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The effect of pre-vulcanized latex usage on Marshall characteristics and stiffness modulus in hot mix asphalt wearing course (AC-WC) mixtures

Keywords: pre-vulcanized latex, AC-WC, modified asphalt binder, Marshall characteristics, stiffness modulus

Introduction

Asphalt pavement is the most widely used type of flexible pavement globally. Flexible pavements are composed of aggregates and asphalt mixed at high temperatures, commonly referred to as hot mix asphalt (HMA). Hot mix asphalt pavements typically consist of 93–96% aggregate and 4–7% asphalt by weight. However, factors such as increased traffic volume, harsh climate and environmental conditions, as well as inappropriate material usage can negatively impact the quality of HMA pavements, leading to issues like fatigue cracking and rutting (Özel et al., 2023). To address these concerns, it's essential to enhance the

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quality of the existing asphalt materials. Various additives have been used to improve the behavior and performance of asphalt in different settings (Shaffie et al., 2016; Hasaninia & Haddadi, 2017; Wu, 2018). By incorporating these additives, it's possible to increase the durability and lifespan of asphalt pavements, ultimately reducing maintenance costs and promoting sustainable infrastructure development. Engineers and material scientists have been trying to modify the properties of binders using various modifiers, such as fillers, fibers, extenders, plastics, anti-stripping agents, oxidizers, antioxidants, recycled rubber, polymers, and non-materials in an effort to solve or reduce these problems (Behnood & Gharehveran, 2019; Dai & Jia, 2022; Nguyen et al., 2022; Tamele Jr. et al., 2022; Jimmyanto et al., 2023; Ramadhani et al., 2023). Asphalt binders are typically modified to enhance one or more basic characteristics of asphalt, such as stiffness, elasticity, brittleness, storage stability and durability, and resistance to cumulative damage. Engineers can select the best modifier to achieve desired qualities by analyzing how the modifier affects the performance of an asphalt binder (Behnood & Gharehveran, 2019).

Rubber is one of the ways polymers are used to enhance the characteristics of asphalt mixtures at high temperatures. Used tires, natural rubber, and synthetic rubber have all been used in previous studies, but there is currently only limited data on the use of natural rubber in research (Prastanto et al., 2019; Guo et al., 2020; Irfan et al., 2022). Natural rubber latex is a sustainable and renewable resource. Natural rubber latex can be easily obtained by tapping rubber trees. Natural rubber can be utilized as a thermoplastic elastomer form to create modified polymer bitumen. The thermoplastic elastomer known as natural rubber, commonly referred to as latex, helps improve the stiffness and elasticity of asphalt while reducing its sensitivity to temperature fluctuations (Daniel et al., 2019; Poovaneshvaran et al., 2020; Jamaris et al., 2021). Natural rubber is available in liquid and solid forms. Latex refers to natural rubber in a liquid form, while cup lump refers to natural rubber in a solid form. The thick sap extracted from tapped trees is known as latex (Putri & Sari, 2021).

Previous studies on the use of pre-vulcanized latex as a material in HMA have been conducted by Irfan et al. (2021) and Prastanto et al. (2019). These studies utilized pre-vulcanized latex at levels ranging from 3% to 7% as an additive in asphalt mixtures. Prastanto et al. (2019) focused on asphalt concrete-wearing course (AC-WC) mixtures, while Irfan et al. (2022) investigated asphalt concrete-binder course (AC-BC). The results obtained by Prastanto et al. (2019) indicated that the use of pre-vulcanized latex at levels of 5–7% in AC-WC asphalt mixtures can enhance physical characteristics and Marshall parameters with stability ranging from 1,046 to 1,103 kg. Irfan et al. (2021), on the other hand, stated that the addition of pre-vulcanized latex at levels of 3–7% reduces the penetration value while increasing viscosity and softening point. Moreover, the incorporation of this pre-vulcanized latex can significantly improve Marshall stability up to 1,618–1,771 kg. Wan et al. (2023) revealed that Marshall is a commonly used indicator for evaluating the performance of asphalt mixtures. The Marshall method allows for selecting appropriate aggregate sizes based on desired design criteria. This method can determine the optimum asphalt binder content in an asphalt mixture measured by stability, flow, and air void parameters. Previous studies have discussed the influence of rubber concentration with asphalt binder content, such as Siswanto (2019), although they focused on latex rubber.

Liquid latex has been widely used in asphalt mixed applications, according to the literature currently in publication. Pre-vulcanized latex is a liquid latex modified to blend easily with asphalt mixtures and made by Indonesian natural rubber products. Prior studies only included pre-vulcanized latex as an additional material in asphalt mixtures. Nevertheless, there is a study gap because no data about the impacts of utilizing pre-vulcanized latex as a substitute for asphalt binder has been discovered. This substitution aims to reduce the use of asphalt binder in the HMA mixture, thereby saving costs and energy associated with the asphalt binder production process (Bindu et al., 2020). This paper uses the AC-WC mixture design in HMA mixtures to test the impact of pre-vulcanization latex content as an asphalt binder substitute. Laboratory testing methods include physical and rheological characterization tests for asphalt binder materials and Marshall and stiffness modulus tests for HMA mixtures.

Material and methods

Materials

In this paper, asphalt binder with a penetration of 60/70 is used. The rubber used comes from the Indonesian Rubber Institute Bogor, with the type of pre-vulcanized latex. Table 1 shows the testing characteristics of pre-vulcanized latex, where the total solid content is 55.73%, pH is 11.48, and polymer content is 87.28%.

TABLE 1. Testing the characteristics of pre-vulcanized latex

Test type	Result	Test method
Total solid content [%]	55.73	ASTM D 1076 (ASTM International [ASTM], 2023)
Mechanical stability time [s]	> 1 800	ASTM D 1076
pH	11.48	ASTM D 1076
Chloroform number	4	ASTM D 6370-99 (ASTM, 2019)
Acetone extract [%]	9.23	ASTM D 297 (ASTM, 2021)
Polymer content [%]	87.28	ASTM D 6370-99

Source: own elaboration.

