Baggase Bio-asphalt

1. INTRODUCTION

One of the major efforts to promote an efficient, environmentally friendly, and economically viable road construction industry is the adoption of sustainable material approaches, particularly through the utilization of Reclaimed Asphalt Pavement (RAP). RAP is a recycled material obtained from existing asphalt layers that have deteriorated or reached the end of their service life. The use of RAP enables significant savings in virgin aggregates and asphalt binders while simultaneously reducing the volume of construction waste released into the environment [1].

However, the primary challenge in implementing RAP lies in the degradation of the asphalt binder due to oxidative aging during its service life. This aging process increases stiffness, decreases elasticity, and leads to a higher risk of premature cracking in pavements reconstructed using RAP [2]. To alleviate these limitations, rejuvenating agents are introduced to reestablish the viscoelastic performance of aged asphalt, thereby approximating the properties of virgin binders [3–4]. Rejuvenators function by softening and partially dissolving aged binder fractions, improving compatibility and dispersion between the old and new binder components [5].

In recent years, research attention has increasingly focused on bio-based rejuvenators derived from renewable biomass sources such as agricultural residues, plantation by-products, wood waste, and vegetable oils. Biomaterials offer distinct advantages in terms of sustainability, local availability, and potential reduction of the carbon footprint throughout the road construction life cycle [6]. Furthermore, bio-asphalt—derived from bio-oil fractions of lignin-containing biomass—contains aromatic compounds, esters, and organic acids with chemical characteristics similar to conventional asphalt. These compounds can actively enhance the rheological behavior of aged asphalt, reduce stiffness, and improve rheological parameters to approach those of virgin asphalt [7–9].

Several studies have also reported that lignin and cellulose derived from agricultural biomass such as straw and wood residues can form physical interaction networks with aged asphalt, thereby improving thermal stability and aging resistance [10]. The utilization of lignin from fibrous plants is particularly advantageous, as it allows not only the production of fiber as the main product but also the valorization of lignin for manufacturing value-added chemicals and renewable energy sources [11]. Moreover, bio-asphalt containing polar and oxygen-rich functional groups has been shown to improve the chemical stability of asphalt mixtures [12]. The incorporation of lignin can also enhance the quality of hard or dense asphalt binders and provide antioxidant properties beneficial to asphalt performance [13–15].

Dynamic Shear Rheometer (DSR) testing is a fundamental method for evaluating the rheological behavior of asphalt binders. DSR analysis measures two key parameters: the complex shear modulus (G*) and the phase angle (δ). The complex modulus (G*) represents the binder's resistance to deformation under cyclic shear loading, whereas the phase angle (δ) indicates the lag between applied stress and resulting strain. The G* value is a resultant vector of the elastic component, denoted as G' (storage modulus), and the viscous component, denoted as G'' (loss modulus). Changes in G' and G'' are influenced by temperature and loading time during testing. DSR testing is commonly performed under three conditions: unaged (original), after short-term aging using the Rolling Thin Film Oven Test (RTFOT), and after long-term aging using the Pressure Aging Vessel (PAV). These conditions simulate different stages of asphalt aging. The original condition represents unaged binder, RTFOT simulates short-term aging that occurs during mixing at the Asphalt Mixing Plant and field compaction, while PAV simulates long-term aging during pavement service life [16–18].

This study investigates the influence of bio-asphalt derived from sugarcane bagasse on the rheological properties of Asphalt Concrete Wearing Course (ACWC) mixtures containing RAP. The evaluation of bio-based rejuvenators developed from biomass processing—recognized as the only renewable carbon source—not only provides technical insights but also establishes a scientific foundation for designing environmentally friendly asphalt mixtures. With appropriate formulation, bio-rejuvenators can contribute to global solutions addressing climate change and resource scarcity challenges in the road construction sector.

2. RESEARCH SIGNIFICANCE

The reuse of reclaimed asphalt pavement (RAP) in new asphalt mixtures represents a key strategy for reducing the consumption of virgin aggregates and petroleum-based binders. However, the high stiffness and oxidative aging of the RAP binder often lead to imbalanced rheological properties and reduced crack resistance in asphalt mixtures. The incorporation of bio-asphalt derived from sugarcane bagasse biomass waste as a rejuvenating agent for RAP offers an innovative and sustainable alternative. Due to its rich content of aromatic compounds, esters, and active polar functional groups, sugarcane bagasse-based bio-asphalt is expected to restore the rheological characteristics of aged asphalt and enhance the overall performance of RAP mixtures. This study aims to evaluate the potential of sugarcane bagasse-derived bio-rejuvenator in recovering the viscoelastic properties of aged binders and improving their resistance to deformation and fatigue cracking, based on rheological parameters. Furthermore, the findings of this research are expected to provide a scientific foundation for promoting the use of bio-asphalt rejuvenators in environmentally friendly and sustainable pavement technologies, while simultaneously increasing the valorization of agro-industrial waste toward greener and more sustainable road infrastructure development.

