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Research Article

Study of Bendo Sap *(Artocarpus Elasticus Reinw)* Polyurethane Adhesive on Modified Asphalt through Marshall Testing

Adiansyah Adiansyah, Tamrin Tamrin*, Marpongahtun Marpongahtun, Sovia Lenny, Lua Shun Kuang, and Ronn Goei

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Abstract
Bendo latex–based polyurethane (BD–PU) adhesive demonstrates strong potential as a bio-based modifier for improving asphalt performance and providing a sustainable alternative to petroleum-derived polymers. The novelty of this study lies in the utilization of bendo latex as a locally sourced renewable feedstock for polyurethane synthesis and its direct application as an asphalt modifier, which remains largely unexplored compared to conventional petroleum-based or partially bio-based polyurethane systems. In this work, bendo latex was converted into polyol via controlled condensation and addition reactions, followed by blending with polyethylene glycol (PEG 1000) and reaction with toluene diisocyanate (TDI) to produce BD–PU adhesive. The synthesized polyurethane exhibited mechanical properties comparable to conventional isocyanate-based polymers, confirming its suitability for asphalt modification. At the optimum BD–PU content of 20 wt%, the modified asphalt demonstrated a Marshall stability of 27.6 kN, a flow value of 4.5 mm, and a stiffness of 6.5 kN/mm. It represents a significant improvement over the control asphalt, with a 75% increase in Marshall stability and an 85% enhancement in stiffness, indicating markedly improved resistance to permanent deformation. These improvements are attributed to the formation of a crosslinked polyurethane network that enhances interfacial bonding between asphalt and aggregates, resulting in improved load distribution and structural integrity. Compared to previously reported polyurethane-modified asphalt systems, this study offers a key contribution by (i) introducing a fully bio-based polyol derived from bendo latex, (ii) demonstrating competitive or superior mechanical performance, and (iii) promoting the use of locally available renewable resources for sustainable infrastructure materials. Overall, the findings highlight the significant potential of BD –PU as an eco-friendly and high-performance asphalt modifier, supporting the development of more durable and sustainable road construction materials.

Keywords: adhesive material, *Artocarpus Elasticus Reinw*, modified asphalt, natural polyol, polyurethane

1. INTRODUCTION

Polyurethane (PU) polymers are highly versatile materials used in many applications, such as foams, adhesives, coatings, and elastomers [1]. The main raw materials for PU synthesis are polyols and isocyanates. To date, conventional polyols have mostly been derived from petrochemical sources, which have limited availability and a significant environmental impact [2]. Polymer-modified asphalt (PMA) has been extensively developed to overcome the limitations of conventional asphalt, particularly its susceptibility to temperature variations, rutting, and oxidative aging. Among various modifiers, PU has attracted increasing attention due to its mechanical strength, thermal stability, and tunable crosslinked network structure. Recent studies in pavement engineering journals report that PU-modified asphalt (PUA) significantly enhances high-temperature performance, fatigue resistance, and durability [3].

The selection of bendo latex as a precursor for polyol synthesis is strongly supported by its unique chemical composition and inherent functional group availability. Bendo latex is known to contain a significant fraction of terpenoid and triterpenoid compounds, many of which possess hydroxyl (–OH) functionalities or can be readily converted into diol structures through mild oxidation processes. This intrinsic –OH functionality makes bendo latex particularly suitable for PU synthesis, as it can directly participate in reactions with isocyanates without requiring extensive chemical modification [4][5]. In contrast, most conventional biomass-derived polyols exhibit structural limitations. Vegetable oil–based polyols are primarily composed of triglycerides with ester linkages and unsaturated fatty acid chains, which require additional processing steps such as epoxidation and ring-opening reactions to introduce –OH groups. Similarly, lignin-based polyols consist of highly