The materials used as ingredients in the asphalt mixture consist of coarse aggregates [a combination of Split A (max 9.5 mm), Split B (max 4.75 mm), and Split C (max 2.36 mm)]. Fine aggregates are made using Musi River sand, and filler material uses stone dust that passes through a sieve size of 0.075 mm. Each of these aggregates undergoes characteristic testing referring to SNI 1969:2016 (Badan Standardisasi Nasional [BSN], 2016) and SNI 1970:2008 (BSN, 2008b). Table 2 shows the results of aggregate and filler characteristic testing, where each aggregate has a specific gravity ranging from 2.49 to 2.75 and water absorption ranging from 1.10% to 3.50%. For coarse aggregate abrasion testing, it follows SNI 2417:2008 (BSN, 2008a), and the obtained results meet the specification which is less than 40%.

TABLE 2. Test results for aggregate and filler characteristics

Test type	Split A	Split B	Split C	Musi River sand	Stone dust filler	Spec.	Method
Particles passing the 0.075-millimeter sieve [%]	1.70	0.20	2.79	5.60	100	max. 2	SNI 03-4142:1996 (BSN, 1996)
Abrasion with Los Angeles engine 500 rotation [%]	14.48	12.19	–	–	–	max. 40	ASTM C 131-76 (ASTM, 1976)
Bulk specific gravity	2.64	2.75	2.49	2.52	2.73	–	ASTM C 127-84 (ASTM, 1984) ASTM D 854-02 (ASTM, 2002)
Apparent specific gravity	2.72	2.84	2.73	2.67	2.73	–	
Water absorption [%]	1.10	1.10	3.50	2.04	–	–	

Source: own elaboration.

Preparation of modified asphalt binder

Latex pre-vulcanization, as seen in Figure 1a, is used as a partial substitute for asphalt binder where the content should not be too high. According to a study by Wititanapanit et al. (2021), using a rubber content of up to 6% in asphalt binder can improve its performance and stability at high temperatures.

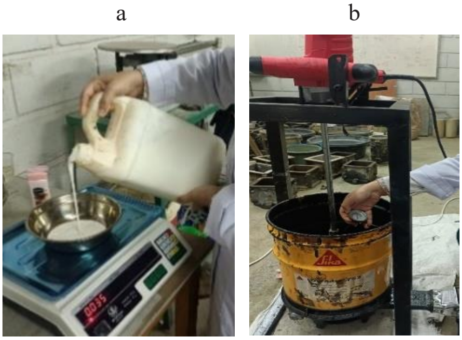

FIGURE 1. Preparation of modified asphalt: a – pre-vulcanized latex; b – design of asphalt binder mixing equipment

Source: own elaboration.

However, Jitsangiam et al. (2021) suggest that the rubber content should not exceed 12% as it may result in poorer performance. Therefore, this study uses latex pre-vulcanization content of 7% (LP 7%) and 9% (LP 9%) by weight of asphalt binder as substitutes (Table 3). The mixing of asphalt binder and latex pre-vulcanization is done using a mixer with specifications of 800 rpm and 750 W. The mixing is carried out in a container equipped with a thermometer and gas stove to maintain the mixing temperature (Fig. 1b).

TABLE 3. Testing the characteristics of pre-vulcanized latex

Code samples of modified asphalt binder	Asphalt binder penetration 60/70 content [%]	Latex pre-vulcanization content [%]
Aspen or LP 0%	100	0
LP 7%	93	7
LP 9%	91	9

Source: own elaboration.

The temperature and mixing time for the modified asphalt binder used in this paper refer to previous researchers (Ramadhani et al., 2023), where liquid form latex pre-vulcanization is easier to mix with asphalt binder due to their phase similarity.

The design mix formula (DMF) and job mix formula (JMF) for AC-WC mixture

The design mix formula (DMF) is a proposed asphalt binder content design (Pb) that can be determined using an approach based on the percentage of aggregate retained on sieve 8 (2.36 mm) and passing through sieve 200 (0.075 mm). The AC-WC is the asphalt mixture used in this study (asphalt concrete – wearing course), referring to the Bina Marga Specification Year 2018 (Revision 2) in Indonesia. Figure 2 shows the proposed job mix formula (JMF) for AC-WC used in this research. Based on the matrix analysis from sieve analysis testing for each aggregate and filler, the composition of AC-WC obtained is Split A at 32.24%, Split B at 26.62%, Split C at 25.56%, river sand at 10.37% and filler at 5.21%. In determining the optimum asphalt binder content (KAO) with Marshall testing, a range of asphalt binder contents are used: 5.0%; 5.5%; 6.0%; 6.5% and 7.0% with three specimens tested for each mixture proportion.

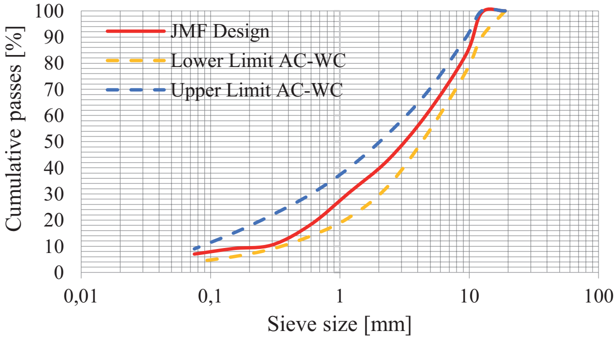

FIGURE 2. AC-WC mixed plan gradation

Source: own elaboration.