3. MATERIALS AND METHODS

This research is an experimental laboratory study designed to evaluate the potential of sugarcane bagasse-based bio-asphalt as a rejuvenating agent for Reclaimed Asphalt Pavement (RAP) in hot mix asphalt (HMA) applications. The study focuses on assessing the rheological, physical, and performance characteristics of the rejuvenated mixtures through standardized laboratory testing. The experimental approach involves direct testing of asphalt specimens prepared under controlled conditions in accordance with established standards and technical specifications. Data obtained from the laboratory tests were subsequently analyzed and interpreted in relation to relevant literature to ensure scientific validity and consistency with existing findings.

The primary materials used in this study include:

1. Base asphalt binder (Virgin Asphalt):
   60/70 penetration-grade asphalt was used as the control binder.
2. Reclaimed Asphalt Pavement (RAP):
   RAP materials were obtained from existing pavement layers that had reached the end of their service life.
3. Bio-rejuvenator:
   The rejuvenating agent was produced from sugarcane bagasse-derived bio-asphalt.

Laboratory investigations were conducted in strict accordance with internationally recognized standards to systematically evaluate the physical and rheological properties of the asphalt binders and mixtures. Rheological characterization was primarily performed using the Dynamic Shear Rheometer (DSR), a fundamental tool for assessing the viscoelastic response of asphalt binders under oscillatory shear loading. The DSR test yields critical parameters, including the complex shear modulus (G*) and phase angle (δ), which reflect the balance between elastic and viscous behavior and are closely associated with rutting resistance, fatigue performance, and aging sensitivity. To represent various stages of binder aging encountered during production and service, DSR testing was carried out on binders in three conditions: unaged (original), short-term aged through the Rolling Thin Film Oven Test (RTFOT), and long-term aged using the Pressure Aging Vessel (PAV). The unaged condition corresponds to the virgin binder state, whereas RTFOT and PAV simulate aging during asphalt mixing, field compaction, and prolonged pavement service life, respectively. Furthermore, complementary conventional physical tests were performed to corroborate the rheological results and provide an integrated assessment of binder performance.

3.1 Reclaimed Asphalt Pavement/RAP

The RAP material used in this study was obtained from PT. Jaya Konstruksi Manggala Pratama Indonesia, which is material scraped from roads in DKI Jakarta, Indonesia. The characteristics of bitumen from extracted RAP material can be seen in Table 1.

Table 1. RAP Bitumen Properties

Property	Unit	Test Result
Asphalt Bitumen Content	%	5,30
Penetration (25ºC, 100g. 5s)	0,1mm	25,67
Softening Point	° C	78,50

3.2 Virgin Asphalt

The type of asphalt used in this study was Shell's asphalt Pen 60/70. The results of testing the characteristics of Asphalt Pen 60/70 are shown in Table 2.

Table 2. Virgin Asphalt Pen 60/70 Basic Properties

Property	Unit	Specification	Test Result
Penetration (25ºC, 100g. 5s)	0,1mm	60-70	60,7
Softening Point	° C	≥ 48	50,8
Ductility (10 °C, 5cm/min)	cm	≥ 100	≥ 150
Flash Point	° C	≥ 232	321
Specific Gravity	%	≥ 1	1,031
Mass Loss After TFOT	%	≤ 0,8	0,029
Penetration After TFOT	mm	≥ 54	68,89
Ductility After TFOT	cm	≥ 50	≥ 150

3.3 Bio-Asphalt

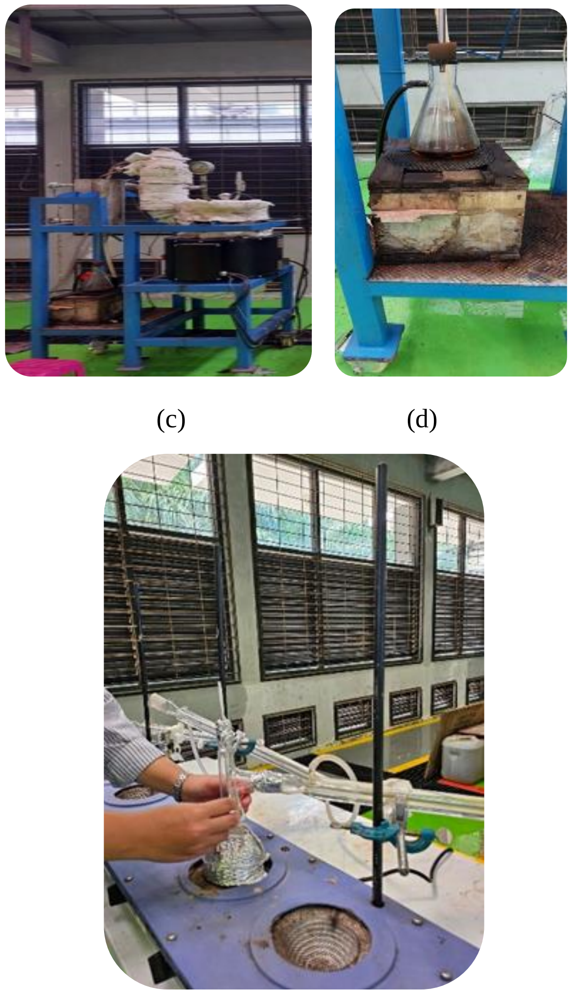
In this study, the bio-asphalt derived from sugarcane bagasse was obtained from the residual fraction of bio-oil distillation, which originated from the pyrolysis of sugarcane bagasse — a lignocellulosic by-product of sugar extraction from sugarcane stalks. The preparation of the bio-asphalt followed a multi-step process designed to ensure consistency and purity of the resulting material.

