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THE RUTTING RESISTANCE AND RESILIENT MODULI OF PRE-VULCANIZED LIQUID NATURAL RUBBER MODIFIED ASPHALTIC CONCRETE IN WARM-MIX TEMPERATURE CONDITION

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Abstract. Pre-Vulcanized Liquid Natural Rubber (PVLNR) modified asphalt leaves problems such as increasing the viscosity, thereby increasing the mixing and compaction temperature up to 175 °C, accelerating the ageing process. Therefore it is necessary to do developing methods using PVLNR at lower mixing temperatures requires warm-mix technology. This study aimed to evaluate the use of PVLNR modified asphalt in warm mix asphalt (WMA). Laboratory testing includes rheological modified asphalt, the workability analysis, Resilient Modulus and Deformation. The results showed that the PVLNR content decreased penetration increased the softening point and asphalt viscosity. In addition, additive Rediset LQ plays a role in reducing asphalt viscosity. The advantages of PVLNR modified asphalt are increasing elastic recovery, saving asphalt consumption and increasing the Modulus of hot mix asphalt rubber (HAR) and warm mix asphalt rubber (WAR). In addition, the Rutting resistance of WAR is better than that of HMA and WMA.

Keywords: Pre-Vulcanized Liquid Natural Rubber, warm mix, Rediset LQ.

Introduction

Economic growth is directly proportional to the increase in demand for infrastructure networks both in quality and quantity. Can be in the form of improving the quality of the road network, especially asphalt pavement (Asian Development Bank, 2012). The conventional 60/70 Pen asphalt limitations are easy to deform at high temperatures and fatigue at low temperatures (Rezvan & Hassan, 2017). Heavy load vehicles can accelerate and damage roads, affecting costs, encouraging modified asphalt to improve asphalt quality such as viscosity, softening point, and elasticity (Ibrahim et al., 2017; Zurni et al., 2013). Commonly used modified asphalt uses a polymer (Babagoli et al., 2021). Several types of polymer used are imported materials, which burden the country foreign exchange.

Liquid natural rubber is widely available in Indonesia; most of this rubber is exported. Currently, the demand for rubber for export is declining. Therefore, through the Ministry of Public Works and Housing, the government encourages liquid natural rubber to absorb rubber as a modified asphalt material. The use of liquid natural rubber has benefits where it is easier to mix with asphalt and more homogenous because it is in liquid form (Al-Sabaeei et al., 2019; Visakh et al., 2013; Poovaneshvaran et al., 2020). It also increases the modified asphalt elasticity (Azahar et al., 2021).

Rubber particle size in the range of 0.15 μm to 3 μm (Kohjiya & Ikeda, 2014), the function of rubber in asphalt mixtures can be classified based on the structure or particle size, for particle sizes with a length of 1 mm it can function as an elastic filler, and if the particle size is smaller than 50 nm then these rubber particles can function as nano binders (Wang et al., 2015).

The use of conventional liquid natural rubber (without vulcanization process) can increase the Resilient Modulus of the mixture (Ekwulo & Igwe, 2011; Wen et al., 2017; Abdul Hassan et al., 2019). However, conventional liquid natural rubber (without vulcanization process and with high ammonia content) causes white rubber granules to appear on the pavement surface several years after its use in the field. In addition, the high content of ammonia can interfere with work in the field because of the steam produced. For this reason, the Ministry of Public Works

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and Housing and the Indonesia Rubber Institute modified conventional liquid natural rubber through the vulcanization process into Pre-Vulcanized Liquid Natural Rubber (PVLNR).

Liquid Natural Rubber comes from rubber plantations. This rubber is in liquid form with a milky white colour and high ammonia content to maintain its fluid shape (Prastanto et al., 2018; Ansari et al., 2021). Modifying Liquid Natural Rubber into PVLNR is conducted by mixing natural rubber concentrate with liquid natural rubber dispensing chemical liquid. The content of this depressant consists of activators, accelerators, antioxidants, and sulfur dispersions. The mixing was done at a temperature of 70 °C for 4 hours (Blackley, 1997). PVLNR from the vulcanization process is more stable and stored for up to 300 days (Sasidharan et al., 2004).