Testing of modified asphalt binder characteristics

To determine the characteristics of the asphalt binder used, penetration testing, softening point testing, viscosity testing, specific gravity testing, and rheology testing are conducted. Penetration testing (ASTM D 5 – ASTM, 2020), softening point testing (ASTM D 36 – ASTM, 2010), viscosity testing (ASTM D 4402 – ASTM, 2012), and specific gravity (ASTM D 70-03 – ASTM, 2003) testing are intended to analyze the physical characteristics of the asphalt. Rheology testing using a dynamic shear rheometer (DSR) is performed to determine the complex modulus of the asphalt binder based on AASHTO T315-10 (American Association of State Highway and Transportation Officers [AASHTO], 2010).

Testing characteristics of asphalt mixtures

The asphalt mixture samples made can be seen in Table 4, which includes three variations. The first variation consists of a control sample using 60/70 asphalt binder, the second variation consists of a sample using 7% LP modified asphalt binder, and the third variation consists of a sample using 9% LP modified asphalt binder. Each variation was used to make 15 Marshall test specimens to determine the optimum asphalt binder content (OAC) for each variation. Table 5 shows the number of Marshall test specimens made using OAC, where each variation is made with six units. The characteristics of the asphalt mixture are tested using the Marshall test apparatus and stiffness modulus test. The Marshall testing follows the ASTM D 1559-89 standard (ASTM, 1989), while the stiffness modulus testing follows BS DD 213-1993 (British Standards Institution [BSI], 1993) using a universal testing machine (UTM) 30 with a pulse width of loading of 250 ms and a pulse repetition period of 3,000 ms. Stiffness modulus testing is conducted at temperatures of 25°C and 40°C, with the number of samples indicated in Table 6.

TABLE 4. Samples for making Marshall test specimens using the planned asphalt content binder

Variation	Sample	Asphalt binder used	Amount (unit)	Plan asphalt binder content
1	M-ASP	Aspen (0% LP)	15	5%; 5.5%; 6%; 6.5%; 7%
2	M-LP 7%	7% LP	15	
3	M-LP 9%	9% LP	15	
×	×	Total	45	×

Source: own elaboration.

TABLE 5. Marshall test object samples with KAO

Variation	Sample	Asphalt binder used	Amount (unit)
1	KAO-M-ASP	Aspen (0% LP)	6
2	KAO-M-LP 7%	7% LP	6
3	KAO-M-LP 9%	9% LP	6
×	×	Total	18

Source: own elaboration.

TABLE 6. Samples of stiffness modulus testing specimens

Sample	Asphalt binder used	Testing temperature (*T*) [°C]	Asphalt binder content	Total
Mod-ASP-25	Aspen (0% LP)	25	KAO M-ASP	2
Mod-ASP-40	Aspen (0% LP)	40	KAO M-ASP	2
Mod-LP7%-25	7% LP	25	KAO-M-L 7%	2
Mod-LP7%-40	7% LP	40	KAO-M-L 7%	2
Mod-LP9%-25	9% LP	25	KAO-M-L 9%	2
Mod-LP9%-40	9% LP	40	KAO-M-L 9%	2

Source: own elaboration.

Results and discussion

Asphalt binder physical characteristics test results

The results of the penetration testing can be seen in Table 7, where the addition of 7% LP reduces asphalt binder penetration, while the addition of 9% LP increases it. This is because at 9% LP, asphalt binder becomes more elastic as the asphaltene particles absorb more rubber. On the other hand, for 7% LP with lower penetration, it can provide advantages in terms of intermediate temperature resistance characteristics and also improve durability in asphalt mixtures (Al-Mansob et al., 2014; Abdelmagid & Feng, 2019; Al-Sabaeei et al., 2020).

The results of the softening point testing of modified asphalt binder using pre-vulcanized latex can be seen in Table 7. The results show an increase in the softening point when the LP content is increased, indicating that the use of LP can increase both the value of asphalt's softening point and its penetration. As a result, resistance to permanent deformation increases due to this higher softening point. Therefore, the use of LP can improve rutting performance due to an increase in the softening point.

TABLE 7. Basic characteristics of the modified asphalt binders

Basic characteristics of the binders	Sample of modified asphalt binder					
	Aspen (0% LP)		7% LP		9% LP	
	result	*SD*	result	*SD*	result	*SD*
Penetration testing (0.1 mm)	60.4	1.3	45.3	2.5	68.1	1.5
Softening point test R&B [°C]	54	0.0	56.5	1.4	65.5	1.4
Viscosity at 0.2 Pa·s for mixing temperature [°C]	151	–	168	–	166	–
Viscosity at 0.4 Pa·s or compaction temperature [°C]	137	–	157	–	160	–

Source: own elaboration.

The calculation of the penetration index (*PI*) is intended to indicate the susceptibility of modified asphalt binder to temperature. The range of *PI* values is between –3 (high-temperature susceptible asphalt binder) and 7 (low-temperature susceptible asphalt binder). The results of the penetration index, where for asphalt binder without LP, a *PI* value of 0.218 was obtained, for asphalt binder with 7% LP it was 0.065, and for asphalt binder with 9% LP it was 2.926. This means that asphalt binder mixed with 7% LP is more susceptible to high temperatures, while asphalt binder with 9% LP is more susceptible to low temperatures. Asphalt binder with 7% LP has a stiffer nature compared to asphalt binder with 9% LP, which has elastic properties, so when influenced by temperature changes, the viscosity of asphalt binder with 9% LP changes faster. The rotational viscometer is used to measure viscosity in modified asphalt binders at different levels. The test results reveal that increasing amounts of pre-vulcanized latex have an impact on the viscosity properties of the asphalt binder. In particular, when comparing samples with 0% and 7% LP content, they display similar characteristics in terms of their viscosity gradient lines; however, there is an observed difference in temperature between these two samples. According to the Superpave specification, the viscosity value at a temperature of 135°C should not exceed 3.0 Pa·s because high viscosity can lead to difficulties related to workability. The results of the viscosity testing at a temperature of 135°C show that the test values are not higher than 3.0 Pa·s, indicating that the addition of pre-vulcanized latex still falls within acceptable workability limits. The results of viscosity testing can also determine the mixing temperature and compaction temperature limits in making Marshall samples. The viscosity limit for mixing temperature is 0.2 Pa·s and the viscosity limit for compaction temperature is 0.4 Pa·s. Based on Table 7, it can be determined that the mixing temperature for the 0% LP, 7% LP and 9% LP samples respectively is 151°C, 168°C and 166°C, while the compaction temperature for the 0% LP, 7% LP and 9% LP samples respectively is equal to 137°C, 157°C and 160°C.

