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Performance Comparison of Conventional and Biopolymer-modified Asphalt Mixtures for Airport Pavement

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ABSTRACT

Raising the temperature of airport pavement softens its surface, leading to rutting or thermal cracking. As aircraft manufacturers lean toward heavier planes with higher tire pressures, challenges arise. To tackle these problems, incorporating polymers like high-density polyethylene into asphalt binders has emerged as a solution. This study investigates biopolymer-modified asphalt, blending conventional asphalt with high-density polyethylene and pine resin. This study aims to compare the performance of asphalt mixtures using both conventional and biopolymer-modified asphalt binders. Various tests–physical, Fourier transform infrared, energy dispersive X-ray, dynamic shear rheometer, volumetric properties, Marshall stability, retained stability, indirect tensile strength and Cantabro loss-were conducted. The results highlighted that integrating pine resin and high-density polyethylene increased the performance grade (PG) of the conventional asphalt from PG 64 to PG 82. Asphalt mixtures using biopolymer-modified binders exhibited superior stability, stiffness and resistance to moisture damage compared to those with conventional asphalt. These properties aligned with the specifications outlined in Item P-401 of the Federal Aviation Administration Advisory Circular 150/5370-10H.

Keywords: Pine resin, High-density polyethylene, Biopolymer-modified asphalt, Performance grade 64, Performance grade 82.

INTRODUCTION

Over the past decade, global climate change has significantly increased surface temperatures, posing a challenge to airport-pavement stability. As the temperature increases, the pavement softens, leading to increased deflection and vulnerability. Rutting and fatigue damages become prevalent issues in airport hot-mix asphalt. Consequently, the choice of materials is crucial for safeguarding airport pavement against weathering damages.

Aircraft manufacturers are increasingly designing planes with heavier gross weights and higher tire pressures. These factors contribute to the likelihood of rutting in airport pavements. Anticipating even greater future loads, there is a growing need for high-strength and durable mixtures of these pavements. The quality of asphalt mixtures depends heavily on the properties of the asphalt binder, which is responsible for bonding the aggregate particles. Enhancing the properties of this binder material becomes pivotal in addressing these challenges.

The use of polymer-modified asphalt binders in hot-mix asphalt (HMA) is one approach to mitigate the influence of heavier loading encountered by aircrafts. The ability of polymer-modified asphalt to improve the performance of asphalt pavement has been widely acknowledged. Polymer-modified asphalt exhibits good resistance to rutting, fatigue, stripping and thermal cracking (Wen et al., 2002; Tayfur et al., 2007). A diverse range of polymers have been employed to improve the properties of asphalt binders. Examples include styrene-butadiene-styrene (SBS), styrene-butadiene-rubber (SBR), polypropylene (PP), polyvinyl chloride (PVC), ethylene vinyl acetate (EVA), low-density polyethylene (LDPE), high-density polyethylene (HDPE), among others (Yildrim, 2007; Buruiana et al., 2023; Köfteci et al., 2020; Jain et al., 2021; Khan and Marjan, 2023; Piromanski et al., 2020). Among various types of polymers, high-density polyethylene (HDPE) is one of the modifiers used in asphalt binder industry (Rodrigues and Hanumanthgari, 2015).

Nejad et al. (2014) investigated the effects of HDPE as modifier of asphalt binder on HMA performance. The mixture without HDPE was used as the control mix. The results showed that the fatigue life of the HDPE-modified mixtures was higher than that of the control mixture. Compared to the mixture without HDPE, the ability of the asphalt mixture containing HDPE to resist repeated loading without experiencing fatigue cracking increased, because HDPE modification can improve the adhesion of asphalt to aggregates. The temperature susceptibility of the modified asphalt is also a key factor that influences fatigue resistance. Because the HDPE modification may alter the temperature susceptibility, the fatigue life of the HDPE-modified mixtures increased. In addition, the use of HDPE in the mixture results in improved resistance to rutting due to its higher stiffness. The mixture is less likely to deform under the influence of traffic and high temperatures, which contributes to improved rutting resistance. As previously stated, HDPE modification can increase high-temperature performance, making it more resistant to deformation at elevated temperatures commonly associated with rutting.

The manner in which the polymer is blended with asphalt can have a significant impact on the final properties of the mixture, including factors, such as the mixing temperature, time and mixer speed. According to Zanchetta et al. (2007) in International Publication Patent Number WO 2007/030448 A2, mixing of polyethylene, including low-density polyethylene (LDPE), high-density polyethylene (HDPE) or a combination of both, with asphalt is typically carried out at temperatures ranging from 150ºC to 240ºC. The preferred temperature range for mixing was between 180ºC and 210ºC, with a blade stirrer operating at speeds between 400 rpm and 1000 rpm for a time from 3 hours to 6 hours. In one embodiment of the invention, the polyethylene-asphalt composition comprises from 1% to 20% by weight of polyethylene. Most preferably, the composition was between 5% and 10% by weight of polyethylene.