The vulcanization process is a systematic process for converting Liquid Natural Rubber into a non-sticky and hard polymer material by adding sulfur, accelerators, antioxidants, and fillers. The chemical process cannot be changed. The mechanical properties of PVLNR increase during the vulcanization process due to cross-linking of the PVLNR chains. Pre-Vulcanized Liquid Natural Rubber has very high resistance to organic solvents with enhanced elastic and flexible properties (Pojanavaraphan & Magaraphan, 2008; Marković & Visakh, 2017). Therefore, developing high-performance thermoplastic materials with improved mechanical properties and low hardness (Bendahou et al., 2010).

One disadvantage of PVLNR is that it increases asphalt viscosity, increasing mixing and compaction temperature to 175 °C (Prastanto et al., 2018; Irfan et al., 2021). Heating asphalt up to 175 °C may accelerate the ageing process of asphalt (Petrauskas & Saleem, 2015). In addition, the application in the field is relatively more complex. Maintain the compaction temperature to remain high; this condition coupled with the distribution of the area where the distance of the AMP is far from the project location, causing the hauling time to increase, thereby increasing the risk of decreasing the temperature of the mixture. From the above background, Warm Mix Asphalt (WMA) technology is used on modified asphalt to reduce the mixing and compaction temperature of the mix.

WMA technology is a method for lowering the mixing and compaction temperature of the asphalt. Technology to lower the production temperature by using various types of organic additives and chemical additives. The use of organic additives such as paraffin wax, Sasobit, Zycotherm used commonly used in the original 60/70 Pen asphalt (Ziari et al., 2015; Norouzi et al., 2021). The broader use of organic additives in stone matrix asphalt (SMA) mixtures effectively reduces the production temperature. Although the use of these organic additives has different effects on modulus performance and rutting resistance, each of these additives has its advantages (Ameli et al., 2020). For WMA, which uses rubber-modified asphalt and other polymer types, it is more suitable to use chemical additives, such as in Yang et al. (2017), Wang et al. (2018) research.

Chemical additives such as Evotherm and Rediset LQ effectively reduce production temperature, increasing the Resilient modulus and Rutting resistance of the WMA modified crumb rubber. The Rediset LQ is a combination of surfactants (surface active agents) and organic additives (Rheology Modifier) (Kheradmand et al., 2014). Surfactants are surface-active ingredients, that work to lower the surface tension of liquids. This active property is from the dual nature of the molecules. The surfactant part of this product (such as chemical additives) reduces the surface tension of the asphalt binder (Banerjee et al., 2012). Surfactants are surface-active materials that work to lower the liquid's surface tension. This active property from the dual nature of the molecule; the surfactant portion of this product (such as chemical additives) reduces the surface tension of the asphalt binder (Bennert et al., 2011). As a result, it reduces the interfacial friction between the thin films of the asphalt binder and aggregates (Capitão et al., 2012). It improves the coating of aggregates by asphalt binders (Banerjee et al., 2012) while the organic part reduces the viscosity of the asphalt binder and provides a lubricating effect for easier coating and compaction (Kheradmand et al., 2014). The use of chemical additives in the WMA mixture using PVLNR modified asphalt is still limited, so it is necessary to evaluate the performance of the mixture.

Workability is defined as the ease of placing the asphalt mixtures on the road's surface, ease of working by hand, and compaction of asphalt mixtures to the desired mat density (Bennert et al., 2010). The advantage of warm mix asphalt is its better workability, making it possible for compaction to at lower temperatures. Based on information from suppliers and contractors, the advantages and workability of warm mix asphalt are: (a) reduced risk of not achieving density due to weathering and asphalt hardening (polymer modified asphalt, use of RAP) and (b) potential for reducing the number of tools used for the compaction process in the field. These are essential reasons (Kristjánsdottir et al., 2007).

This study aims to evaluate the performance of the warm mix asphalt modified with PVLNR at a lower mixing and compaction temperature of 30 °C, using the Rediset LQ additive WMA technology. The percentage of Rediset LQ usage is 0.25%, 0.5%, 0.75% (from asphalt weight), and the rate of PVLNR usage is 3% (from asphalt weight).