1. The sugarcane bagasse was first chopped into small pieces with an average length of approximately 3–5 mm to facilitate uniform thermal decomposition during pyrolysis.
2. The chopped bagasse was then soaked in clean water for 24 hours to remove soluble impurities and residual sugars. After soaking, the material was filtered and sun-dried for approximately 3–5 hours to achieve partial dehydration.
3. To further minimize moisture content, the bagasse was oven-dried at 105 °C for 2 h until the moisture level reached approximately 10%. The dried material was then pyrolyzed at 500 °C for 60 min under oxygen-limited conditions to produce bio-oil through the thermal decomposition of organic matter.
4. The resulting bio-oil was subsequently distilled at 100°C until all volatile fractions had evaporated, yielding a dark viscous residue identified as bio-asphalt. The distillation process served primarily as a purification step without altering the fundamental chemical characteristics of the bio-oil [19]. This distillation stage is particularly important given that bio-oil typically exhibits chemical instability, high water content, and susceptibility to thermal degradation. The quality and rejuvenating performance of bio-oil depend strongly on parameters such as biomass feedstock, pyrolysis temperature, and purification method [20].

Both the bio-oil and the resulting bio-asphalt were characterized using Fourier Transform Infrared Spectroscopy (FTIR) to identify functional groups associated with rejuvenating activity, such as carbonyl, hydroxyl, and aromatic compounds. Figures 1 illustrate the preparation and production process, while Figure 2 presents the appearance of the final bio-asphalt product obtained from these stages. This approach demonstrates a sustainable pathway for transforming agricultural waste into a value-added rejuvenating material, aligning with the broader objectives of resource circularity and environmentally responsible pavement technology.

(a) (b)

Fig.1(a) Sugarcane bagasse , (b) Processed sugarcane bagasse particles



(c) (d)

Fig.1 (c) Pyrolysis process, (d) Bio-oil, (e) Distillation process

Fig.2 Sugarcane Bagasse Bio-asphalt

The sugarcane bagasse bio-asphalt was incorporated as a rejuvenating agent into the RAP binder through a blending process conducted at 120°C using a magnetic stirrer operating at a rotational speed of 0.4–0.6 kr/s for 15–20 minutes. The mixing and compaction temperatures for the asphalt mixtures were maintained at 160°C and 145°C, respectively.

4. TEST RESULT AND DISCUSSION

4.1 FTIR Test

The Fourier Transform Infrared Spectroscopy (FTIR) results were used to identify the functional groups present in the analyzed compounds. As shown