The properties of polymer-modified asphalt depend on the percentage of polymer used. It is recommended that HDPE be applied at concentrations of approximately 4% by weight of asphalt binder (Hınıslıoglu and Agar, 2004). Meanwhile, the influences of HDPE on the morphology and rheological properties of a modified binder have been investigated by Pérez-Lepe et al. (2005). Penetration-grade bitumen of 60/70 was mixed with 1%, 2%, 3% and 5% HDPE. Adding 1% or 2% HDPE to bitumen resulted in a dispersed polymer phase, but it did not significantly modify the mechanical behaviour of bitumen. However, increasing the HDPE content to 3% or 5% led to a structured polymer phase and improved resistance to permanent deformation at high temperatures.

According to Habib et al. (2011), the best results were achieved when the HDPE proportion was maintained below 3%. When higher percentages of polymers were used, issues associated with material properties surfaced. With an increase in polymer content, the polymer tends to absorb the oil fraction from the asphalt, causing heightened polymer swelling. Consequently, these swollen polymer chains interconnect and create a three-dimensional network. Polymer-modified asphalt undergoes a transition, shifting from a continuous asphalt phase to a polymer phase. Due to this fact, incompatibility issues may manifest (Fernandes et al., 2008).

The incompatibility between asphalt binder and polymer can be overcome by applying aromatic oil to the mixture (Dou et al., 2007). Aromatic oil is a good solvent for asphaltene molecules. This compound proceeds as a bridge between saturate fraction of asphalt and the mixed micelle, so that mixed micelles dispersed in the saturate effectively (Zendehboudi et al., 2014; Fan et al., 2002).

The aromatic compound can be found in plants. In recent years, various natural resins derived from plants have been explored as asphalt modifiers. This interest arises from their similarity to conventional asphalt (Huang et al., 2012; Yang et al., 2016). Several publications have reported the use of bio-derived materials as rejuvenators. According to Bailey and Phillips (2010), oils derived from sunflower, sesame, corn, soybean, peanut and palm are suitable for rejuvenating asphalts. Nigen-Chaidron and Porot (2010) stated that palm oil is applicable as a rejuvenating agent for asphalt-pavement recycling. Asli et al. (2012) also assessed the potential of using waste cooking oil as a rejuvenating agent in reclaimed asphalt pavement. The results showed that the addition of waste cooking oil can revive the physical and rheological properties of aged asphalt to those of the original asphalt. Gong et al. (2016) demonstrated that lightweight components of waste cooking oil could improve the properties of aged asphalt binders. Additionally, Kumar and Aggarwal (2023) concluded that waste cooking oil could increase the workability of aged binder, extend the fatigue life of rejuvenated bitumen and enhance its resistance to fatigue cracking.

In this study, natural resin from pine tree (*Pinus merkusii*) was chosen, because it contains aromatic compounds (Coppen and Hone, 1995; Silvestre and Gandini, 2008). The use of aromatic components can improve the solubility of polymers in asphalt binders. This increased solubility leads to a better dispersion of the polymer within the asphalt matrix, which prevents the formation of agglomerates or clusters. Additionally, aromatic components can enhance the mobility of the polymer chains, allowing the polymer to spread more evenly within the asphalt, resulting in a more homogeneous mixture.

The utilization of pine resin also involves accessibility and viscoelastic characteristics. According to the Indonesian Forest State Corporation, pine-resin production amounted to 92,550 tons in 2018 (Perhutani, 2020). Similar to asphalt binder, the softness of pine resin is influenced by temperature, becoming softer as it increases and harder as it decreases. The use of pine-processing product as part of plastic-modified bitumen shows better viscoelastic properties, such as resistance to deformation, compared to the use of only bitumen (Pinomaa, 1993). As previously concluded by some researchers, materials derived from plants can be used as rejuvenating agents; thus, the use of pine resin in this study prevented aging during the mixing process of biopolymer-modified asphalt.

Pine resin is naturally hydrophobic, meaning that it repels water. This property is due to the presence of aromatic rings and functional groups, such as phenols, alcohols and carboxylic acids, in the resin molecules (Chang et al., 2020). Because of this waterproofing characteristic, pine resin has traditionally been used to preserve wooden ships (Barnett, 2019). Therefore, the use of pine resin as an asphalt modifier, which is hydrophobic and waterproof, has the potential to increase resistance to moisture damage compared to conventional asphalt.