Asphalt binder rheology test results

When modifying materials such as pre-vulcanized latex (LP) are added, changes in the viscoelastic properties of the asphalt binder are thought to be a significant factor because of the strong interaction between elastic modulus and rutting resistance at high temperatures. In this study, the viscoelastic properties of asphalt binder are characterized by the complex modulus (G^*) and phase angle (δ). The time lag between the applied shear stress and the shear strain is known as the phase angle. Perfectly elastic materials have a phase angle value of zero, while viscous materials have a phase angle value of nearly 90°. Thus, in order to examine the rheological properties of modified asphalt, DSR testing was done (Fig. 3; Rahman & Zega, 2018; Bethary & Subagio, 2020).

The DSR test result (Fig. 3) shows that the complex modulus value decreases as the test temperature increases. The complex modulus (G^*) value decreases with each addition of LP between 52 and 70°C, with 7% LP having the highest complex modulus value. The Aspen (0% LP) sample failed at 76°C, indicating that the addition of pre-vulcanization latex increased resistance to high temperatures (Wen et al., 2017; Poovaneshvaran et al., 2020). A 1.0 kPa criterion limit for unaged

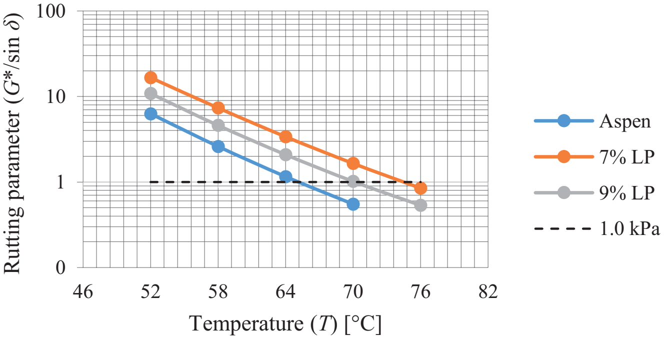

FIGURE 3. Effect of pre-vulcanization latex (LP) on $G^*/\sin\delta$ and temperature
Source: own elaboration.

asphalt binder, or a $G^*/\sin\delta$ limit value of 1.0 kPa, is stated by Superpave (Superior PERforming asphalt PAVEment). This allows for the determination of the asphalt binder classification, which is PG 64 for Aspen, PG 70 for 7% LP, and 9% LP based on performance grade (PG).

Testing asphalt mixture characteristics

Marshall testing is done in order to examine the properties of asphalt mixtures that contain pre-vulcanized latex. The results of the Marshall test for the M-ASP, M-LP 7%, and M-LP 9% samples are illustrated in Table 8 for the asphalt binder content range of 5% to 7%. Five parameters have specifications based on the Indonesian rubber asphalt recommendations. For every sample, the test findings for the sta-

TABLE 8. Marshall test results for the asphalt binder content range of 5–7%

Parameter	Spec.	M-ASP		M-LP 7%		M-LP 9%	
		result	*SD*	result	*SD*	result	*SD*
Type of asphalt binder used	–	Aspen (0% LP)	–	7% LP	–	9% LP	–
VMA [%]	min. 15	15–17	0.8	15–18	0.7	15–17	0.9
VIM [%]	3–5	2–8	2.4	3–8	1.6	1–7	2.1
VFA [%]	min. 65	52–88	13.8	53–84	10.1	59–90	12.7
Stability [kN]	min. 8.83	8.47–14.16	1.62	10–18	2.19	9–16	1.85
Flow [mm]	2–5	4–7	1.1	4–7	1.0	3–8	1.4
Marshall quotient (MQ) [kN·mm^{-1}]	–	1.65–3.04	0.45	1.49–3.94	0.82	1.24–3.22	0.65

Source: own elaboration.

bility and VMA criteria met the required standards. The Marshall test is performed with a compression machine, in which the sample is put in and gradually compressed to the maximum load.

The outcome of creating Marshall samples from M-LP 7% and M-LP 9% for each intended asphalt binder content is shown in Figure 4. To determine the sample's density, its dry weight, submerged water weight, and dry surface weight are all measured.

FIGURE 4. Results of making Marshall samples
Source: own elaboration.

The asphalt binder percentage limit known as the optimal asphalt binder content, or KAO, can produce high stability values while satisfying the criteria for flow, VIM, VMA, and VFA. As seen in Table 9, the KAO results from samples M-ASP, M-LP 7%, and M-LP 9% differ in value. This is because the viscosity and density of the asphalt mixture are impacted when pre-vulcanized latex is used. It can be observed that the KAO value of the M-ASP sample is higher than the KAO values of the M-LP 7% and M-LP 9% samples, indicating that the use of pre-vulcanized latex can minimize the amount of asphalt binder in the mixture.

Six Marshall samples were made for KAO, three of which were soaked for 30 min at 60°C and the other three of which were soaked for 24 h at 60°C, in order to learn more about the properties of the asphalt mixture. This is to examine the asphalt mixture's ability to withstand the effects of being immersed in water for a full day, a condition known as Marshall residual stability.

The results of the Marshall test, which uses KAO and has seven parameters with specifications, are displayed in Table 9. KAO-M-ASP has the highest VMA value of 15.94%, while the KAO-M-LP sample has the lowest VMA value of 7%.