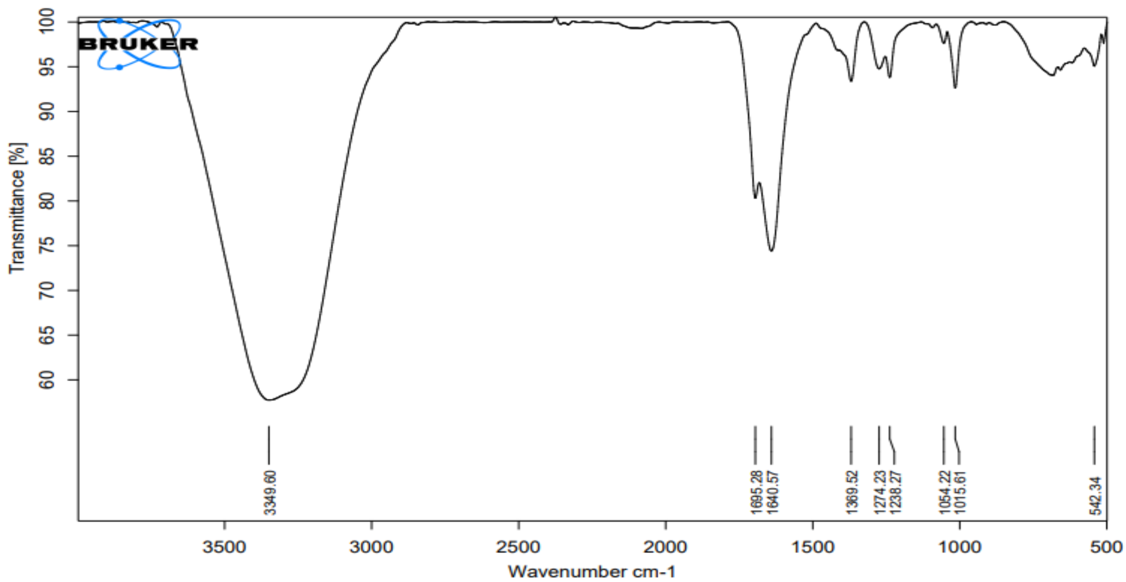


Fig.3 FTIR Results of Sugarcane Bagasse Bio-oil

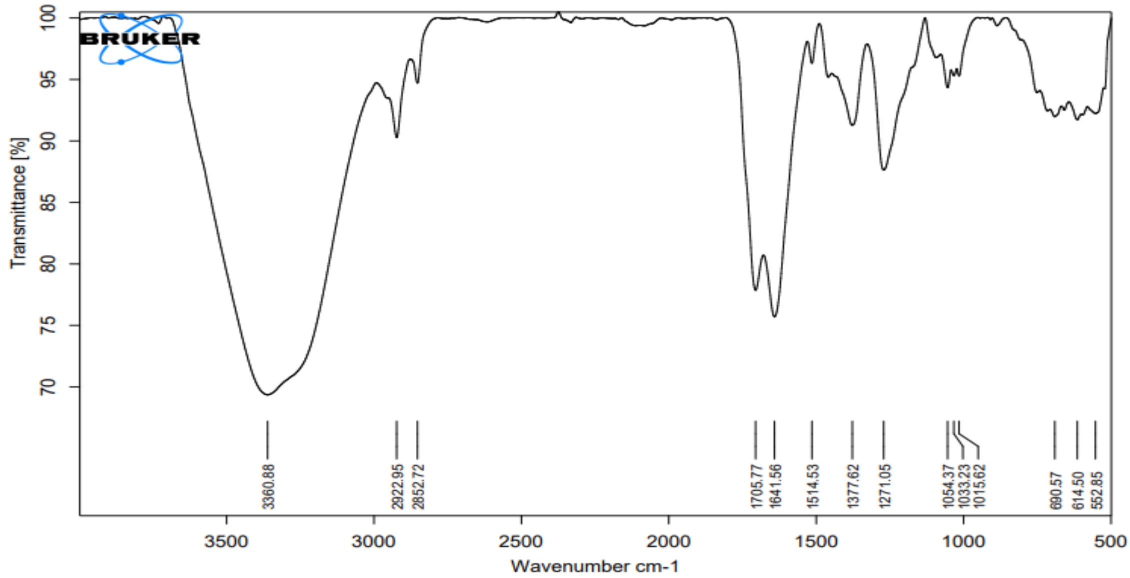


Fig.4 FTIR Results of Sugarcane Bagasse Bio-asphalt

Based on the FTIR spectra shown in Figures 3 and 4, the absorption peak corresponding to hydroxyl (–OH) stretching vibrations of phenolic compounds appeared at 3360 cm^{-1} for the sugarcane bagasse bio-asphalt sample and at 3350 cm^{-1} for the sugarcane bagasse bio-oil sample. The C–H stretching vibration was detected in the bio-asphalt sample at approximately 2900 cm^{-1}, whereas this peak was not observed in the bio-oil sample. The stretching vibration of the carbonyl (C=O) group, which represents the presence of carboxylic acids and ketones, was observed at around 1700 cm^{-1} for bio-asphalt and 1600 cm^{-1} for bio-oil. Both samples exhibited absorption peaks attributed to the polysaccharide cellulose ring (C–H and C–O) near 1300 cm^{-1}, while the C–O–C stretching vibration associated with pyranose rings appeared around 1050 cm^{-1}.

The appearance of the C–H group in the bio-asphalt sample indicates the presence of hydrocarbons that constitute the fundamental chemical backbone of asphalt, contributing to its elasticity and viscosity. This suggests that bio-asphalt possesses hydrocarbon characteristics similar to those of conventional asphalt. Furthermore, C–H groups enhance molecular stability and improve resistance to oxidation. The presence of C–H, C–O, and C–O–C groups—commonly found in carbohydrate-based structures—indicates the potential for hydrogen bonding with other molecules, thereby enhancing oxidation resistance and extending material durability.

The detection of multiple characteristic absorption bands corresponding to C–H, C–O, and C–O–C functional groups in sugarcane bagasse bio-asphalt suggests that the material contains saturated hydrocarbons and oxygenated compounds such as alcohols, esters, and ethers, derived from the pyrolysis of lignocellulosic biomass. The C–H group reflects the presence of aliphatic chains similar to the maltene fraction in virgin asphalt, while the C–O and C–O–C groups represent polar functionalities that can interact with oxidized molecules in aged asphalt.

As summarized in Table 3, the functional groups identified in the bio-asphalt play a crucial role in the rejuvenation mechanism of Reclaimed Asphalt Pavement (RAP) by influencing both chemical interactions and rheological behavior. The C–H functional group primarily contributes to the plasticizing effect of the rejuvenator, as it is associated with nonpolar hydrocarbon chains that reduce intermolecular forces within the aged asphalt binder. This reduction in molecular interaction leads to lower viscosity, increased molecular mobility, and improved flexibility of the rejuvenated binder, thereby mitigating the brittleness commonly observed in aged asphalt.

The presence of C–O functional groups, typically originating from alcohols or ester compounds in bio-based materials, introduces polar characteristics that enhance chemical compatibility with aged asphalt. These groups are capable of forming hydrogen bonds with oxidized functional groups such as carbonyl (C=O) and sulfonate (S=O) groups, which develop during long-term oxidative aging. Such interactions promote a more balanced distribution between maltene and asphaltene fractions, facilitating the partial restoration of the original colloidal structure of the asphalt binder.