HMA mixtures used as the surface layers of airport pavements are currently designed based on the Federal Aviation Administration FAA P-401 specification. This specification provides a direction for the production and placement of HMA mixtures with dense graded aggregates and PG 64-22, PG 70-22 or PG 76-22 asphalt binder (Guercio and McCarthy, 2015; Chehab et al., 2019). However, to address predicted future air traffic and climate conditions in Asia-Pacific airport, it is suggested that polymer-modified asphalt be upgraded from the performance grade of PG 76 to PG 82 (Nurkama et al., 2019).

Since the requirement has been suggested to use PG 82, this study seeks to identify the composition of polymer-modified asphalt that achieves the targeted PG 82 and assess its ability to effectively bind aggregate particles in HMA mixtures. The focus is on examining the properties of biopolymer-modified asphalt, comprising conventional asphalt, HDPE and pine resin, to ensure that they meet the PG 82 criteria. Additionally, it aims to analyze the performance of mixtures employing biopolymer-modified asphalt binder and draw comparisons with mixtures utilizing neat asphalt, as specified in the FAA P-401 guideline.

MATERIALS AND METHODS

In the production of biopolymer-modified asphalt, a combination of conventional asphalt (60/70 penetration grade), HDPE sourced from oil-tank containers and pine resin extracted from East Java's pine trees was utilized. The process involved blending conventional asphalt with varying percentages (4%, 5%, 6% and 7% by weight) of biopolymer-modified asphalt and consistently incorporating 3% pine resin across all mixtures. The mixture was heated at 220ºC, stirred manually for 30 minutes and maintained at 1480 rpm for the next 90 minutes.

According to Woqod (2019), a minimum softening point of PG 82 is required at 70ºC; thus, this study began with a softening-point test of biopolymer-modified asphalt. To investigate the influence of biopolymer on the physical properties of asphalt binders, penetration and ductility tests were also conducted. Based on the penetration and softening-point values, the temperature susceptibility of asphalt binders can be analyzed using the penetration index. The penetration index parameter is believed to reflect the rheological behaviour of asphalt binders due to temperature (Anderson et al., 1983; McLeod, 1972). According to Pfeiffer and van Doormaal, as stated by Koenders (2015), the penetration index was calculated from the penetration and softening point using Equations (1) and (2).

$$\mathrm{PI} = \frac{20\,(1-25\mathrm{A})}{1+50\mathrm{A}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$\mathrm{A} = \frac{\log \text{pen at T1} - \log 800}{\mathrm{T1} - \mathrm{SP}} \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

where:
PI = Penetration index.
A = The slope of penetration logarithm.
Pen at T1 = The penetration at the required temperature T1 (0.1 mm).
SP = Softening point of asphalt binder (ºC).

Furthermore, Fourier transform infrared (FTIR) spectroscopy was conducted to characterize the functional groups of the binder's compounds. From the FTIR spectrum, the presence of various organic compounds can be determined in term of Carbonyl Index. It is often used to quantify or compare the concentrations of carbonyl functional groups in various samples. Carbonyl Index was calculated using Equation (3) as follows (Lamontagne et al., 2001):

$$\mathrm{I}_{\mathrm{C=O}} = \frac{\text{Carbonyl band area around 1700 cm}^{-1}}{\text{Summation of spectral band area between 2000 and 600 cm}^{-1}} \quad \ldots\ldots\ldots\ldots \quad (3)$$

To find out the elemental content of conventional and biopolymer-modified asphalt, energy dispersive X-ray (EDX) test was conducted using the spectrum of X-rays emitted from the specimens after excitation by high-energy electrons. Dynamic shear rheometer (DSR) test was conducted at high and intermediate temperatures. From the DSR test results, the grades of the asphalt binders can be correlated according to the specifications of the Superpave binder (AASHTO M-320).

The coarse aggregates, fine aggregates and fillers utilized in producing the asphalt mixture were sourced from an asphalt-mixing plant located in Pringgabaya, East Lombok, Indonesia. The aggregates were cleaned, dried and sieved using FAA point grading. The asphalt mixture produced was a dense mixture of surface course layer for airport pavement. Five asphalt contents were designated for the asphalt mixture: 4.5%, 5%, 5.5%, 6% and 6.5%. Aggregate and biopolymer-modified asphalt were mixed at 175ºC and 75 blows of compaction were applied on each side.

Marshall criteria were employed to assess the mixture properties and obtain the optimum asphalt content. Furthermore, the resistance to degradation due to contact with water was investigated for samples prepared at the optimum asphalt content after immersion at 60°C for 24 h. The ratio of the Marshall immersion of the soaked specimen to that of the standard Marshall can be calculated as:

$$\mathrm{RSI} = \frac{\text{Stability of soaked specimen}}{\text{Stability of standard Marshall}} \quad \ldots\ldots\ldots\ldots \quad (4)$$

where:
RSI = Retained stability index (%).