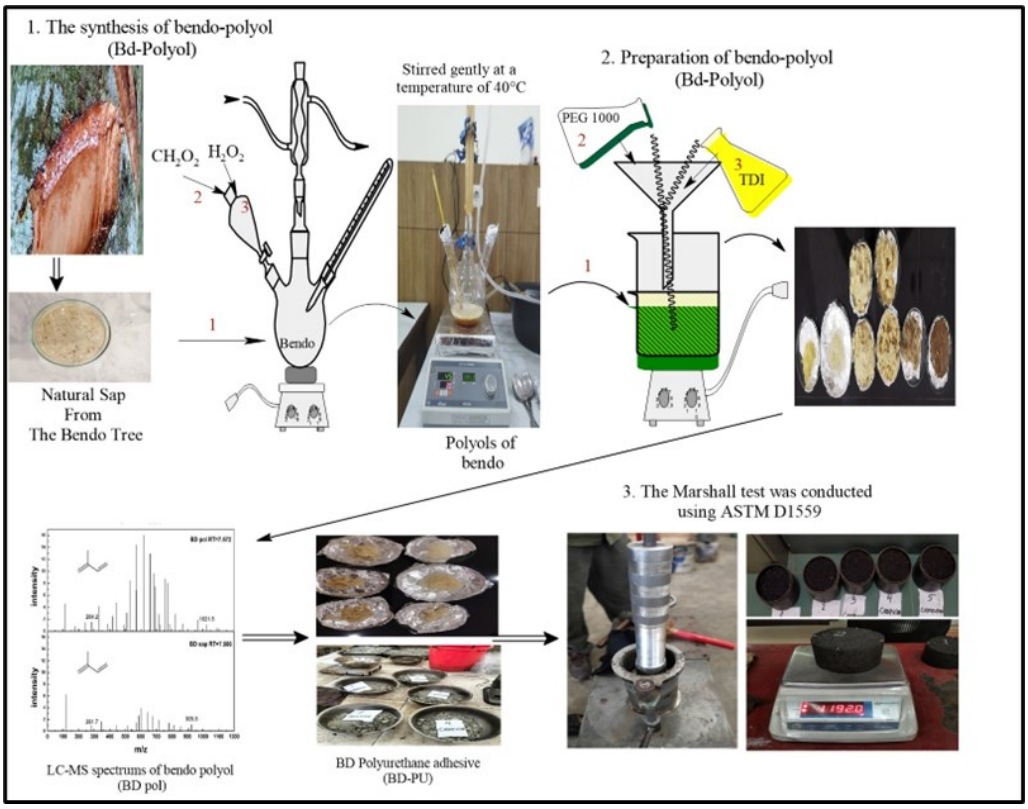

Figure 1. Process schematic of polyol synthesis, polyurethane formation, and asphalt modification.

aromatic and heterogeneous macromolecular structures with limited accessibility of reactive –OH groups, resulting in lower reactivity and less controlled PU network formation [6][7].

Therefore, research on the development of polyols from renewable sources has become increasingly relevant. The use of natural materials as alternative sources of polyols offers great potential for reducing dependence on petroleum-based polyols and strengthening the transition toward sustainable polymer technology. This research is especially important today, as increasing environmental pressures and the depletion of fossil resources demand immediate innovation in renewable materials. Natural polyol precursors not only provide abundant and locally available alternatives but also enable the development of greener, lower-carbon polymers for industrial applications. Conducting this study now is essential to accelerate sustainable material development, support circular economy goals, and ensure future resilience in polymer-based industries [8][9].

The base asphalt binder used was a conventional penetration-grade asphalt (60/70), which is widely applied in flexible pavement construction, particularly in tropical regions. The binder exhibited a penetration value of 60–70 dmm at 25 °C, indicating moderate hardness and adequate workability during mixing and compaction. The softening point 52 °C reflecting its susceptibility to deformation at elevated temperatures, while the ductility exceeded 100 cm at 25 °C, demonstrating sufficient flexibility to resist cracking under tensile stress. The dynamic viscosity at 135 °C was at 0.5 Pa·s, ensuring proper coating of aggregates and ease of processing during asphalt mixture production. In addition, the specific gravity at 1.05, which is essential for accurate volumetric mix design calculations [10]-[12].

Various types of biomasses have been explored as polyol precursors, including vegetable oils, agricultural residues, and lignocellulosic materials, reflecting a growing global effort to shift toward renewable polymer sources. Its richness in terpenoid compounds and naturally occurring polymers, combined with a complex structure containing abundant O groups, makes it highly suitable for polyol synthesis. Given the increasing demand for sustainable, bio-based materials and the urgency to reduce reliance on petroleum resources, investigating bendo sap as a renewable polymer precursor is both timely and essential for advancing

current material science research [13].

Furthermore, the sap of plants belonging to the bendo contains significant amounts of polyisoprene polymers, which naturally confer strong adhesive and tacky properties. This intrinsic stickiness is attributed to the high molecular mobility and elasticity of polyisoprene chains, making the sap an attractive raw material for developing bio-based adhesives. The presence of these polymers not only enhances the sap's natural bonding ability but also provides a valuable structural foundation for chemical modification into polyols and subsequently polyurethane. As interest in renewable adhesive materials continues to grow, the polyisoprene-rich composition of bendo sap further underscores its potential as a sustainable and functional polymer precursor [14], and is often used as an adhesive in briquette production [15]. The synthesis of polyol from bendo tree sap offers an environmentally friendly alternative [16].

Polyisoprene possesses an unsaturated hydrocarbon backbone containing reactive double bonds that are highly susceptible to oxidative degradation. This chemical vulnerability, while often considered a limitation, can be strategically utilized in the synthesis of polyols through controlled oxidation processes. The introduction of oxygen-containing functional groups, particularly –OH groups, enhances the reactivity of polyisoprene, enabling its conversion into PU adhesives. When applied to asphalt modification, this transformation becomes highly significant, as the resulting PU can improve bonding strength, enhance stiffness, and increase resistance to deformation under traffic loads. Thus, the inherent chemical structure of polyisoprene not only facilitates its modification but also contributes directly to the improved performance of PU-modified asphalt [17], Making it easy to shift into –OH groups and highly potential to become polyols. These polyols then form cross-links to create a PU network through reaction with diisocyanate compounds [18].

PU adhesive derived from bendo sap holds strong potential to serve as a foundation for future advancements in asphalt–PU technologies. Its renewable origin, reactive functional groups, and ability to form robust crosslinked networks make it a promising alternative to conventional petroleum-based modifiers. As the demand for durable, sustainable, and high-performance pavement materials continues to increase, bio-based PU from bendo sap offers a strategic pathway toward environmentally responsible asphalt modification. Moreover, its compatibility with asphalt binders and its capacity to enhance mechanical properties—such as stability, stiffness, and resistance to deformation—position it as a valuable candidate for next-generation pavement engineering solutions [3]. Currently, the use of PU from biomass as an asphalt material has become an interesting case study due to its potential as an environmentally friendly and sustainable solution [7]. However, there are still no studies on the use of bendo sap based PU adhesive in modified asphalt. Therefore, this study focuses on the effect of adding bendo sap-based PU adhesive on asphalt quality through the Marshall test.