TABLE 9. Marshall test results for KAO samples

Parameter	Spec.	KAO-M-ASP		KAO-M-LP 7%		KAO-M-LP 9%	
		result (AVG)	*SD*	result (AVG)	*SD*	result (AVG)	*SD*
KAO [%]	–	6.00	–	5.90	–	5.65	–
VMA [%]	min. 15	16	1.8	15	2.4	16	0.5
VIM [%]	3–5	4	2.0	4	2.7	5	0.5
VFA [%]	min. 65	73	9.7	73	12.7	70	2.5
Stability, 30-minute immersion [kN]	min. 8.83	11.68	1.20	11.63	1.15	10.69	2.77
Stability, 24-hour immersion [kN]	min. 8.83	11.09	0.67	10.84	0.39	9.85	1.92
Flow [mm]	2–5	4	0.3	4	1.5	4	0.4
Marshall quotient (MQ) [kN·mm^{-1}]	–	2.72	0.16	2.81	1.10	2.84	0.61
Residual Marshall stability after 24-hour immersion [%]	min. 90	94.9	–	93.2	–	92.1	–

Source: own elaboration.

This results from the asphalt being absorbed on the aggregate surface, where the VIM value is also impacted by the KAO-M-ASP sample filling more aggregate pores than the KAO-M-LP 7% and KAO-M-LP 9% samples. Despite getting the highest VIM value of 9%, the KAO-M-LP sample still meets the requirements. The behavior of the 9% LP asphalt filled the aggregate pores more than the air spaces in the mixture is what is causing this large VIM value. This 9% pre-vulcanized latex content might be stickier and thicker, which would make covering the aggregate's surface easier than just inserting it in air spaces. When compared to the stability specification value of 8.83 kN, the Marshall stability value using pre-vulcanized latex had a positive effect, increasing by 32.28% for a grade of 7% and 21.06% for a grade of 9%.

When comparing pre-vulcanized latex samples to the control sample (KAO-M-ASP), Table 9 additionally shows a decrease in the Marshall stability; nevertheless, the resulting Marshall stability still satisfies specification requirements. In addition, the application of pre-vulcanized latex can lower the amount of asphalt binder needed in the AC-WC mixture; the control sample needs 6% of asphalt binder, whereas the pre-vulcanized latex sample needs 5.9% and 5.65% of asphalt binder. This demonstrates that utilizing pre-vulcanized latex in asphalt mixtures has the major benefit of allowing for a reduction in the quantity of asphalt binder used. The sample using pre-vulcanized latex has a lower Marshall stability than the control sample, but it is still within the acceptable ranges. The pre-vulcanized latex samples showed a decrease in flow parameter results from 4.30 mm to 4.13 mm, or 3.95%, for the 7%

content, and from 4.30 mm to 3.77 mm, or 12.33%, for the 9% content. The mixture utilizing pre-vulcanized latex tends to be stiffer than the control sample, as shown by the resulting decrease in flow values.

To find the remaining Marshall stability, each KAO sample was immersed in water at 60°C for 30 min and then for 24 h. The sample using modified asphalt binder with pre-vulcanized latex has a smaller residual Marshall stability than the control sample, where the smallest residual stability value is at KAO-M-LP 9%, according to the results of the residual Marshall stability test, which are depicted in Table 9. This is also consistent with a study by Jitsangiam et al. (2021) that suggests the quantity of pre-vulcanized latex that can be used in asphalt binder has a limit. The storage stability of asphalt binder can be affected using excessive amounts of pre-vulcanized latex.

Table 10 presents a comparative analysis between the findings of previous research and the current study. Prastanto et al. (2019) and Irfan et al. (2022) looked at the impact of applying pre-vulcanized latex to asphalt mixtures with a rubber content of 3–7% for AC-WC and AC-BC. When compared to the specification value of 8.83 kN, the use of pre-vulcanized latex has the ability to increase Marshall stability, as demonstrated by the comparison of previous research results in Table 10. In the current study, pre-vulcanized latex was substituted for asphalt binder at weights of 7% and 9%. Previous research had used it as an additive to asphalt binder. In contrast to the research findings of Prastanto et al. (2019), there is a decrease of 8.22% in the flow value and an increase in Marshall stability from 10.32 kN to 11.63 kN, or 12.69%. This shows that the substitution effect of pre-vulcanized latex in asphalt binder has a better impact than as an additional in asphalt binder. In addition, this substitution has the benefit of absorbing natural rubber's usage as a hot asphalt mixture material while using less asphalt binder overall.

TABLE 10. Comparison of Marshall test results with previous researchers

Parameter	Current study		Prastanto et al. (2019)		Irfan et al. (2022)
	substitution pre-vulcanized latex		addition pre-vulcanized latex		
Rubber content	7%	9%	5%	7%	3%
Mixed gradation type	AC-WC	AC-WC	AC-WC	AC-WC	AC-BC
KAO [%]	5.90	5.65	6.00	6.08	5.58
Stability, 30-minute immersion [kN]	11.63	10.69	10.82	10.32	–
Flow [mm]	4.1	3.8	4.4	4.5	–
Marshall quotient (MQ) [kN·mm^{-1}]	2.81	2.84	2.46	2.29	–

Source: own elaboration.

Stiffness modulus of asphalt mixture (S_{mix})

According to Irfan et al. (2022), the stiffness modulus, which is determined by dividing the load size by the recoverable stress, indicates the asphalt mixture's capacity to withstand loading without losing its elastic properties.

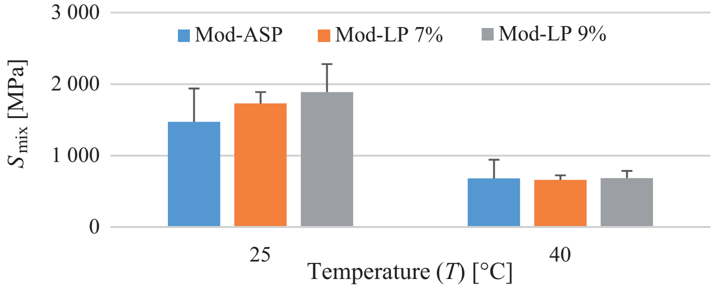

FIGURE 5. Stiffness modulus of asphalt mixture test results with the UTM tool

Source: own elaboration.