An indirect tensile strength (ITS) test was performed to examine the performance of the asphalt mixture under compressive loading. The formula for determining the indirect tensile strength is as follows:

$$\mathrm{ITS} = \frac{2\,\mathrm{P_{max}}}{\pi\, t\, d} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where:
ITS = Indirect tensile strength (kPa).
P_{max} = Maximum applied load (kN).

t = Specimen thickness (cm).
d = Specimen diameter (cm).

The ITS test was conducted under two conditions: unconditioned and conditioned. Unconditioned specimens were tested after curing at 40ºC for 72 h, whereas conditioned specimens were obtained by immersing the unconditioned samples in water at 25ºC for 24 h. Furthermore, the tensile strength ratio can be obtained as:

$$\mathrm{TSR} = \frac{\mathrm{ITS\ wet}}{\mathrm{ITS\ dry}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where:
TSR = The indirect tensile strength ratio (%).
ITSwet = The indirect tensile strength of the conditioned samples (kPa).
ITSdry = The indirect tensile strength of the unconditioned samples (kPa).

Finally, a Cantabro-loss test was conducted to assess the impact of load on the pavement. The result of the Cantabro-loss test can be calculated as:

$$\mathrm{CL} = 100\left(\frac{P_1 - P_2}{P_1}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

where:
CL = Cantabro loss (%).
P1 = Weight of initial specimen (g).
P2 = Weight of final specimen (g).

The average of three replicate specimens of the asphalt mixture was used to determine the results for each test category.

RESULTS AND DISCUSSION

Physical Properties of Asphalt Binders

The softening-point test is an initial effort to determine the temperature at which the correlating requirement of PG 82 is fulfilled according to Woqod (2019). Table 1 shows the softening-point values and other physical properties of conventional asphalt and biopolymer-modified asphalt with different HDPE percentages.

The penetration value of biopolymer-modified asphalt decreases as the percentage of HDPE increases, as shown in Table 1. This reduction in penetration value is due to the change in consistency that occurs when HDPE is added to the biopolymer-modified asphalt. With higher HDPE content, the polymer swells and absorbs the lighter components in the asphalt binder. Consequently, this leads to heightened viscosity and a subsequent hardening effect on the biopolymer-modified asphalt.

Table 1. Physical properties of asphalt binders

Binder type	Softening point (ºC)	Penetration (0.1 mm)	Ductility (cm)	Slope (A)	Penetration Index
Conventional asphalt	47.9	64.3	160	0.0478	-1.152
H1 (93% conventional asphalt + 4% HDPE + 3% pine resin)	54.7	44.2	34.6	0.0423	-0.376
H2 (92% conventional asphalt + 5% HDPE + 3% pine resin)	57.8	41.6	33.1	0.0391	0.144
H3 (91% conventional asphalt + 6% HDPE + 3% pine resin)	63.8	37.0	32.8	0.0344	1.029
H4 (90% conventional asphalt + 7% HDPE + 3% pine resin)	71.3	32.9	32.5	0.0299	2.016

The increase in softening point directly correlates with the increased HDPE content. This increase can primarily be linked to the increasing percentage of HDPE, given that the concentration of pine resin remains constant at 3% for all variations in the biopolymer-modified asphalts. When juxtaposed with conventional asphalt, the softening point registers a significant increase, elevating from 47.9°C to 71.3°C at

7% HDPE concentration. This delineates the enhanced thermal stability and stiffening properties inherent to biopolymer-modified asphalt.

Table 1 illustrates the ductility values of conventional asphalt and biopolymer-modified asphalt, reflecting their flexibility. As the concentration of HDPE increases, the ductility of the asphalt binder decreases. This is because the increased dosage of HDPE leads to a less homogeneous mixture of biopolymer-modified asphalt, which reduces its ability to elongate and results in lower ductility.

Table 1 presents the penetration index of the conventional asphalt, which was -1.152 and that of the biopolymer-modified asphalt was in the range from -0.376 to 2.016. The higher the HDPE percentage in the biopolymer-modified asphalt, the higher the penetration index. This demonstrates that biopolymer-modified asphalt is less susceptible to temperature than conventional asphalt. Based on the penetration-index value, it is suggested that biopolymer-modified asphalt is suitable for use in hot climates, where flexibility at high temperatures is crucial.

As shown in Table 1, at 4%, 5% and 6% HDPE, the softening point of biopolymer-modified asphalt was below the minimum value of 70ºC. Therefore, biopolymer-modified asphalt consisting of 90% conventional asphalt, 7% HDPE and 3% pine resin was selected for further investigation in the subsequent phase of this study.

FTIR Analysis

The spectra of conventional and biopolymer-modified asphalt obtained from FTIR method are shown in Figure 1. Based on the peak spectra and referring to the table of compound functional groups as stated by Coates (2006) and Skoog et al. (2007), the functional-group identification of the binders can be interpretated.