2. MATERIALS AND METHODS

2.1. Materials

Bendo sap (obtained from north Sumatera, Indonesia), H_2O_2 30 % (Merck, Germany), CH_3COOH (Merck, Germany), CH_2O_2 (Merck, Germany), aquadest (produced from FMIPA USU Laboratory, Indonesia), PEG 1000 (Sigma Aldrich, Singapore), toluene-2,4-diisocyanate 80% (TDI, Merck, Germany), and aggregate (coarse size 0 to ½ mesh; medium size ½ to 4 mesh; and fine size 4 to 200 mesh).

Table 1. The composition of mixing process.

Asphalt content (%)	Aggregate content (%)	BD-PU content (%)
6	94	0
6	91	3
6	89	5
6	87	7

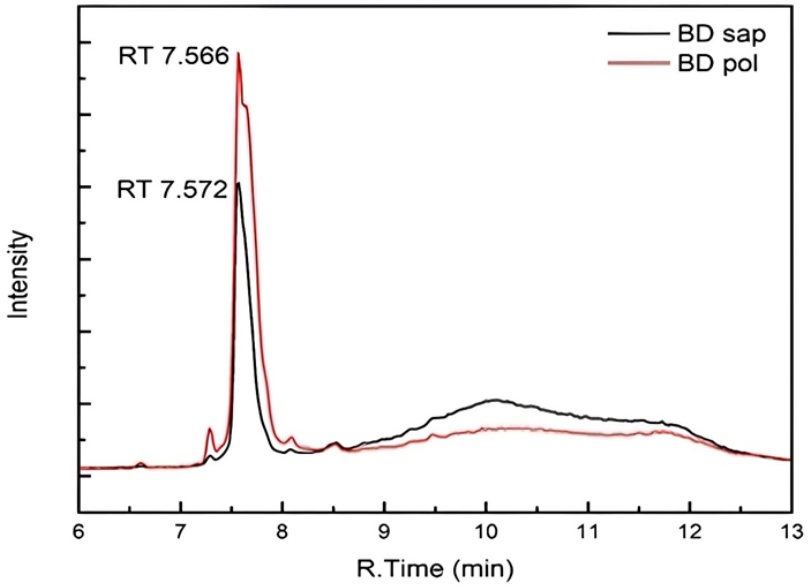

Figure 2. LC chromatogram of bendo sap (BD sap).

2.2. The synthesis of bendo-polyol (Bd-Polyol)

The sap of the bendo (BD) is heated to 40 °C and then reacted with CH_2O_2 and H_2O_2 for 90 min. The reaction product is then separated using a separating funnel and the precipitate is washed repeatedly with distilled water. BD-polyol and PEG1000 (mass of ratio 2:3) were mixed, added by TDI, and stirred for 15 min at 80 °C. BD-PU adhesive (BD-PU) was then poured into petri dish and cooled at room temperature (Figure 1). The mixing process of specimen was carried out as follows on Table 1. The asphalt was first heated in a pot until it melted at 150 °C, then BD-PU adhesive was added, and the mixture was stirred until homogeneous. Aggregate was added to the asphalt and BD-PU mixture and stirred until evenly distributed. The entire mixture is poured into a Marshall mold and compacted using a 4.5 kg hammer dropped from a height of 45 cm, with 75 blows per area.

2.3. Asphalt modification with hybrid polyol-based PU

The modification of asphalt using hybrid BD-PU was carried out to evaluate its effect on the mechanical and rheological performance of asphalt mixtures. In this study, the asphalt binder content was maintained constant at 6 wt%, while the BD-PU content was varied at 0%, 3%, 5%, and 7% by weight of the total mixture. Correspondingly, the aggregate content was adjusted to 94%, 91%, 89%, and 87% to ensure a consistent total mixture composition of 100%. The selected variation range of BD-PU content was designed to systematically investigate the influence of increasing polymer concentration on the properties of the asphalt mixture, including stability, flow, stiffness, and resistance to deformation. The control mixture (0% BD-PU) represents conventional asphalt, while the modified mixtures allow for direct comparison of performance improvements resulting from the incorporation of the bio-based PU.

2.4. Characterizations

2.4.1. Liquid Chromatography–Mass Spectrometry (LC-MS)

The analysis was conducted using a high-performance liquid chromatography system coupled with a mass spectrometer equipped with an electrospray ionization (ESI) source operating in positive ion mode. Chromatographic separation was achieved using a C18 reversed-phase column with a mobile phase consisting of water (A) and acetonitrile (B), both containing 0.1% formic acid to enhance ionization efficiency. A gradient elution program was applied starting from 30% B to 90% B over 20–30 min, at a flow rate of 0.3 $mL \cdot min^{-1}$. The injection volume was 5 µL, and the column temperature was maintained 40 °C. The mass spectrometer was operated under the following

conditions: capillary voltage of 4.5 kV, desolvation temperature of 300–350 °C, and scan range of m/z 100–1000. Nitrogen was used as both nebulizing and drying gas. Prior to sample analysis, mass calibration was performed using standard calibration solutions sodium formate to ensure mass accuracy within acceptable limits (<5 ppm).