1. Materials and methods

1.1. Aggregates

The aggregate used was from Karawang Regency, West Java Province, Indonesia. The test results are shown in Table 1.

The gradation design referred to the Bina Marga General Specifications for Asphalt Concrete – Binder Course (AC-BC) gradation type (Ditjen Bina Konstruksi, 2018). The gradation design used the middle boundary in the Fuller curve, as shown in Figure 1.

Table 1. Aggregate properties

Test	Test Method	Aggregate	
		Course	Fine
Specific Gravity	ASTM C127-84 (American Society for Testing and Materials [ASTM], 2015)	2.619	2.656
Water Absorption (%)	ASTM C127-84 (ASTM, 2015)	1.763	0.732
LA Abrasion (%)	ASTM C131 (ASTM, 2001)	5.12	–
Flakiness and Elongation (%)	ASTM D4791 (ASTM, 1999)	7.2	–

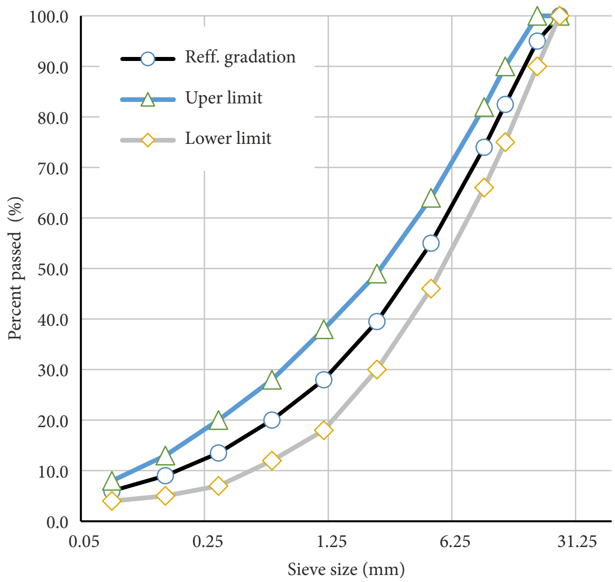

Figure 1. Gradation curve (Bina Marga, 2018)

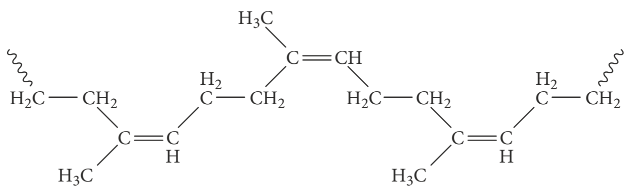

Figure 2. Chemical structure of Liquid Natural Rubber (Marković & Visakh, 2017)

Figure 3. Pre-Vulcanized Liquid Natural Rubber (PVLNR)

Figure 4. Rediset LQ

1.2. Pre-Vulcanized Liquid Natural Rubber

Liquid Natural Rubber is generally known as cis-1,4-poly (isoprene) with a chemical structure, as shown in Figure 2. Pre-Vulcanized Liquid Natural Rubber (PVLNR) is a modification of conventional liquid natural rubber, mainly used as an asphalt modification material. Indonesia Rubber Institute Bogor produces PVLNR. The type of this rubber is shown in Figure 3.

1.3. Rediset LQ

The type of Rediset LQ used was the Rediset LQ 1106 in a liquid form with an Amine content of 540–640 mgKOH/g and 1% water (AzokNobel, 2015a). The Rediset LQ type is shown in Figure 4.

1.4. Asphalt Pen 60/70

The original used in this research was the Pen 60/70 Asphalt from PT Pertamina (Table 2). This type of asphalt is generally used pavement material in Indonesia.

1.5. Preparation of binder modification

Asphalt modification was made in ITB Laboratory with the wet mix method. There were three types of asphalt modified: the PVLNR modified Asphalt, Rediset LQ modified Asphalt, and Rediset LQ and PVLNR Modified Asphalt.