Figure 1 shows the peaks at 3466 cm^{-1} and 3465 cm^{-1} for conventional and biopolymer-modified asphalts, which illustrate the oxygen-hydrogen (O-H) bonding. The wavenumbers in the range of 2860-2880 cm^{-1} indicate the presence of O-H bonds. Furthermore, the peaks around 1600 cm^{-1} are associated with the C=C double bond or with the compound containing aromatic oil. Conventional asphalt exhibits a large amount of C-H out of plane bending. However, alcohol, methylene and methyl are contained in both conventional and bio-polymer-modified asphalts. The peaks in the range of 700-900 cm^{-1} indicate that conventional and biopolymer-modified asphalts have aromatic components. Based on Figure 1, this analysis indicates a similarity in functional groups between conventional and biopolymer-modified asphalts, showing resemblances in their chemical compositions.

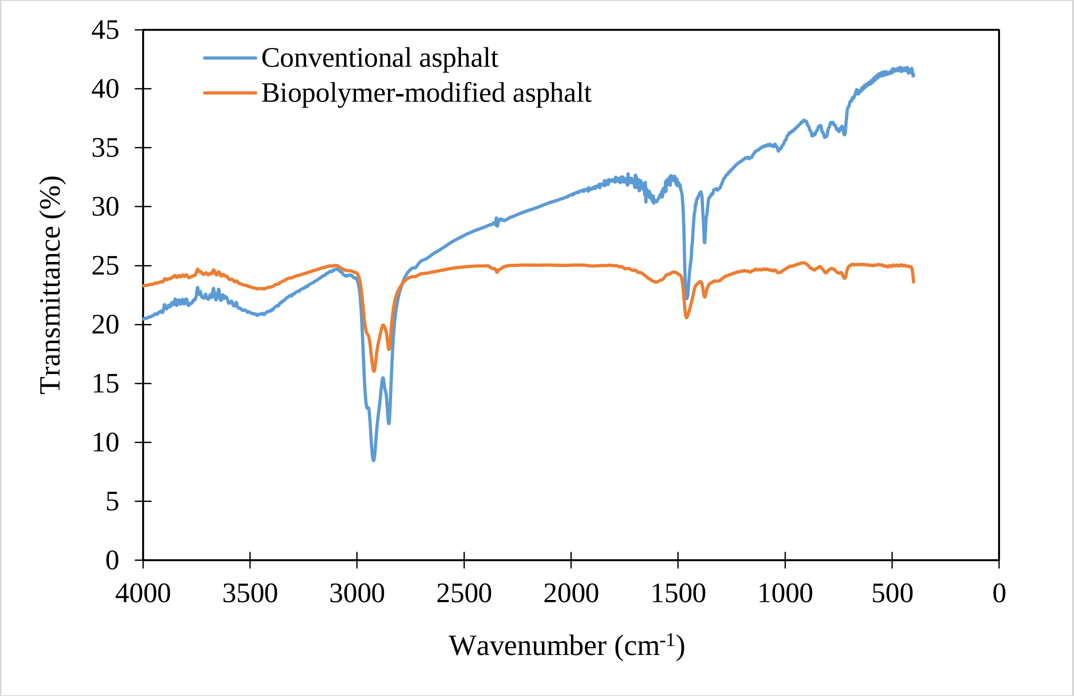

Figure (1): Transmission spectra of asphalt binders

To determine the Carbonyl Index (CI) value in Equation (3), the absorbance peaks in the range between 2000 cm^{-1} and 600 cm^{-1} were integrated into OriginPro software. By plotting the absorbance values against the wavenumber range (2000 to 600 cm^{-1}) and using the Peak Analyzer tool, it was found that the CI of conventional asphalt and biopolymer-modified asphalt were 0.019 and 0.206, respectively. A higher Carbonyl Index in biopolymer-modified asphalt generally indicates a higher concentration of carbonyl functional groups in the sample, which can influence the physical and chemical properties of the asphalt binder, such as its hardness and viscosity. Biopolymer-modified asphalt hardens compared to conventional asphalt because of its higher Carbonyl Index value.

Elemental Composition of Asphalt Binders

EDX test results show that conventional asphalt is predominantly composed of carbon (83.7%), followed by sulfur (11.13%) and oxygen (5.16%). In contrast, biopolymer-modified asphalt contains 78.10% carbon, with oxygen content more than doubled at 10.58% compared to conventional asphalt. The increase in the oxygen mass fraction is the result of oxygen bonding during the mixing process of biopolymer-modified asphalt.

Furthermore, the sulfur content in the biopolymer-modified asphalt decreased to 6.58% compared to that of the conventional asphalt. This decline was attributed to the evaporation of low-molecular-weight sulfur during the heating process. Additionally, aluminum and iron were detected in amounts of 2.94% and 1.81%, respectively, in asphalt modified with HDPE. These elemental variations significantly influence the physical and rheological properties of asphalt binders, resulting in performance differences in the asphalt mixture.