The LC–MS spectra of raw BD sap showed dominant peaks corresponding to terpenoid compounds indicating the presence of unsaturated hydrocarbon structures. After oxidation, the LC–MS profile of BD-polyol exhibited significant changes, including (i) the appearance of new peaks at higher m/z values, corresponding to oxygenated species, (ii) increased signal intensity in regions associated with hydroxylated compounds, and (iii) a reduction in peaks related to unsaturated precursor molecules. These spectral changes indicate successful oxidation of double bonds and incorporation of –OH functionalities. Furthermore, the shift toward more polar compounds was evidenced by earlier retention times in the chromatographic separation, consistent with the formation of polyol structures. The combined evidence from mass spectral fragmentation patterns and chromatographic behavior confirms the conversion of BD sap into –OH-rich BD-polyol, suitable for subsequent PU synthesis [19].

2.4.2. Penetration test

The penetration test was carried out using ASTM D6927. The asphalt is heated until it melts, mixed with BD-PU, and cooled for 2 h at room temperature. The cooled specimen is immersed in a water bath at room temperature. The penetrometer needle is installed vertically with a load of 100 g. The needle is placed on the asphalt surface, then the penetrometer indicator is set to zero, and then the needle is released for 5 s and the penetration value is recorded to the nearest 0.1 mm [20].

2.4.3. Softening point measurement

The measurement of asphalt softening point is carried out using ASTM D6927. The asphalt is heated until it melts and mixed with BD-PU adhesive. The mixture is then poured and cooled in a brass ring. A steel ball is then placed on the surface of the specimen and inserted into a container filled with water at normal temperature. The water in the container is heated until the steel ball falls and touches the base plate under the specimen [21].

2.4.4. Density measurement

The measurement of asphalt softening point was carried out using ASTM D6927. The asphalt was heated and mixed with BD-PU adhesive. The

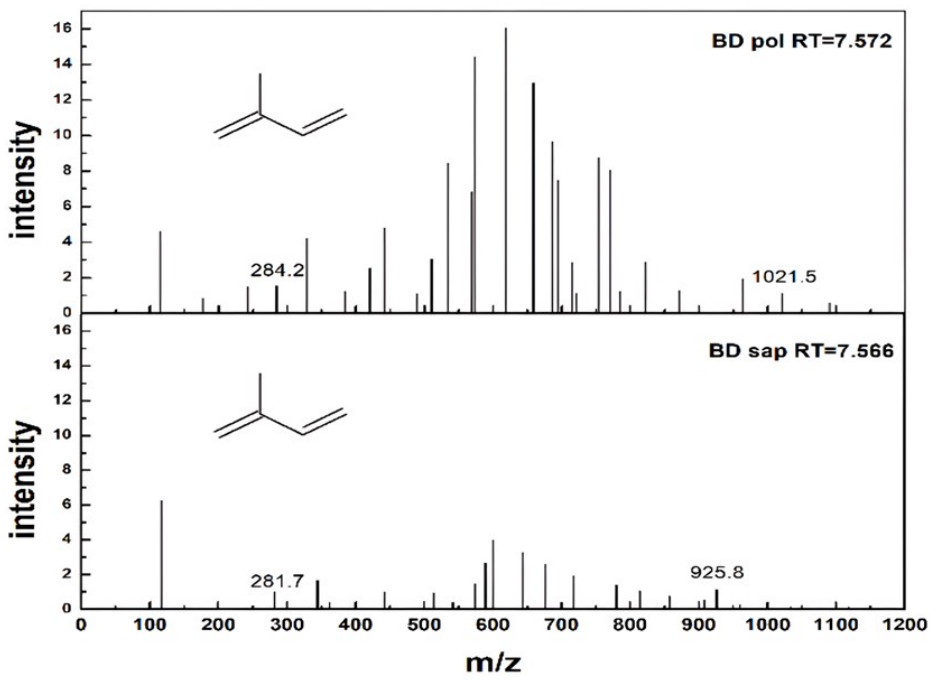

Figure 3. MS spectra of bendo polyol (BD pol).

Table 2. Specifications for BD-PU modified asphalt.

No	Specification	Modified asphalt				Bina Marga Spec.
		BD-PU 0%	BD-PU 3%	BD-PU 5%	BD-PU 7%	
1	Aggregate total, %	94.00	91.18	89.30	87.42	-
	Coarse, %	8.46	8.56	7.52	7.48	-
	Medium, %	31.96	32.58	31.02	30.04	-
	Fine, %	53.58	50.05	50.76	49.90	-
2	asphalt content, %	±6	±6	±6	±6	6
3	Penetration 25 °C 100 g, 5 s, 0.1 mm	63	69	68	67	60–70
4	Softening point, °C	48.6	50.7	52.4	52.1	50-58
5	Density, g/ml	1.03	1.072	1.058	1.051	1
6	Marshall Stability, kN	15.43	23.89	27.64	23.62	≥7.85
7	Marshall flow, mm	3.1	3.7	4.5	3.8	3–5
8	Marshall Stiffness, kN/mm	4.92	6.51	6.19	6.15	≥3.92

mixture was then poured into a 50 mL pycnometer and weighed using an analytical balance (w_1). The weight of the pycnometer (w_0), the pycnometer + water (w_2), and the weight of the pycnometer + specimen + water (w_3) was also measured. The specific specimen density (ρ_s) was then calculated using Equations (1) – (5) [22].