Asphalt modification with PVLNR was done by adding PVLNR to hot asphalt using a mixer with a speed of 2000 rpm for 20 minutes at a temperature of 150 °C. PVLNR was added slowly to hot asphalt gradually to reduce foam from water evaporation. The standard for this modified asphalt referred to Laston interim special specifications for asphalt with rubber (SKh-1.6.25) (Kementerian Pekerjaan Umun Direktorat Jenderalbina Marga, 2018) and General specification (Bina Marga, 2018).

Table 2. Original asphalt aditif Rediset LQ

	Properties	Original Asphalt Additives Rediset LQ		Standard	Binamarga Spesification for WMA
		0%	0,50%		
Original binder	Penetration (0,1 mm)	63.2	61.0	SNI 2456:2011 (National Standardization Agency, 2011a)	55–68
	Softening point (°C)	49.65	49.2	SNI 2434:2011 (National Standardization Agency, 2011b)	≥48
	Ductility @ 25 °C (cm)	≥100	≥100	SNI 2432:2011 (National Standardization Agency, 2011d)	≥100
	Flash point (°C)	248	233	SNI 2433:2011 (National Standardization Agency, 2011e)	≥232
	Solubility in C_2HCl_3 (%)	99.92	99.91	AASHTO T 44-14 (American Association of State and Highway Transportation Officials [AASHTO], 2018)	≥99
	Specific grafity	1.040	1.040	SNI 2441:2411 (National Standardization Agency, 2011c)	≥1.0
RFTO	Weight loss RFTO (%)	0.0030	0.0250	SNI 06-2441-1991 (National Standardization Agency, n.d.)	≤0.8
	Penetration RFTO (%)	80.4	79.4	SNI 2456:2011(National Standardization Agency, 2011a)	≥54
	Ductility RFTO (cm)	≥ 100	≥ 100	SNI 2432:2011 (National Standardization Agency, 2011d)	≥50

Rediset LQ modified asphalt using a mixer with a low speed of 500 rpm for 5 minutes at a temperature according to the target mixing temperature (Hamzah et al., 2015; Martinho et al., 2017; Wen et al., 2002).

Rediset LQ and PVLNR modified asphalt was done by mixing PVLNR with asphalt. Then, the mixture with Rediset LQ (Yu et al., 2017; Bressi et al., 2019).

1.6. Asphalt mix performance test

The mixed test includes the mix workability test, Resilient Modulus test, and Rutting test. The used tool can be found in Figures 5a, 5b and 5c.

The Marshall parameters determined the optimum binder content (OBC) following the General specification (Bina Marga, 2018). The estimated range of asphalt content was determined using the formula for the design asphalt content (Pb), and we obtained a value of 5.25%. The Marshall test to get the percentage of OAC with a varied range of 4.5%, 5%, 5.5%, 6%, and 6.5% was used, the value-added with ± 0.5% with a range of 6%.

The workability test uses a Marshall compactor. This test aimed to determine the percentage of optimum additive use and the optimum temperature reduction. Workability test by simulating compaction at the same number of collisions was done, namely 2×75 collisions, then a volumetric evaluation of the mixture was carried out. Mixtures with equivalent volumetric values were used to have equivalent workability. Trials on each mixture with the percentage of Rediset additive 0.25%, 0.5%, and 0.75% were performed. The optimum temperature drop at 30 °C from conventional HMA and HAR mixture. Workability testing refers to the General specification (Bina Marga, 2018). Bennert et al. (2010) conducted a mixture temperature trial on a WMA mixture using a Marshall compactor to determine the optimum mixing and compaction temperature and the optimum percentage of Rediset additive.

The Resilient Modulus test used the Universal testing machine (UTM). This test refers to the ASTM D4123 – *Standard test method for indirect tension test for resilient modulus of bituminous mixtures* (ASTM, 1995). Horizon-