This test is performed using the UTM instrument depicted. A mathematical model presented by Brown and Brunton (1984), and Read and Whiteoak (2003) can be used to calculate the stiffness modulus prediction (Rahman & Zega, 2018). According to Rahman and Zega (2018), and Bethary and Subagio (2020), the magnitude of the asphalt stiffness modulus (S_{bit}) acquired from DSR testing affects each of these mathematical models. The results of the stiffness modulus testing with the UTM tool and the stiffness modulus results from calculations using a mathematical model were compared in this study.

The S_{mix} test results for samples with 0% LP, 7% LP, and 9% LP asphalt are shown in Figure 5. The average value of the test results carried out three times on one specimen was used to determine the S_{mix} test results at 25°C and 40°C. When the asphalt mixture reaches a temperature of 25°C, it is considered to be in normal condition; in Indonesia, however, the pavement temperature is 40°C (Irfan et al., 2021). It demonstrates that at 25°C, the sample with 9% LP has the largest S_{mix} value (1,888 MPa), followed by the Mod-LP7% sample (1,729 MPa). The Mod-LP7% sample and the Mod-LP9% sample both observed increases in S_{mix} of 17.46% and 28.26%, respectively, in comparison to the control sample (Mod-ASP). The Mod-LP9% sample had the largest S_{mix} at 685 MPa, followed by Mod-LP7% at 661 MPa, with an increase of 8.21% and 4.42%. The results of the S_{mix} test at 40°C revealed the same trend as at 25°C.

Stiffness modulus prediction model for asphalt mixtures

Predictive stiffness modulus models for asphalt mixtures are currently available solely for petroleum asphalt binder; however, no progress has been made in the area of modified asphalt binder utilizing pre-vulcanized latex. Ramadhani et al. (2023) have studied the prediction model for asphalt binder stiffness (S_{bit}) using pre-vulcanized latex; however, their research is restricted to asphalt binder.

TABLE 11. Results of making a prediction model for stiffness modulus of asphalt mixture S_{mix} containing pre-vulcanized latex

Model	Model type	Equation	R^2
1	linear	$S_{\text{mix}} = -2\,064.813 + 24.382 \cdot LP + 111.465 \cdot VMA + {}$ $+ 616.839 \cdot VIM + 45.603 \cdot S_{\text{bit}} - 50.006 \cdot T$	0.8441
2	nonlinear	$S_{\text{mix}} = \mathrm{e}^{(5.591 + 0.007 \cdot LP + 0.012 \cdot VMA + 0.548 \cdot VIM + 0.039 \cdot S_{\text{bit}} - 0.048 \cdot T)}$	0.8519
3	nonlinear	$S_{\text{mix}} = 10^{(2.428 + 0.003 \cdot LP + 0.005 \cdot VMA + 0.238 \cdot VIM + 0.017 \cdot S_{\text{bit}} - 0.021 \cdot T)}$	0.8519

By gathering test results from the laboratory, this stiffness modulus prediction model for asphalt mixtures can be developed. The dependent variable (y) in the model created is S_{mix}, while the independent variable (x) is the percentage of pre-vulcanization latex content in asphalt binder (LP), *VMA* value, *VIM* value, S_{bit} value and temperature (T). To create this model, a multiple linear regression model was used, creating linear and non-linear models. The proposed model's regression analysis is depicted in Table 11, which shows the results for three different model types – linear and nonlinear. Model 2 and Model 3 have an R^2 value of 0.8519, indicating that the model in Table 11 is closer to the laboratory results, as indicated by a larger R^2 value.

Conclusions

The behavior of pre-vulcanized latex AC-WC mixtures has been thoroughly studied. The impact of pre-vulcanization latex on the physical properties and rheology of asphalt binder and asphalt mixtures offers positive effects, according to the procedure and test objects used. Many inferences can be made from the test results that have been conducted:

1) Pre-vulcanized latex may decrease penetration and raise the softening point, which is beneficial for modified asphalt binder. In comparison to 9% pre-vulcanized latex, 7% pre-vulcanized latex performs better in terms of resistance to high temperatures, according to the penetration index computation results.
2) Based on Marshall test results, the AC-WC mixture using pre-vulcanized latex achieved Marshall stability of 11.63 kN or increased by 32.28% at 7% content, while at 9%, it resulted in Marshall stability of 10.69 kN or increased by 21.06%, compared with the specification limit which is 8.83 kN.
3) The stiffness modulus value of the asphalt mixture increases in tandem with an increase in the pre-vulcanization latex content, according to the results of the stiffness modulus test conducted using the UTM tool at 25°C and 40°C. Using pre-vulcanized latex, the stiffness modulus prediction model for asphalt mixtures is obtained as a nonlinear model with ln and log functions, and its R^2 value is 0.8519.

References

Abdelmagid, A. A., & Pei Feng, C. (2019). Evaluating the effect of rice-husk ash and crumb-rubber powder on the high-temperature performance of asphalt binder. *Journal of Materials in Civil Engineering*, *31* (12), 4019296. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002962

Al-Mansob, R. A., Ismail, A., Alduri, A. N., Azhari, C. H., Karim, M. R., & Yusoff, N. I. M. (2014). Physical and rheological properties of epoxidized natural rubber modified bitumens. *Construction and Building Materials*, *63*, 242–248. https://doi.org/10.1016/j.conbuildmat.2014.04.026

Al-Sabaeei, A. M., Agus Mustofa, B., Sutanto, M. H., Sunarjono, S., & Bala, N. (2020). Aging and rheological properties of latex and crumb rubber modified bitumen using dynamic shear rheometer. *Journal of Engineering and Technological Sciences*, *52* (3), 385–398. https://doi.org/10.5614/j.eng.technol.sci.2020.52.3.6

American Association of State Highway and Transportation Officers [AASHTO], (2010). *Determining the rheological properties of asfhalt binder using a dynamic shear rheometer (DSR)*. (AASHTO T315-10).