$$Specimen\ weight\ (w_s) = w_1 - w_0 \quad (1)$$

$$Full\ weight\ of\ water\ in\ a\ picnometer\ (w_{fw}) = w_2 - w_0 \quad (2)$$

$$Weight\ of\ water\ (w_w) = w_3 - w_s \quad (3)$$

$$Weight\ of\ water\ in\ specimen\ volume\ (w_{sv}) = w_{fw} - w_w \quad (4)$$

$$Density = \frac{w_s}{w_{sv}} \quad (5)$$

2.4.5. Marshall stability and flow test

The asphalt mixture design was conducted using the Marshall method in accordance with (SNI 2489:2018), which is equivalent to ASTM D6927. The aggregate gradation was selected to meet the requirements for dense-graded asphalt mixtures, ensuring a well-interlocked structure and adequate load distribution. The determination of the optimum asphalt content (OAC) was carried out by preparing a series of asphalt mixtures with varying binder contents 0.5%. For each variation, Marshall specimens were compacted using a 4.5 kg hammer with a drop height of 45 cm, applying 75 blows on each face. The specimens were then subjected to Marshall stability and flow testing at 60 °C. Key parameters, including stability, flow, bulk density, VIM, VMA, and VFA, were evaluated and plotted against asphalt content to generate characteristic curves. The OAC was determined as the average asphalt content corresponding to (i) maximum stability, (ii) maximum bulk density, and (iii) the target air void level (3–5%). All mixture design and testing procedures complied with the requirements specified in SNI 2489:2018, including specimen preparation, compaction effort, and testing conditions. The incorporation of BD-PU modifier into the asphalt binder was performed at the predetermined optimum binder content, and the modified mixtures were evaluated using the same Marshall design criteria to ensure consistency and comparability [23].

2.4.6. Scanning electron microscopy (SEM)

SEM characterization was performed to determine the morphology and to observe the homogeneity of the specimen surface. The specimen with 5% bendo sap PU adhesive BD-PU was observed using a TM 3000 SEM at a voltage of 15,000 V and further analysis was performed using ImageJ.

3. RESULTS AND DISCUSSIONS

3.1. LC-MS spectrums of bendo sap (BD sap)

In this study, bendo sap was utilized as an additive adhesive to enhance asphalt modification, demonstrating its effectiveness as a bio-based PU precursor. The asphalt blending process required a melting temperature 150 °C, ensuring proper viscosity and facilitating homogeneous mixing between the asphalt binder, aggregates, and bendo sap PU adhesive. Under these controlled conditions, the modified asphalt exhibited improved mechanical performance as confirmed through Marshall testing. The incorporation of bendo sap adhesive contributed to increased stability, optimal flow characteristics, and higher stiffness, indicating a stronger and more durable asphalt mixture. These results highlight the promising role of bendo sap-based PU in producing high-performance, sustainable asphalt materials [24] Although bendo sap degrades at such high temperatures, it must be converted into polyurethane by first undergoing a polyol stage. Polyol is transformed from bendo sap