Rheological Properties of Asphalt Binders

Dynamic shear rheometer (DSR) test results are presented in Table 2. Dynamic shear rheometer (DSR) test measures the resistance of the asphalt binder to deformation through shear loading. The rutting resistance factor (G*/sin δ) on original specimen is used to predict the pavement condition during construction, whereas the value of G*/sin δ on rolling thin-film oven test (RTFOT) is used to foresee the early-stage condition of the pavement. Moreover, G*sin δ value on pressure aging vessel (PAV) is used to gather fatigue cracking during the service life of the pavement.

As stated previously, biopolymer-modified asphalt hardens and the use of HDPE significantly enhances its ability to resist rutting. Table 2 shows that the rutting resistances of biopolymer-modified asphalt at all test temperatures were higher than those of the conventional asphalt. According to Superpave PG specifications, G*/sin δ for unaged specimens should be more than 1.0 kPa and a minimum of 2.2 kPa for short-term aged asphalt binder to be rut resistant. The maximum temperatures required to satisfy the requirements of Superpave PG for conventional and biopolymer-modified asphalts were 64°C and 82°C, respectively.

Table 2. DSR-test results

Binder state	Parameter	Conventional asphalt		Biopolymer-modified asphalt		Requirement (kPa)
		Temperature (°C)	Result (kPa)	Temperature (°C)	Result (kPa)	
Original	G*/sin δ, at 10 rad/s	64	1.757	64	11.907	≥ 1.0
		70	0.847	70	5.095	
		76	-	76	2.414	
		82	-	82	1.263	
		88	-	88	0.756	
RTFOT aged	G*/sin δ, at 10 rad/s	64	4.657	64	41.181	≥ 2.2
		70	2.137	70	17.358	
		76	-	76	7.530	
		82	-	82	3.206	
		88	-	88	1.673	
PAV aged	G*sin δ, at 10 rad/s	22	5156	28	5605	≤ 5000
		25	3790	31	4266	
		28	2663	34	3136	
		31	1783	37	2364	
		34	1156	40	1719	

For the aged asphalt binder examined at the intermediate temperatures, G*sin δ should not be greater than 5000 kPa to be fatigue-cracking resistant. The minimum temperatures at which the requirement met for conventional and biopolymer-modified asphalts were 25°C and 31°C, respectively. Based on the results of DSR test, conventional asphalt is equal to performance grade of PG 64, whereas biopolymer-modified asphalt is satisfying the grade of PG 82. In other words, the use of pine resin and HDPE as modifiers increases the performance grade of conventional asphalt from PG 64 to PG 82. As reported by Nurkama et al. (2019), the asphalt binder for airport-pavement material at Asia-Pacific airport should be upgraded to the performance grade of PG 82; thus, the result of this study fulfills this suggestion.

Properties of Aggregate

Aggregate-impact value of the coarse aggregate was 9.7%. It is foreseen that the aggregate is sufficiently tough to resist loading during the construction and service life of the pavement. The bulk specific gravity of the coarse aggregate, fine aggregate and filler are 2.657, 2.756 and 2.683, respectively. Moreover, apparent specific gravities were 2.775, 2.795 and 2.718, respectively. The bulk specific gravity satisfies the requirement in the range of 2.6-3.0 based on the specification of Federal Aviation Administration (FAA, 2018). The affinity of 100% to asphalt binder demonstrates that the entire aggregate surface area can be effectually coated.

Volumetric and Mechanical Properties of Asphalt Mixture

As presented in Table 3, the voids in the mineral aggregate (VMA) generally increased with an increase in the asphalt binder content. In general, a higher content of binder causes the thickness of the asphalt film to become larger and the voids formed between aggregate particles tend to increase. VMA values of the mixture using biopolymer-modified asphalt were lower than those of conventional asphalt with the same percentage of binder. The use of HDPE and pine resin strengthened bonding in the asphalt mixture, resulting in better adhesion. Good adhesiveness in the mixture generates a closer distance between the aggregate particles and forms smaller voids.

As in crescent the percentage of asphalt binder in the mixture, voids in mix (VIM) decrease because of the thicker coverage of the binder. The VIM values in the mixture applying biopolymer-modified asphalt were lower than those of the mixture using conventional asphalt. The high solubility and sticky features of pine resin generate biopolymer-modified asphalt which strongly binds the aggregate, thus affecting smaller air voids. Moreover, the density of the mixture utilizing biopolymer-modified asphalt is larger than that of conventional asphalt. Pine resin, as part of the modified asphalt, improves the bonding properties in the mixture and produces a higher density.