a) Gyratory compactor b) UTM mechine c) HWT mechine

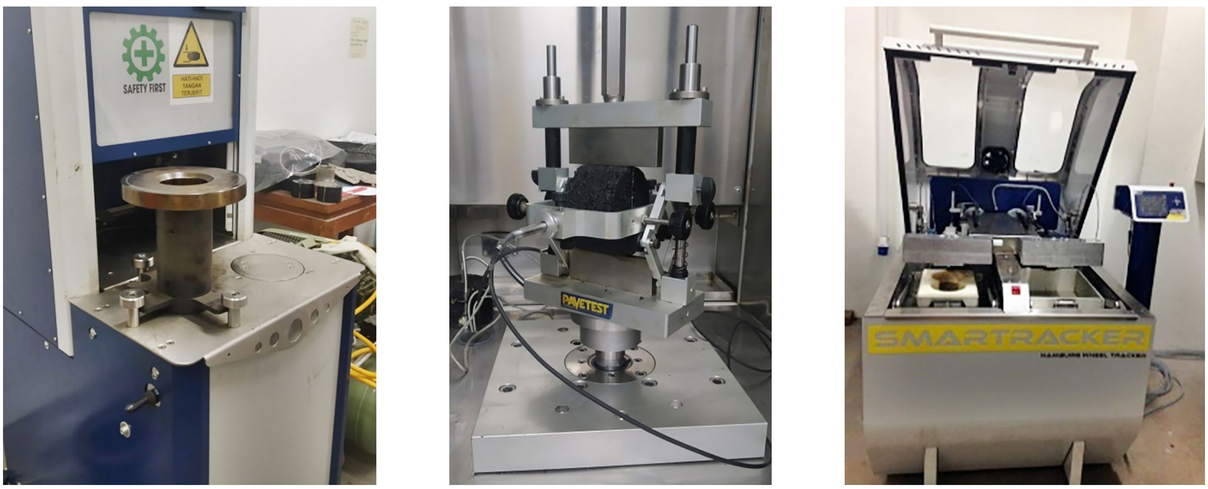

Figure 5. Gyratory compactor, UTM machine and HWT machine

tal deformation measurements on two sides of the sample with a diameter of 100 mm were performed. The test conditions: at loading pulse width 250 ms, pulse repetition period 3000 ms – test temperatures at 20 °C, 30 °C, 41 °C, and 50 °C. The 1200 gram mixture sample was compacted using a Gyratory compactor, referring to the standard AASTHO T 312 – *Standard method of test for preparing and determining the density of asphalt mixture specimens by means of the duperpave gyratory compactor* (AASHTO, 2013). The density of each mixture refers to the results of the previous volumetric analysis.

The Rutting test used the Hamburg Wheel Tracking (HWT) machine. This test referred to the standard AASHTO T 324-04 – *Standard method of test for Hamburg Wheel-Track testing of compacted Hot-Mix Asphalt* (*HMA*) (AASHTO, 2017). The sample was a cylinder size of 20 inches and a thickness of 5 inches which was compacted using a Superpave Gyratory Compactor (SGC). Gyratory compaction referred to the standard AASTHO T 312 (AASHTO, 2013). The test temperature set at 50 °C, with a maximum number of passes of 20000 and a maximum Rutting depth of 20 mm.

1.7. Description of asphalt mixture

This research made four mixture types based on modified asphalt, shown in Table 3 below.

Table 3. Description of mixture

Sample ID	PVLNR (%)	Rediset LQ (%)
HMA	–	–
HAR	3	–
WMA	–	0.5
WAR	3	0.5

2. Results and discussion

2.1. PVLNR modified asphalt

The original asphalt used in this research was 60/70 Pen Asphalt produced by PT. Pertamina. Next, this asphalt was modified using PVLNR and Rediset LQ. Each type of asphalt and modified asphalt referred to General specification (Bina Marga, 2018) and Laston interim special specifications for asphalt with rubber (SKh-1.6.25) (Kementerian Pekerjaan Umun Direktorat Jenderalbina Marga, 2018).

The Rediset LQ additive added to the original asphalt makes the asphalt harder so that the penetration decreases (Table 3). Likewise, the softening point of asphalt decreases so that asphalt becomes more sensitive to changes in temperature. The decrease in asphalt viscosity supports lower mixing and compaction temperatures. The decrease in penetration is associated with an increase in the stiffness of the mixture.