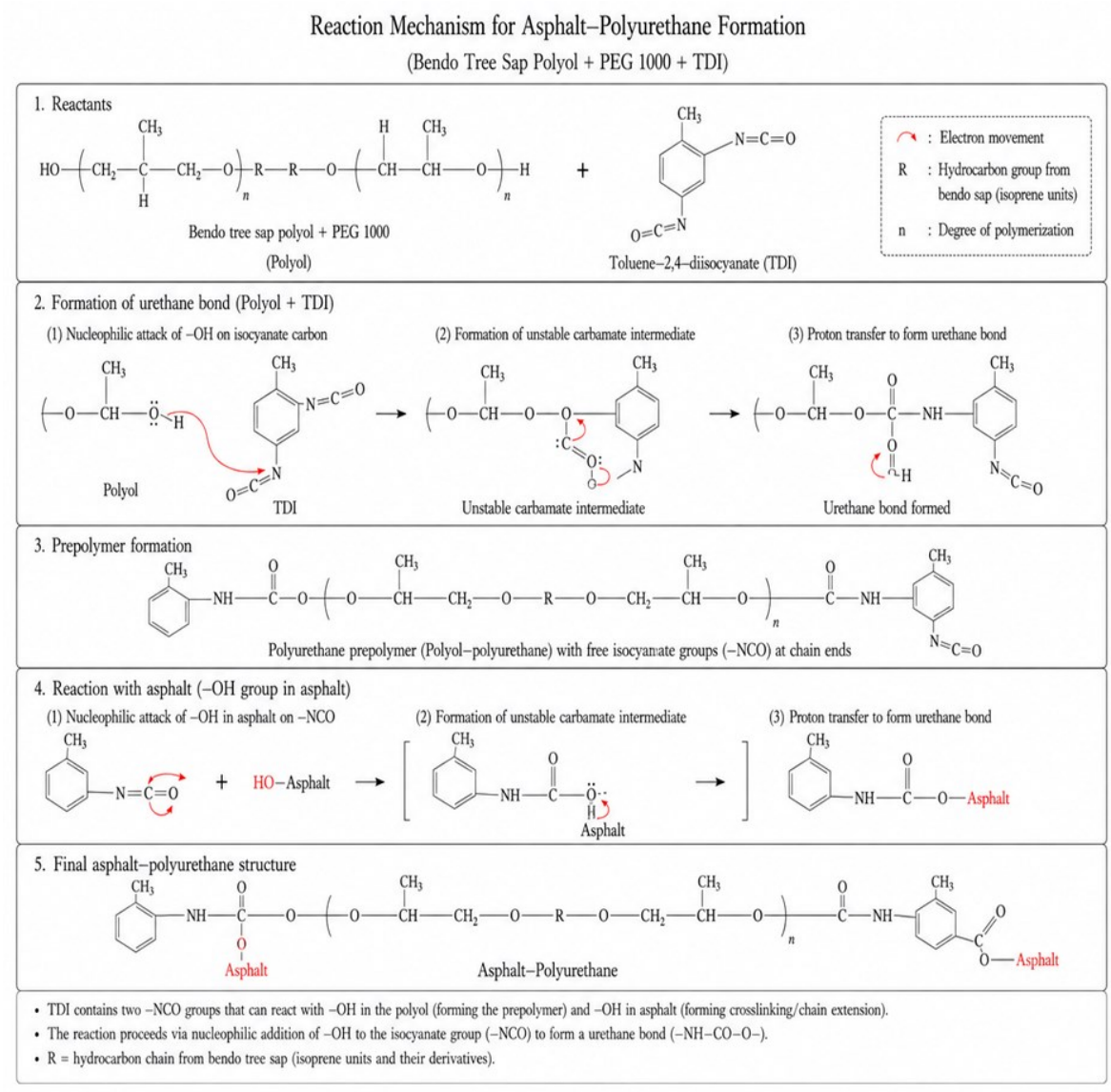

Figure 4. The chemical reaction of polyurethane synthesis and its interaction with asphalt.

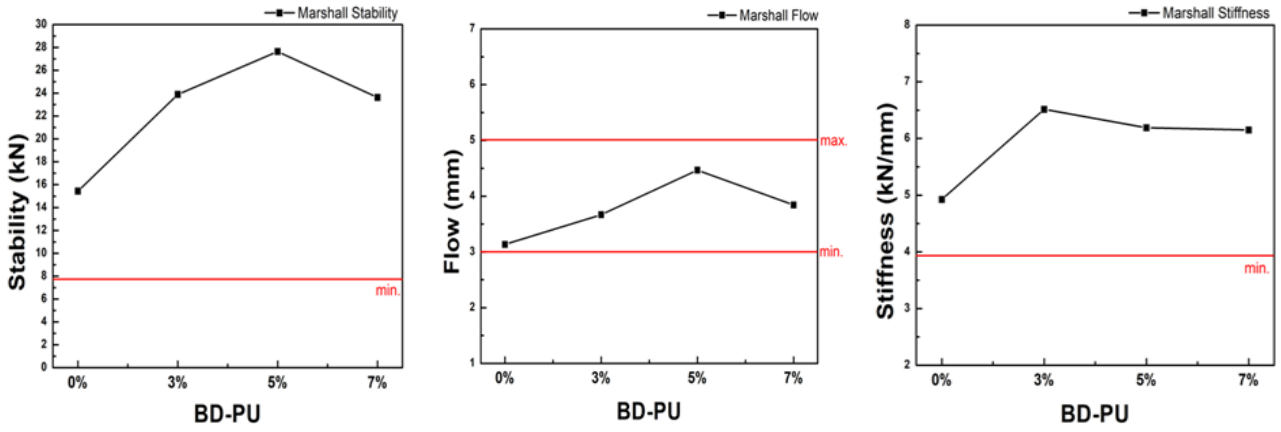

Figure 5. Adding BD-PU effect of modified asphalt through Marshall stability (a), Marshall flow (b), and Marshall stiffness (c), comparison with Bina Marga specification.

through a controlled oxidation reaction using formic acid and hydrogen peroxide.

This chemical change is shown in Figure 2, where the oxidation of polyisoprene from bendo sap results in a structural change to polyol, indicated by an increase in intensity at a retention time of 7–8 min and a decrease at 9–12 min. In addition, the peak of the isoprene molecule load and its largest molecular unit also shifted from 281.7 m/z to 284.2 m/z and from 925.8 m/z to 1021.5 m/z (Figure 3), respectively [25].

The incorporation of bendo sap polyol (BD-polyol) with PEG1000 at the optimized mass ratio of 2:3, followed by reaction with TDI isocyanate, resulted in the successful formation of BD-PU exhibiting remarkable thermal stability. The material's resistance to temperatures up to 174 °C is particularly significant, as it minimizes the risk of polymer degradation during asphalt mixing, where elevated temperatures commonly induce depolymerization in conventional bio-based polymers. This enhanced stability indicates that BD -PU possesses a more robust crosslinked network and improved phase compatibility, likely arising from the synergistic interaction between BD-polyol and PEG segments (Figure 4). These findings underscore the relevance of utilizing locally sourced bendo sap as a sustainable polyol precursor and demonstrate the substantial potential of BD-PU as a high-performance additive for asphalt modification [26]. Aggregates are then added to the adhesive mixture and stirred until the asphalt and BD-PU mixture coats all the surfaces of the aggregates. The mixture is poured into a Marshall mold design and stirred slightly to adjust the distribution of the aggregate. The specimen is then compacted using an impact tool of Marshall compaction for seventy-five blows to increase the bond between the aggregate surfaces [27]. Resultant specimen specification was demonstrated on Table 2.

3.2. BD-PU effect of modified asphalt

Table 2 displays the overall composition, penetration, softening point, specific gravity, and Marshall test results. The coarse aggregate content is approximately 7–9%, the medium aggregate content is 30–33%, and the fine aggregate content is 49–54%. The specimens used a mixture of fine aggregate as the dominant component and a small amount of coarse aggregate to reduce air voids and reduce cracking [28]. Additionally, the base asphalt has a penetration of 63. After adding BD-PU, the penetration slightly increases to 68–70 due to changes in the asphalt's rheological structure [29]. Furthermore, the softening point of the base asphalt rises after adding BD-PU, limiting the free movement of asphalt molecules and requiring a higher temperature to soften [30].