Table 3. Volumetric and Marshall properties of asphalt mixtures

Asphalt content	VMA (%)	VIM (%)	Density (gr/cm^3)	Marshall (lbs)	Flow (mm)
Conventional asphalt					
4.5	14.67	5.46	2.413	4547.83	3.15
5	14.56	4.12	2.429	4682.47	3.21
5.5	15.09	3.49	2.433	3832.13	3.46
6	15.83	3.10	2.472	3515.25	3.60
6.5	16.35	2.46	2.494	3002.92	3.79
Biopolymer-modified asphalt					
4.5	14.23	4.77	2.471	5243.63	2.62
5	14.21	3.50	2.493	5897.73	2.86
5.5	15.06	3.20	2.514	5412.91	3.14
6	15.62	2.58	2.530	5223.92	3.34
6.5	16.34	2.15	2.552	3830.81	3.60
Requirement	Min. 15	2.5-4.5	N/A	Min. 2150	N/A

N/A = not available.

The Marshall-stability test plays a crucial role in assessing a pavement's ability to endure loading without experiencing detrimental effects, such as rutting, cracking or permanent deformation. According to Brown et al. (2001), Marshall-stability test is an empirical test to assess the response of asphalt pavement to permanent deformation. Marshall stability of the mixtures utilizing biopolymer-modified asphalt was higher than that of the mixtures using conventional asphalt. This evidence strengthens the research conducted by Taherkhani and Arshadi (2017) that polymer-modifieds asphalt can increase the stability of the mixture.

As presented in Table 3, the deflection of the asphalt mixture which is depicted through the flowmeter increases in parallel with increasing asphalt content. Compared to the mixture using conventional asphalt, the flexibility of the mixture applying biopolymer-modified asphalt was lower. Because utilizing HDPE hardens the modified-asphalt binder, the mixtures become denser and the values of flow become smaller.

Laboratory testing of asphalt mixtures is fundamental to ensure that the airport-pavement surface meets the functional-property requirements and is crucial for safe aircraft operation. The hot-mix asphalt design specifications utilized for airport pavements are Item P-401 authenticated in the Federal Aviation Administration Advisory Circular 150/5370-10H (FAA, 2018). According to this specification, pavements designed for aircrafts with a gross weight of more than 60,000 lbs or tire pressures greater than 100 psi require a minimum Marshall stability of 2150 lbs, a range of VIM between 2.5% and 4.5% and a minimum VMA of 15%. Based on these requirements, it can be determined that the optimum asphalt contents for conventional and biopolymer-modified asphalts are 6% and 5.8%, respectively.

Furthermore, the values of Marshall immersion and retained stability index at the optimum asphalt content were calculated based on Equation (4). Retained stability index was determined as 91.42% for the mixture using conventional asphalt and 93.95% for the mixture using biopolymer-modified asphalt. This result indicates that the mixture using biopolymer-modified asphalt is more resistant to water. It is thought that the increase in the resistance of the mixture to water damage was caused by the waterproof characteristic of pine resin, which uniformly glued HDPE in biopolymer-modified asphalt.

Moisture Susceptibility of Asphalt Mixture

According to Figure 2, indirect tensile strength (ITS) values in dry and wet conditions of the mixture using biopolymer-modified asphalt were higher than those of the mixture with conventional asphalt. The results of the ITS test strengthen the results of the other tests that biopolymer asphalt produces a higher density, because the adhesion between biopolymer-modified asphalt and aggregate increases due to the sticky properties of the pine resin. The mixture using biopolymer-modified asphalt is more feasible for resisting cracking when subjected to loading, so that it is more resistant to permanent deformation.