The PVLNR reduces asphalt penetration because the asphalt becomes harder, softening points increase, asphalt is more resistant to temperature changes (Table 4). The decrease in penetration and the increase in softening point is due to the PVLNR particles well dispersed into the asphalt liquid. With the addition of PVLNR into hot asphalt at a temperature of 150 °C, the asphalt begins to melt, and the rubber particles begin to expand. The rubber particles then absorb the asphalt, making the asphalt harder.

The addition of Rediset LQ on PVLNR modified asphalt reduces penetration and is followed by lowering softening points (Table 4). Compared with the Rediset LQ additive original asphalt, the PVLNR modified asphalt has a lower penetration value and higher softening points. The high softening point value illustrates better resistance to temperature changes when compared to the Rediset LQ additive original asphalt. Meanwhile, the decrease in viscosity contributes to a decrease in the mixing temperature.

Table 4. PVLNR modified asphalt additive Rediset LQ

	Properties	PVLNR Modified Asphalt Additives Rediset LQ				Standard	Bina Marga Specification for WMA
		0%	0.25%	0.50%	0.75%		
Original Binder	Penetration (0.1 mm)	60.8	60.4	59.7	59.3	SNI 2456:2011 (National Standardization Agency, 2011a)	55–68
	Softening point (°C)	51.8	51.5	51.2	50.9	SNI 2434:2011 (National Standardization Agency, 2011b)	≥48
	Ductility @ 25 °C (cm)	≥100	≥100	≥100	≥100	SNI 2432:2011 (National Standardization Agency, 2011d)	≥100
	Flash point (°C)	323	318	312	308	SNI 2433:2011 (National Standardization Agency, 2011e)	≥232
	Solubility in C_2HCl_3 (%)	99.72	99.72	99.75	99.79	AASHTO T 44-14 (AASHTO, 2018)	≥99
	Specific Grafity	1.033	1.033	1.033	1.032	SNI 2441:2411 (National Standardization Agency, 2011c)	≥1.0
RFTO	Weight loss (%)	0.000	0.014	0.017	0.021	SNI 06-2441-1991 (National Standardization Agency, n.d.)	≤0.8
	Penetration RFTO (%)	85.3	85.8	86.2	86.7	SNI 2456:2011 (National Standardization Agency, 2011a)	≥54
	Ductility RFTO (cm)	≥100	≥100	≥100	≥100	SNI 2432:2011 (National Standardization Agency, 2011d)	≥50
	Elastic Recovery (%)	55.0	58.0	60.0	61.0	AASHTO T 301-98 (AASHTO, 1998)	

From Table 3 and Table 4, PVLNR modified asphalt has an increasing Elastic Recovery. The Rediset LQ additive further enhances the Elastic Recovery of the PVLNR modified asphalt. The increase in elastic recovery is influenced by the presence of rubber particles that absorb the asphalt liquid (solvent), that rubber particles expand (swelling ratio) 7 to 15 (Sasidharan et al., 2004; Farouk et al., 2017). In addition, the bonding process between rubber particles with asphalt increases the elastic recovery of modified asphalt (Wang et al., 2015). Rediset LQ additive increases asphalt absorption into rubber particles by reducing the viscosity of PVLNR modified asphalt.

2.2. Viscositas PVLNR Modified Aspal aditif Rediset LQ

Asphalt viscosity test using Sybolt Furol determines the mixing and compaction temperature for the PVLNR modified asphalt with the Rediset LQ additive. The mixing temperature is at a viscosity of 170 cSt, and the compaction temperature is at 280 cSt.

Figure 6 shows that the addition of Rediset LQ to Asphalt reduces the viscosity and makes the asphalt more liquid. Adding Rediset LQ up to 0.5 % can reduce the mixing temperature (170 cSt) from 8 °C to 154 °C and the compaction temperature (280 cSt) from 7.2 °C to 144.8 °C.

The decrease in temperature from the viscosity test has not reached the target for decreasing the mixing and compaction temperature. However, according to the specifications and brochure information from the distributor, Rediset LQ 0.5% can reduce the mixing and compaction temperature by up to 22 °C to 33 °C compared to conventional HMA (AzokNobel, 2015b).