According to ASTM D1559, Marshall stability is a primary indicator of an asphalt mixture's resistance to plastic deformation under load. The unmodified asphalt exhibited a stability value of 15.43 kN, whereas the incorporation of BD-PU resulted in a pronounced increase to 23.89 kN at 3% BD-PU and reached a maximum value of 27.64 kN at 5% BD-PU. This represents an increase of

approximately 79% compared to the base asphalt, confirming that BD-PU significantly enhances the load-bearing capacity of the asphalt mixture. All stability values obtained in this study exceed the minimum requirements commonly referenced in Marshall-based specifications, indicating excellent structural performance [31].

The improvement in Marshall stability is attributed to the interaction between PU chains derived from Bendo sap and asphalt components, which form a reinforced binder matrix. This interaction improves cohesion between the binder and aggregate, resulting in a stronger and more stable asphalt mixture. However, a slight reduction in stability at 7% BD-PU suggests that excessive polymer content may reduce internal friction and lead to diminished strength, indicating the existence of an optimum BD-PU content [10].

Marshall flow values, measured in accordance with ASTM D1559, ranged from 3.1 to 4.5 mm, remaining within the acceptable deformation limits specified by the standard. These results indicate that although the asphalt strength increased significantly, the mixtures retained sufficient flexibility to accommodate traffic-induced deformation without becoming brittle. This balance between strength and flexibility is further reflected in the Marshall stiffness values, which increased from 4.92 kN/mm for the unmodified asphalt to values exceeding 6 kN/mm for BD-PU-modified mixtures [23][32][33]. Overall, the Marshall test results evaluated using ASTM D1559 clearly confirm that the addition of Bendo sap polyurethane significantly improves asphalt strength and mechanical performance. The notable increase in Marshall stability and stiffness demonstrates that BD-PU is an effective and sustainable bio-based modifier capable of enhancing asphalt mixture performance while maintaining acceptable deformation characteristics. These findings emphasize the potential application of BD-PU-modified asphalt for durable pavement construction.

Figure 5(a) shows the stability of specimens based on the addition of BD-PU adhesive. Specimens without bendo sap polyurethane (0% BD -PU) showed stability of 15.43 kN. Adding 3% and 5% of PD-PU showed a linear increase of 23.89 kN and 27.64 kN, respectively, while adding 7% BD-PU decreased to 23.64 kN. The precise composition of Bendo polyurethane resin improves the ability of aggregates to adhere to each other, reducing particle shifting when loaded [35]. The increase in stability corresponds to the increase in the softening point of asphalt after adding bendo rubber adhesive, as shown in Table 2. The increase in softening point allows BD-PU modified asphalt to have higher resistance to deformation [31]. However, excessive addition increases the thickness of the layer between aggregates and reduces interlocking, causing the specimen to become too soft [33]. Figure 5(b) shows the Marshall flow of specimens based on BD-PU addition. The base asphalt showed a flow of 3.1 mm, while the addition of 3%, 5%, and 7% BD-PU increased to 3.67 mm, 4.47 mm,

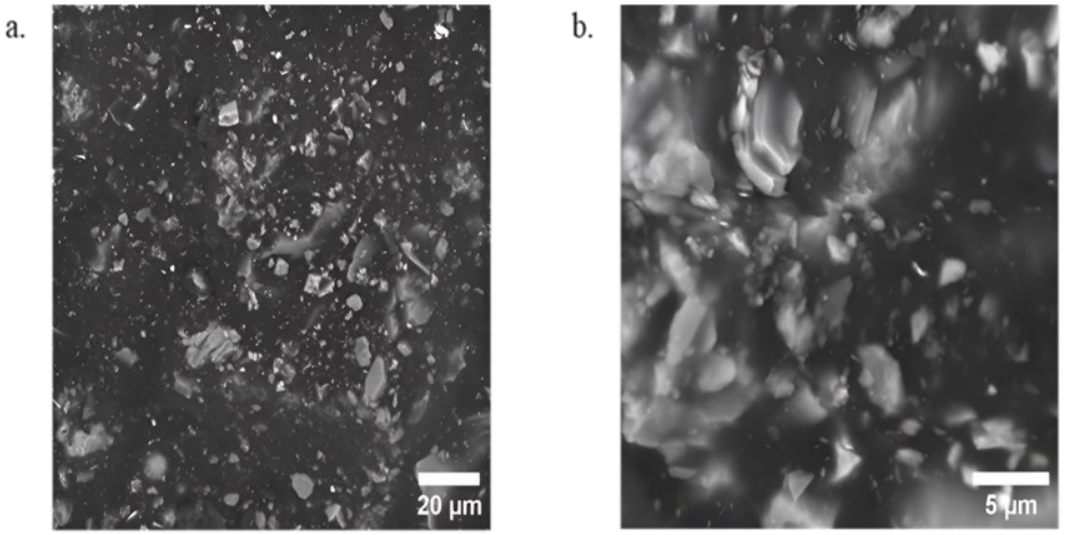

Figure 6. SEM image of 3% BD-PU modified asphalt: zoom in (a) 1000× and (b) 5000×.