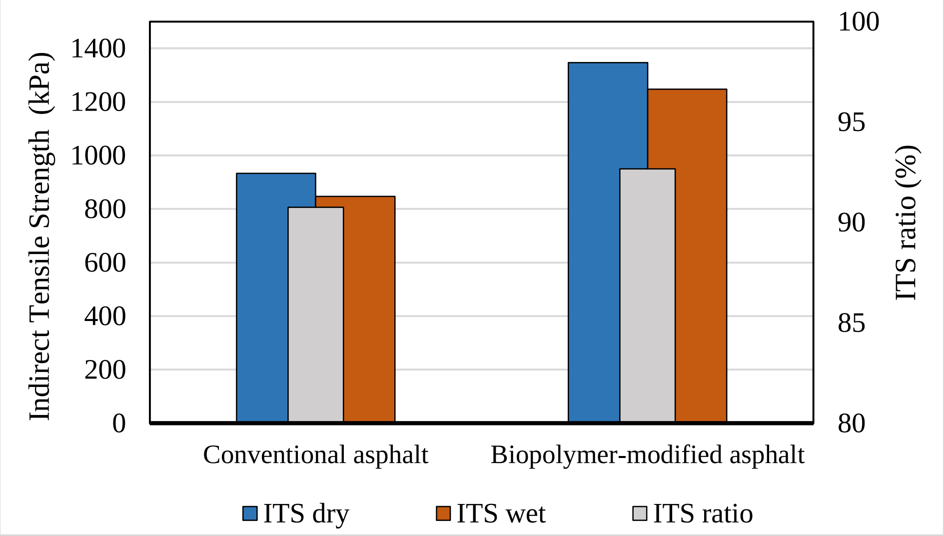

Figure (2): "Biopolymer-modified asphalt" overlaps with the legend text

Under wet condition, the indirect tensile strength of the mixture using conventional asphalt was 847.54 kPa, while that of the mixture with biopolymer-modified asphalt was 1247.79 kPa. The difference between the dry and wet conditions was used to measure the resistance of the mixtures to damage due to water immersion. The higher the value of the indirect tensile strength ratio, the more resistant the mixture is to negative effects of water immersion. Compared to the mixture using conventional asphalt, the use of HDPE and pine resin as ingredients in biopolymer-modified asphalt increased the value of the indirect tensile strength ratio from 90.76% to 92.67%.

Cantabro Test Result

The Cantabro-loss test assesses the impact of load on the pavement, offering insights into the resistance of the mixture to abrasion and material loss caused by wear. It is usually used to assess the resistance of porous-asphalt mixture to degradation (Alvarez et al., 2010). However, Cantabro-loss test has also been developed for dense-graded asphalt mixtures in recent years (Doyle and Howard, 2016).

This test was conducted under two conditions: Cantabro loss and the aging Cantabro loss. The aging process was obtained by placing the specimens in an oven at 60°C for 168 h (7 days). Under the original condition, the mixture using conventional asphalt produced a Cantabro-loss value of 4.93%, whereas the mixture with biopolymer-modified asphalt produced a Cantabro-loss value of 6.58%. The values of the aging Cantabro loss for the mixture using conventional and biopolymer-modified asphalts were 4.99% and 7.88%, respectively.

The results of the Cantabro-loss test also strengthen the results of the previous tests. Biopolymer-modified asphalt is harder than conventional asphalt. Based on the test results of Marshall and indirect tensile strength, the mixture using biopolymer-modified asphalt produced higher stability and had a greater load-carrying capacity than the mixture using conventional asphalt.

Due to the higher hardness of biopolymer-modified asphalt, which increases the stability of the asphalt mixture, its flexibility tends to decrease. This is because stability is regarded as the opposite property of flexibility. Stability is the ability of the asphalt mixture to maintain its shape, whereas flexibility is the ability of the asphalt mixture to adapt to deformation when withstanding loading. Because the stability of the asphalt mixture containing biopolymer-modified asphalt is higher, its ability to resist abrasion is lower; thus, its Cantabro-loss value is higher.

As previously stated, the use of HDPE and pine resin as modifiers improved the PG grade of asphalt and enhanced the performance of the asphalt mixture. Because the surface temperature of airport pavements sharply increases owing to global climate change, the potential benefits of using biopolymer-modified asphalt for airport pavements are anticipating pavement softening and deformation under high temperatures. Biopolymer-modified asphalt enhances resistance to rutting and maintains the structural integrity of the pavement-surface layer even in hot climates. As biopolymer-modified asphalt contains pine resin, which is derived from renewable resources, it aligns with the sustainability goals to contribute to better environmental conditions in the future.

CONCLUSIONS

Based on the results of this study, it can be concluded that:

- The use of pine resin increases the compatibility between conventional asphalt and polymer by up to 7% HDPE. It also increased the stiffness of the biopolymer-modified asphalt compared with that of the conventional asphalt. DSR test analysis showed that the application of pine resin and HDPE in biopolymer-modified asphalt increased the performance grade of conventional asphalt from PG 64 to PG 82.
- VMA and VIM values of the mixture using biopolymer-modified asphalt were lower than those of the mixture using conventional asphalt. Because HDPE hardens the modified asphalt binder, the ability of the mixture using biopolymer-modified asphalt to withstand loading was higher than that of the mixture using conventional asphalt.
- The resistance to moisture damage of the mixture using biopolymer-modified asphalt tended to increase compared to that of the mixture using conventional asphalt, as observed from the value of the retained stability index. The use of pine resin and HDPE increased the indirect tensile strength ratio from 90.76% to 92.67%. Cantabro-loss test results strengthen the results of the other tests in this study.

- According to Item P-401 verified in the FAA Advisory Circular 150/5370-10H, the minimum Marshall stability was set at 2150 lbs, the range of VIM between 2.5% and 4.5% and a minimum of VMA at 15%; the properties of the mixture using biopolymer-modified asphalt produced in this study fulfilled the requirements at the optimum asphalt content of 5.8%.

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