ASTM International [ASTM], (1976). *Standard test method for resistance to degradation of small-size coarse aggregate by abrasion and impact in the Los Angeles machine* (ASTM C 131-76).

ASTM International [ASTM], (1984). Standard test method for density, relative density (specific gravity), and absorption of coarse aggregate (ASTM C 127-84).

ASTM International [ASTM], (1989). *Test method for resistance of plastic flow of bituminous mixtures using Marshall apparatus* (ASTM D1559-89).

ASTM International [ASTM], (2002). *Standard test methods for specific gravity of soil solids by water pycnometer* (ASTM D 854-02).

ASTM International [ASTM], (2003). *Standard test method for specific gravity and density of semi-solid bituminous materials (pycnometer method*) (ASTM D 70-03).

ASTM International [ASTM], (2010). *Standard test method for softening point of bitumen (ring--and-ball apparatus)* (ASTM D 36).

ASTM International [ASTM], (2012). *Standard test method for viscosity determination of asphalt at elevated temperatures using a rotational viscometer* (ASTM D 4402).

ASTM International [ASTM], (2019). *Compositional analysis of rubber by thermogravimetry (TGA)* (ASTM D 6370-99).

ASTM International [ASTM], (2020). *Standard test method for penetration of bituminous materials* (ASTM D 5).

ASTM International [ASTM], (2021). *Standard test methods for rubber products – chemical analysis* (ASTM D 297).

ASTM International [ASTM], (2023). *Standard specification for rubber – concentrated, ammonia stabilized, creamed, and centrifuged natural latex* (ASTM D 1076).

Badan Standardisasi Nasional [BSN], (1996). *Cara uji berat jenis dan penyerapan air agregat halus* [*How to test specific gravity and water absorption of fine aggregates*] (SNI 03-4142:1996).

Badan Standardisasi Nasional [BSN], (2008a). *How to test aggregate wear using a Los Angeles abrasion machine* (SNI 2417:2008).

Badan Standardisasi Nasional [BSN], (2008b). *How to test specific gravity and fine aggregate water absorption* (SNI 1970:2008).

Badan Standardisasi Nasional [BSN], (2016). *How to test specific gravity and water absorption of coarse aggregates* (SNI 1969:2016).

Behnood, A., & Gharehveran, M. M. (2019). Morphology, rheology, and physical properties of polymer-modified asphalt binders. *European Polymer Journal*, *112*, 766–791. https://doi.org/10.1016/j.eurpolymj.2018.10.049

Bethary, R., & Subagio, B. (2020). Rheological characteristics of Reclaimed Asphalt Pavement (RAP) evaluation using reclamite rejuvenating material. *IOP Conference Series: Materials Science and Engineering*, *739* (1), 12006. https://doi.org/10.1088/1757-899X/739/1/012006

Bindu, C. S., Joseph, M. S., Sibinesh, P. S., George, S., & Sivan, S. (2020). Performance evaluation of warm mix asphalt using natural rubber modified bitumen and cashew nut shell liquid. *International Journal of Pavement Research and Technology*, *13* (4), 442–453. https://doi.org/10.1007/s42947-020-0241-7

British Standards Institution [BSI], (1993). *Method for determination of the indirect tensile stiffness modulus of bituminous mixtures* (BS DD 213:1993).

Brown, S. F., & Brunton, J. M. (1984). *An introduction to the analytical design of bituminous pavements.* University of Nottingham.

Dai, J., & Jia, X. (2022). Fatigue performance of high-modulus basalt fiber-reinforced asphalt mixture. *Journal of Applied Science and Engineering*, *26* (8), 1187–1193. https://doi.org/10.6180/jase.202308_26(8).0014

Daniel, N. H., Hassan, N. A., Idham, M. K., Jaya, R. P., Hainin, M. R., Ismail, C. R., Puan, O. C., & Azahar, N. M. (2019). Properties of bitumen modified with latex. *IOP Conference Series: Materials Science and Engineering*, *527* (1), 12063. https://doi.org/10.1088/1757-899X/527/1/012063

Guo, F., Zhang, J., Pei, J., Zhou, B., Falchetto, A. C., & Hu, Z. (2020). Investigating the interaction behavior between asphalt binder and rubber in rubber asphalt by molecular dynamics simulation. *Construction and Building Materials*, *252*, 118956. https://doi.org/10.1016/j.conbuildmat.2020.118956

Hasaninia, M., & Haddadi, F. (2017). The characteristics of hot mixed asphalt modified by nanosilica. *Petroleum Science and Technology*, *35* (4), 351–359. https://doi.org/10.1080/10916466.2016.1258412

Irfan, I., Subagio, B. S., Hariyadi, E. S., & Maha, I. (2021). Performance evaluation of Pre-Vulcanized Liquid Natural Rubber (PVLNR) in Hot Mix Asphaltic Concrete. *GEOMATE Journal*, *20* (78), 107–114.

Irfan, I., Subagio, B. S., Hariyadi, E. S., & Maha, I. (2022). The rutting resistance and resilient moduli of Pre-Vulcanized Liquid Natural Rubber modified asphaltic concrete in warm-mix temperature condition. *Journal of Civil Engineering and Management*, *28* (3), 196–207. https://doi.org/10.3846/jcem.2022.16452

Jamaris, U., Hassan, N. A., Mahmud, M. Z. H., Ismail, C. R., Yaacob, H., & Hassan, S. A. (2021). Properties of bitumen modified with latex under short-term ageing. *IOP Conference Series: Materials Science and Engineering*, *1144* (1), 12084. https://doi.org/10.1088/1757-899X/1144/1/012084

Jimmyanto, H., Arliansyah, J., & Kadarsa, E. (2023). Rheological characteristics of asphalt with a crumb rubber and solid natural rubber combination. *Civil Engineering and Architecture*, *11* (5A), 3051–3062. https://doi.org/10.13189/cea.2023.110819