and 3.84 mm respectively. The increasing is caused by plastic properties of BD-PU adhesive originating from isoprene molecule [36], which is a major component of the moraceae family plant [14]. Figure 5(c) shows the Marshall stiffness of specimens based on differences in BD-PU binder content. Asphalt specimens without BD-PU showed an MQ value of 4.92 kN/mm. The presence of 3% BD-PU adhesive caused the MQ value of the specimens to increase to 6.51 kN/mm. Then, BD-PU with 5% and 7% are decreased in the MQ value to 6.19 kN/mm and 6.15 kN/mm, respectively. High Marshall stability makes specimens more resistant to deformation, as indicated by the Marshall stiffness from BD-PU 3% [37]. However, excessively high Marshall flow can reduce the ability of specimens to maintain their shape, as indicated by the decrease in Marshall stiffness from BD-PU 5% [32]. Additionally, the optimum BD-PU content for modified asphalt is 3% BD-PU. The right amount of BD-PU can affect the mechanical properties and performance of modified asphalt [38]. Furthermore, the stability, melt flow, and stiffness of all specimens met the Bina Marga specifications [34].

3.3. Rheological performance of asphalt-polyurethane (PMA) blends

Figures **6(a)** and **6(b)** show the morphology of modified asphalt using 3% BD-PU at magnifications of 1000× and 5000×, respectively. The surface of the specimen shows an even distribution of course, medium, and fine-sized aggregates bonded by asphalt and BD-PU, indicating good mixture density.

4. CONCLUSIONS

In this study, a novel bio-based polyurethane adhesive (BD-PU) was successfully synthesized through the controlled oxidation of bendo sap, followed by addition reaction polyethylene glycol (PEG 1000) and toluene diisocyanate (TDI). The incorporation of BD-PU into asphalt significantly enhanced both rheological and mechanical properties. The softening point increased from 48.6 °C for neat asphalt to 52.0 °C for the modified system, indicating improved resistance to temperature-induced deformation. Marshall test results showed that the maximum stability value (27.64 kN) was achieved at a BD-PU content of 5%, demonstrating the highest load-bearing capacity at this concentration. However, considering the overall performance criteria, including stability, flow, and stiffness modulus, the optimum BD-PU content was determined to be 3%. At this composition, the asphalt mixture exhibited a balanced performance, satisfying all relevant specifications, including Bina Marga standards and ASTM D6927. The use of 3% BD-PU ensures adequate stiffness and deformation resistance while maintaining sufficient flexibility to prevent cracking. From an engineering perspective, the addition of BD-PU enhances the structural integrity of asphalt mixtures by promoting better interfacial bonding and forming a crosslinked polymer network within the binder. This results in improved resistance to rutting under high temperatures and heavy traffic loads, as well as enhanced durability against long-term aging. Therefore, BD-PU can be considered an effective and sustainable modifier for asphalt applications, particularly in regions with high temperature and traffic intensity. Overall, this study demonstrates that bio-based polyurethane derived from bendo sap has strong potential as an eco-friendly alternative to conventional petroleum-based modifiers, contributing to the development of more durable, high-performance, and sustainable pavement materials.

AUTHOR INFORMATION

Corresponding Author

Tamrin Tamrin — Postgraduate of Chemistry, Universitas Sumatera Utara, Medan-20222 (Indonesia); Department of Chemistry, Universitas Sumatera Utara, Medan-20222 (Indonesia);

orcid.org/0000-0002-7565-8072

Email: tamrin@usu.ac.id

Authors

Adiansyah Adiansyah — Postgraduate of Chemistry, Universitas Sumatera Utara, Medan-20222 (Indonesia);

orcid.org/0000-0003-0327-8510

Marpongahtun Marpongahtun — Department of Chemistry, Universitas Sumatera Utara,

Medan-20222 (Indonesia);
orcid.org/0000-0003-1050-0431
Sovia Lenny — Department of Chemistry, Universitas Sumatera Utara, Medan-20222 (Indonesia);
orcid.org/0000-0001-7417-8627
Lua Shun Kuang — School of Materials Science and Engineering, Nanyang Technological University, Nanyang-639798 (Singapore);
orcid.org/0000-0002-7498-4343
Ronn Goei — School of Materials Science and Engineering, Nanyang Technological University, Nanyang-639798 (Singapore);
orcid.org/0000-0001-6794-0601

Author Contributions

Conceptualization, T. A. and S. L.; methodology M. P.; software, formal analysis, A. D. and R. G.; A. D. and R. G.; validation, investigation, T. A. and M. P.; resources, project administration, T. A. and A. D.; data curation, A. D., T. A., and M. P.; writing—original draft preparation, A. D. and M. P.; writing—and editing, R. G. and T. A.; visualization, A. D. and S. L.; supervision, R. G. and M. P.; funding acquisition, M. P. and S. L. All authors have read and agreed to published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the finances and writing of this work.

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DECLARATION OF GENERATIVE AI

The authors declare that generative artificial intelligence (AI) and AI-assisted technologies were used solely to improve the readability, grammar, and language clarity of the manuscript. These tools were employed exclusively for linguistic refinement and formatting purposes and were not used to generate, interpret, analyze, or manipulate scientific data, research findings, figures, or conclusions. All scientific content, experimental design, data interpretation, and final conclusions presented in this manuscript were independently developed, verified, and approved by the authors. The authors take full responsibility for the accuracy, originality, and integrity of the manuscript.

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