Meanwhile, the C–O–C functional group contributes to chemical stability and structural integrity by supporting molecular linkage and reducing excessive oxidation reactions. This group also promotes a more homogeneous dispersion of bio-asphalt within the oxidized asphalt matrix, minimizing phase separation and ensuring consistent interaction at the molecular level. Collectively, these functional groups contribute to improved rejuvenation efficiency, enhanced rheological performance, and greater durability of RAP-based asphalt mixtures.

Table 3. Evaluation Functional Group of Sugarcane Bagasse Bio-asphalt as Rejuvenator

Functional Group	Function Toward Old Asphalt (RAP)	Chemical Meaning
C-H	Provides plasticizing/ softening properties	This group physically interacts with the aromatic components of aged asphalt, helping to reduce viscosity and improve flexibility
C-O	Provides polarity, enhances chemical interactions	Hydrogen bonds with carbonyl groups (C=O) in aged asphalt, assisting in the redistribution of polar components and improving homogeneity
C-O-C	Provides chemical stability and molecular dispersion	Improving compatibility between new maltenes and aged asphaltenes.

The combination of these three functional groups results in a more elastic system, enhances flowability, and reduces the stiffness modulus of RAP asphalt. Therefore, sugarcane bagasse bio-asphalt demonstrates significant potential as a natural rejuvenating agent capable of restoring part of the rheological and chemical properties of asphalt that have deteriorated due to aging.

4.2 Effect of Rejuvenator on Physical Properties of Asphalt

The results of the penetration and softening point tests presented in Table 4 indicate that the incorporation of sugarcane bagasse bio-asphalt as a rejuvenating agent provides favorable outcomes. This is evidenced by the increase in penetration value as the proportion of bio-asphalt rises, suggesting that the asphalt becomes softer.

The results indicate that the incorporation of sugarcane bagasse bio-asphalt at dosages between 17% and 29% effectively restored the penetration characteristics of the aged asphalt binder, increasing the penetration value from 25.67 dmm to within the specification range of Pen 60/70 asphalt, which was adopted as the reference binder. In addition, the softening point values satisfied the applicable specification requirements, demonstrating that the bio-asphalt contributed to the recovery of the physical performance of the aged asphalt binder.

Table 4. Performance Evaluation of Asphalt Modified with Sugarcane Bagasse Bio-asphalt Rejuvenator

Bio-rejuvenator (%)	Penetration (0,1mm)	Softening Point (ºC)
5	39,00	56,00
11	54,63	54,00
17	60,83	53,60
23	66,33	53,00
29	74,33	51,50
Specification	60-70	≥ 48

Based on the obtained range of experimental results, the optimal dosage of sugarcane bagasse bio-asphalt as a rejuvenating agent was determined to be 21% by weight, as this proportion provided the most balanced improvement in binder properties without inducing excessive softening. This optimal content was subsequently adopted to assess its influence on the rheological performance of the aged asphalt binder. As presented in Table 5, the incorporation of sugarcane bagasse bio-asphalt at the selected dosage resulted in significant modifications to the rheological characteristics of the aged binder, indicating effective restoration of its viscoelastic behavior. The rejuvenated asphalt exhibited improved consistency and enhanced flexibility, reflecting a reduction in aging-induced stiffness and brittleness. Furthermore, the test results demonstrate that all evaluated properties of the rejuvenated binder comply with the General Specifications issued by the Ministry of Public Works and Housing of the Republic of Indonesia. This compliance confirms the technical feasibility of using sugarcane bagasse bio-asphalt as a rejuvenating agent and highlights its potential applicability in practical pavement engineering, particularly for sustainable utilization of reclaimed asphalt materials. [21].

Table 5. Modified Asphalt with Sugarcane Bagasse Bio-asphalt Rejuvenator Properties

Property	Unit	Spesification	Test Result
Penetration (25ºC, 100g. 5s)	0,1mm	60-70	65,17
Softening Point	ºC	≥ 48	53,50
Ductility (10 °C, 5cm/min)	cm	≥ 100	≥ 140
Flash Point	ºC	≥ 232	302
Specific Gravity	%	≥ 1	1,034
Mass Loss After TFOT	%	≤ 0,8	0,574
Penetration After TFOT	mm	≥ 54	75
Ductility After TFOT	cm	≥ 50	>50

Based on the conducted tests, Figure 5 presents a comparison of the penetration and softening point results between the asphalt and the modified asphalt incorporating sugarcane bagasse bio-asphalt as a rejuvenating agent. The use of sugarcane bagasse bio-asphalt demonstrates a favorable effect in restoring the properties of aged asphalt, indicating its effectiveness as a natural rejuvenator.