Jitsangiam, P., Nusit, K., Phenrat, T., Kumlai, S., & Pra-ai, S. (2021). An examination of natural rubber modified asphalt: effects of rubber latex contents based on macro- and micro-observation analyses. *Construction and Building Materials*, *289*, 123158. https://doi.org/10.1016/j.conbuildmat.2021.123158

Nguyen, N-L., Nguyen, M. H., Vo, D-T., Truong, V. Q., Le, T-H., & Tran, D-T. (2022). The influence of short and long term aging on the dynamic modulus of recycled polyethylene asphalt mixture. *Journal of Applied Science and Engineering*, *25* (6), 1205–1216. https://doi.org/10.6180/jase.202212_25(6).0016

Özel, F., Deniz, M. T., & Yüce, M. Ý. (2023). Evaluation of olive pomace and SBS modified bitumen to the performance characteristics. *Case Studies in Construction Materials*, *19*, e02432. https://doi.org/10.1016/j.cscm.2023.e02432

Poovaneshvaran, S., Hasan, M. R. M., & Jaya, R. P. (2020). Impacts of recycled crumb rubber powder and natural rubber latex on the modified asphalt rheological behaviour, bonding, and resistance to shear. *Construction and Building Materials*, *234*, 117357. https://doi.org/10.1016/j.conbuildmat.2019.117357

Prastanto, H., Firdaus, Y., Puspitasari, S., Ramadhan, A., & Falaah, A. F. (2019). Study of physical characteristic of rubberized hot mix asphalt based on various dosage of natural rubber latex and solid rubber. *IOP Conference Series: Materials Science and Engineering*, *509* (1), 12049. https://doi.org/10.1088/1757-899X/509/1/012049

Putri, E. E., & Sari, R. R. (2021). The study of split mastic asphalt pavement with latex addition for flooded road. *IOP Conference Series: Earth and Environmental Science*, *708* (1), 12046. https://doi.org/10.1088/1755-1315/708/1/012046

Rahman, H., & Zega, R. T. (2018). Analisis Kesesuaian Model Modulus Aspal dan Campuran Laston Lapis Aus untuk Aspal Modifikasi Asbuton Murni. *Jurnal Teknik Sipil ITB*, *25* (1), 71–80. https://doi.org/10.5614/jts.2018.25.1.9

Ramadhani, R., Arliansyah, J., & Kadarsa, E. (2023). Rheological behavior of modified asphalt binders using pre-vulcanized latex with dynamic shear rheometer testing. *Civil Engineering and Architecture*, *11* (6), 3355–3369. https://doi.org/10.13189/cea.2023.110611

Read, J., & Whiteoak, D. (2003). *The Shell Bitumen Handbook.* Thomas Telford.

Shaffie, E., Ahmad, J., Arshada, A. K., Kamarun, D., & Awang, H. (2016). Investigation on rutting performance of nanopolyacrylate and natural rubber latex polymer modified asphalt binder mixes. *Jurnal Teknologi*, *78* (7–3), 10–14. https://doi.org/10.11113/jt.v78.9469

Siswanto, H. (2019). Effect of latex to minimize the use of asphalt in asphalt concrete wearing course. *Materials Science Forum*, *961*, 39–44. https://doi.org/10.4028/www.scientific.net/MSF.961.39

Tamele Jr, L., Muiambo, H., Buonocore, G., & Cumbane, C. (2022). Thermal proprieties and decomposition kinetics of asphalt binder modified by thermoplastic polymer and nanoclay Dellite 43B. *Journal of Applied Science and Engineering*, *26* (1), 11–21. https://doi.org/10.6180/jase.202301_26(1).0002

Wan, L., Garcia-Hernández, A., Cui, G., & Liu, P. (2023). A novel performance-based method to design asphalt mixtures. *Construction and Building Materials*, *400*, 132792. https://doi.org/10.1016/j.conbuildmat.2023.132792

Wen, Y., Wang, Y., Zhao, K., & Sumalee, A. (2017). The use of natural rubber latex as a renewable and sustainable modifier of asphalt binder. *International Journal of Pavement Engineering*, *18* (6), 547–559. https://doi.org/10.1080/10298436.2015.1095913

Wititanapanit, J., Carvajal-Munoz, J. S., & Airey, G. (2021). Performance-related and rheological characterisation of natural rubber modified bitumen. *Construction and Building Materials*, *268*, 121058. https://doi.org/10.1016/j.conbuildmat.2020.121058

Wu, S. (2018). Characterization of ductility of field-aged petroleum asphalt. *Petroleum Science and Technology*, *36* (9–10), 696–703. https://doi.org/10.1080/10916466.2018.1443125

Summary

The effect of pre-vulcanized latex usage on Marshall characteristics and stiffness modulus in hot mix asphalt wearing course (AC-WC) mixtures. Flexible pavement itself uses asphalt binder as a binding material between aggregates, but with the increasing number of vehicle loads, the ability of flexible pavement needs to be improved. A rubber is a natural polymer material that can be used to improve the performance of asphalt mixtures. This paper aims to analyze the effect of using pre-vulcanized latex on characteristics in hot mix asphalt wearing course mixtures. Pre-vulcanized latex is used as a substitute material for

asphalt binder at levels of 7% and 9% by weight. Based on Marshall test results, the AC-WC mixture using pre-vulcanized latex achieved Marshall stability of 11.63 kN or increased by 32.28% at 7% content, while at 9%, it resulted in Marshall stability of 10.69 kN or increased by 21.06%, compared to the specification limit, which is 8.83 kN. The stiffness modulus test results of the asphalt mixture showed that at a temperature of 25°C, there was an increase of 17.46% and 28.26%, respectively, when using pre-vulcanized latex at levels of 7% and 9%. These findings indicate that the use of pre-vulcanized latex as a partial replacement for asphalt has a positive impact on temperature changes in the pavement material.