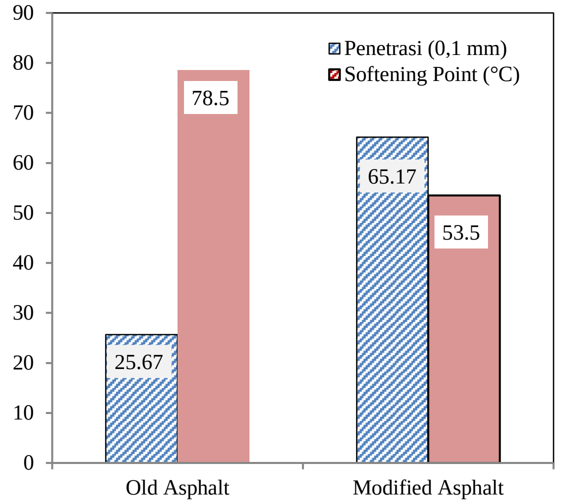


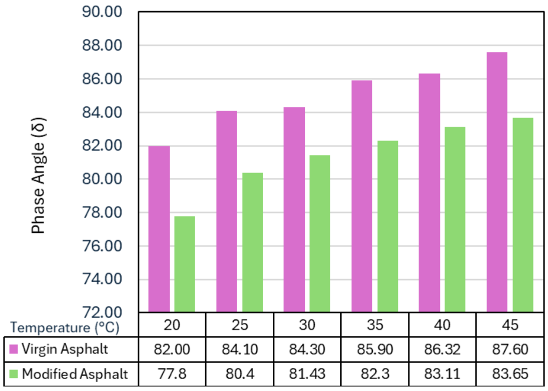
Fig.5 Comparative Performance Assessment of Aged Asphalt and Sugarcane Bagasse Bio-Asphalt Modified Binder

4.3 DSR Test and Performance Evaluation

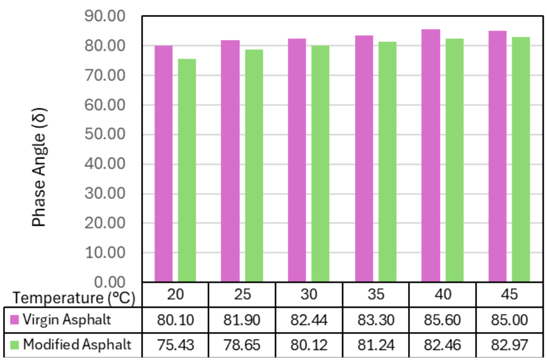
Based on the Dynamic Shear Rheometer (DSR) results obtained under original (unaged) conditions, as illustrated in Figure 6, the phase angle (δ) of both virgin and bio-rejuvenator-modified asphalt binders increases with rising temperature. This behavior reflects the typical viscoelastic response of asphalt materials, in which the viscous component becomes more dominant at elevated temperatures. Nevertheless, the asphalt binder modified with the sugarcane bagasse bio-rejuvenator consistently exhibits lower δ values across the entire temperature range compared to the virgin asphalt. A lower phase angle indicates a greater elastic contribution to the overall viscoelastic response, suggesting an enhanced ability of the modified binder to recover deformation and resist permanent strain.

This response indicates that the incorporation of the bio-rejuvenator not only compensates for the stiffness imbalance caused by aging but also improves the elastic characteristics of the binder at high service temperatures. Consequently, the modified asphalt demonstrates a more favorable rheological balance, which is commonly associated with improved resistance to rutting. A similar trend is observed under Rolling Thin Film Oven Test (RTFOT) conditions, representing short-term aging during mixing and compaction, where the rejuvenatedbinder maintains lower δ values, indicating good resistance to permanent deformation typically occurring in wheel paths.

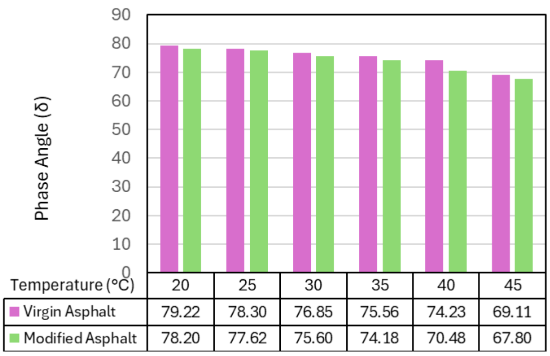
Furthermore, under Pressure Aging Vessel (PAV) conditions, which simulate long-term aging and are closely related to fatigue cracking performance, the rejuvenated asphalt exhibits stable phase angle behavior. This stability suggests that the bio-asphalt rejuvenator helps preserve binder flexibility and reduces susceptibility to fatigue-induced cracking, thereby contributing to improved long-term rheological durability at the laboratory scale.



(a). Phase Angle vs Temperature (Original)



(b). Phase Angle vs Temperature (RTFOT)



(c). Phase Angle vs Temperature (PAV)

Fig.6 Comparison of Phase Angle vs Temperature between Virgin Asphalt and Modified Asphalt

The results presented in Figure 7 show that the complex modulus (G*) of all asphalt binders decreases with increasing temperature, consistent with the viscoelastic behavior typical of asphalt materials. Under the original (unaged) condition, the asphalt binder modified with sugarcane bagasse bio-asphalt rejuvenator consistently exhibited higher G* values than the virgin asphalt across the evaluated temperature range. This indicates that the incorporation of the bagasse-derived bio-rejuvenator enhances the binder's structural integrity and stiffness at medium to high service temperatures (40–70 °C), which is indicative of improved resistance to permanent deformation under repeated loading.

The observed increase in complex modulus suggests an enhancement in rutting resistance, as higher G* values under relevant service temperatures imply a greater ability of the binder to resist shear strain accumulation under cyclic traffic loading. Recent literature supports this finding: studies involving bio-rejuvenators derived from agricultural biomass show that such renewable agents can restore or improve the rheological performance of aged asphalt binders, including complex modulus and high-temperature deformation resistance, approaching levels observed in virgin binders when appropriate dosages are used. For example, investigations of bio-rejuvenators produced from coconut shell biomass have demonstrated significant improvements in resilient modulus and overall mechanical performance when incorporated into reclaimed asphalt pavement (RAP) mixtures, highlighting the potential of bio-asphalt to act as sustainable modifiers in pavement materials. Research on the use of coconut shell bio-asphalt as a modifier in asphalt concrete containing RAP showed that bio-asphalt contributes positively to the resilient modulus of mixtures, suggesting its effectiveness in restoring structural performance in recycled asphalt applications. Although that study focused on resilient rather than complex modulus, the underlying indication of improved mechanical response aligns with the present observation that bio-based rejuvenators can positively influence binder rheology and mixture stiffness [22].

Broader reviews on the application of bio-based rejuvenators consistently emphasize their environmental advantages and their effectiveness in improving the performance of aged asphalt binders through enhanced chemical compatibility and restoration of the maltene–asphaltene balance. The restoration of this balance plays a critical role in governing the rheological behavior of asphalt binders, particularly key parameters such as the complex shear modulus (G*) and phase angle (δ). Previous studies have highlighted that optimizing both the type and dosage of rejuvenators is essential to achieving a balanced viscoelastic response, where sufficient low-temperature flexibility can be restored without compromising high-temperature stiffness. Such balance is fundamental to ensuring adequate resistance to fatigue cracking while maintaining rutting resistance under service conditions.

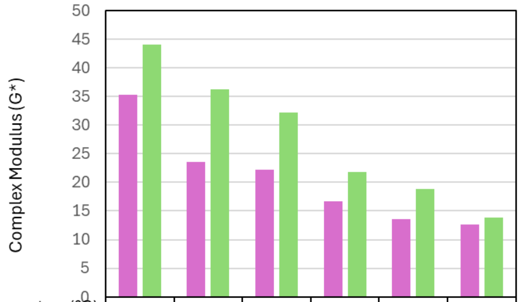
In this context, the results of the present study suggest that sugarcane bagasse bio-asphalt rejuvenator contributes positively to the restoration of the rheological properties of aged asphalt binders. The modified binder demonstrates an improved complex modulus response and enhanced viscoelastic stability, indicating an increased ability to withstand repeated traffic-induced stresses at typical pavement operating temperatures. These observations align with previous findings reported in the literature and further support the potential applicability of bio-based rejuvenators in sustainable asphalt pavement design, particularly for systems incorporating recycled materials or aged binders where performance recovery is required.

Following short-term aging through the Rolling Thin Film Oven Test (RTFOT), an increase in G* was observed for both virgin and modified asphalt binders. This increase is primarily attributed to oxidation processes and the loss of light oil fractions during thermal exposure, which commonly occur during asphalt mixing and compaction. However, the magnitude of the increase in complex modulus for the binder modified with sugarcane bagasse bio-asphalt was more controlled compared to that of the virgin asphalt. This behavior indicates that the presence of the bio-rejuvenator may moderate the rate of oxidative hardening during the initial aging phase, thereby contributing to a more stable rheological response.

Under long-term aging conditions simulated using the Pressure Aging Vessel (PAV), a substantial increase in G* was recorded, particularly for the virgin asphalt binder, reflecting excessive hardening and reduced molecular mobility as a result of prolonged thermo-oxidative aging. In contrast, the modified asphalt exhibited a more gradual increase in complex modulus, suggesting that the bagasse-derived bio-asphalt provides a protective effect against long-term oxidative degradation. This moderated aging response reinforces the role of the bio-rejuvenator in partially restoring the maltene fraction and rebalancing the asphaltene–maltene system of aged asphalt.

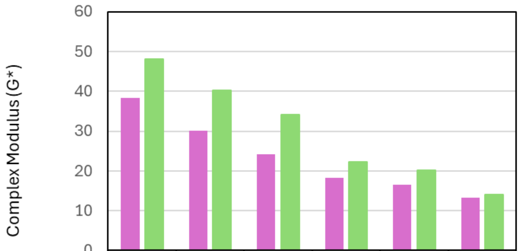
Overall, the laboratory-scale findings indicate that sugarcane bagasse bio-asphalt rejuvenator can enhance the rheological stability of aged asphalt binders by reducing aging susceptibility and maintaining a more favorable viscoelastic balance.

While these results demonstrate promising performance improvements under controlled conditions, further investigations involving mixture-level testing and long-term field evaluations are recommended to fully assess the durability and practical applicability of this bio-based rejuvenator in pavement engineering.



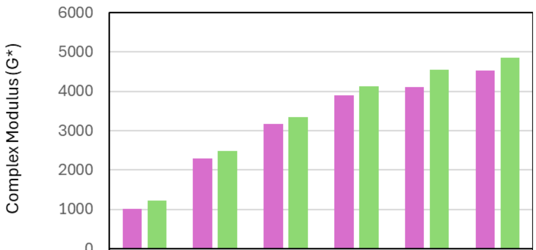
Temperature (°C)	20	25	30	35	40	45
Virgin Asphalt	35.23	23.52	22.24	16.64	13.6	12.61
Modified Asphalt	44.01	36.25	32.22	21.87	18.80	13.85

(a). Complex Modulus vs Temperature (Original)



Temperature (°C)	20	25	30	35	40	45
Virgin Asphalt	38.25	30.04	24.13	18.22	16.49	13.31
Modified Asphalt	48.11	40.18	34.12	22.24	20.16	14.02

(b). Complex Modulus vs Temperature (RTFOT)



Temperature (°C)	20	25	30	35	40	45
Virgin Asphalt	1014.23	2298.47	3176.41	3903.22	4104.86	4522.74
Modified Asphalt	1228.90	2476.39	3345.21	4126.00	4544.20	4857.19

(c). Complex Modulus vs Temperature (PAV)

Fig.7 Comparison of complex modulus vs Temperature between Virgin Asphalt and Modified Asphalt

A comprehensive evaluation of the complex shear modulus (|G*|) and phase angle (δ) indicates that asphalt binders modified with sugarcane bagasse bio-asphalt rejuvenator exhibit improved rheological stability under varying temperature conditions and different levels of aging. The combined interpretation of these parameters reflects a balanced viscoelastic response, in which the modified asphalt maintains sufficient stiffness to resist permanent deformation while retaining adequate elasticity to accommodate repeated loading and mitigate fatigue cracking, particularly at intermediate and low temperatures. The observed increase in |G*|/sin(δ) values compared to the virgin binder suggests an enhancement in rutting resistance without excessive stiffening.

Moreover, the relatively stable phase angle (δ) observed after both short-term and long-term aging indicates that the incorporation of the bio-asphalt rejuvenator may reduce the rate of oxidative hardening and help preserve the balance between viscous and elastic components of the binder. This behavior is closely associated with the rejuvenator's ability to partially restore the asphaltene–maltene equilibrium by replenishing light fractions (maltenes) depleted during aging. The restorative effect is more evident under Pressure Aging Vessel (PAV) conditions, where long-term aging typically induces significant stiffness and brittleness. Under these conditions, the modified binder exhibits improved flexibility and a more stable rheological response.

Overall, the combined rheological evaluation confirms that the incorporation of sugarcane bagasse bio-asphalt rejuvenator systematically modifies the viscoelastic behavior of aged asphalt binders across different aging conditions. Rather than merely altering binder stiffness, the rejuvenator promotes a more balanced rheological response by moderating aging-induced hardening while preserving adequate elasticity. This balanced behavior is clearly reflected in the stabilized phase angle response and the controlled evolution of the complex modulus under both short-term and long-term aging simulations. Such trends indicate that the rejuvenator effectively mitigates excessive stiffness development commonly associated with oxidative aging, while maintaining sufficient resistance to deformation at elevated temperatures. The observed improvements suggest that the bio-asphalt rejuvenator primarily influences the internal binder structure through partial restoration of the maltene–asphaltene balance and enhanced molecular interactions within the aged asphalt matrix. Importantly, these rheological modifications remain within an appropriate performance range, avoiding excessive softening that could adversely affect high-temperature performance or rutting resistance. Although the laboratory-scale results demonstrate improved rheological stability and aging resistance at the binder level, further investigations incorporating mixture-scale performance tests, durability assessments, and long-term field validation are required to comprehensively evaluate the practical implications of these findings for sustainable pavement applications.

5. CONCLUSION

Based on the Dynamic Shear Rheometer (DSR) test results, the incorporation of sugarcane bagasse bio-asphalt rejuvenator significantly improves the rheological performance of aged and modified asphalt binders. The modified asphalt consistently exhibits lower phase angle (δ) values, indicating enhanced elasticity and superior resistance to permanent deformation compared to virgin asphalt. Furthermore, the modified asphalt demonstrates a more stable viscoelastic response across temperature variations, suggesting improved rutting resistance under high-temperature conditions.

The complex modulus (G*) results also confirm that the bagasse bio-asphalt rejuvenator enhances structural stability and mitigates the adverse effects of aging. During both short-term (RTFOT) and long-term (PAV) aging, the rejuvenated asphalt shows a more controlled increase in stiffness, reflecting the rejuvenator's ability to reduce oxidation rates and preserve flexibility. This stabilizing effect is attributed to the bio-rejuvenator's capacity to rebalance the asphaltene–maltene fractions, which are crucial for maintaining optimal rheological behavior.

The incorporation of sugarcane bagasse bio-asphalt rejuvenator significantly enhances the rheological performance of aged asphalt binders. The rejuvenated binder exhibits improved elasticity, stabilized stiffness across aging conditions, and enhanced resistance to permanent deformation and long-term aging. These results confirm that sugarcane bagasse bio-asphalt is an effective and sustainable rejuvenator for RAP applications, supporting the development of durable and environmentally friendly pavement technologies.

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