From the results of previous tests, applying warm mix asphalt (WMA) technology to polymer modified asphalt of the type of crumb rubber can reduce the mixing temperature by 22 °C to 30 °C (Yang et al., 2017; Leng et al., 2017). Likewise, using 0.5% Rediset LQ additive in asphalt Pen 60/70 can reduce the mix temperature to 30 °C (Irfan et al., 2021). However, a further test is necessary, which is the workability test of the mixture using a marshall compactor (Maha et al., 2015; Irfan et al., 2020).

2.3. Workability of mixture

Workability testing by evaluating the volumetric mixture of WMA and WAR with a variation of the percentage of Rediset LQ 0.25%, 0.5% and 0.75% with a large decrease in mixing temperature of 30 °C under HMA and HAR control was performed (Figure 7). Volumetric values for WMA and WAR refer to HMA control.

The Rediset LQ additive add to the original asphalt makes the asphalt harder so that the penetration decreases (Table 3). Likewise, the softening point of asphalt decreases so that asphalt becomes more sensitive to changes in temperature. The decrease in asphalt viscosity supports lower mixing and compaction temperatures. The decrease in penetration is associated with an increase in the stiffness of the mixture.

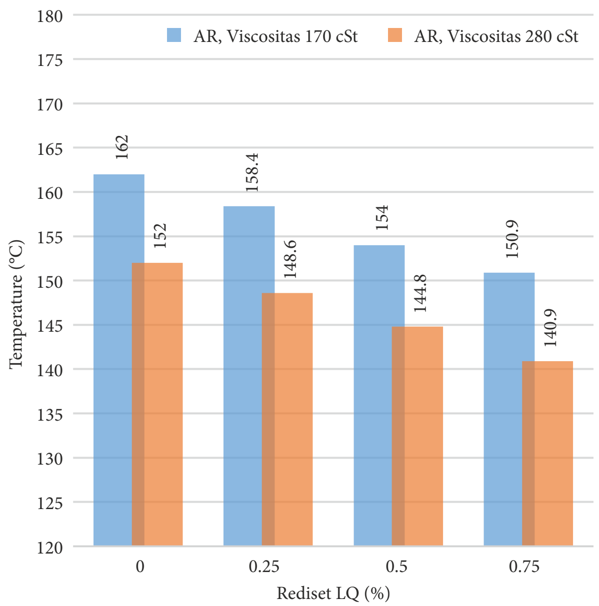

Figure 6. Temperature at viscosity of 170 cSt and 280 cSt of PVLNR modified asphalt in variant percent of Rediset LQ

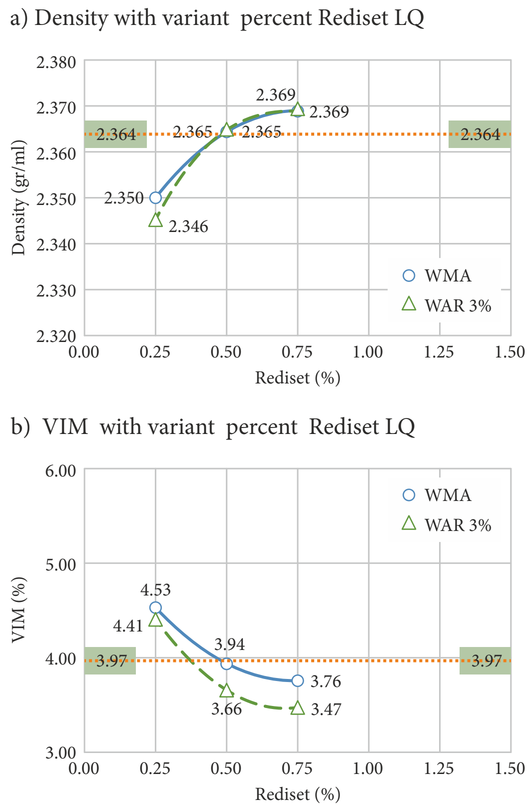

Figure 7. Density and VIM with variant percent of Rediset LQ

Table 4 shows that adding PVLNR to asphalt makes asphalt harder because it reduces asphalt penetration and asphalt softening points increase, so the asphalt is more resistant to temperature changes. The decrease in penetration and the increase in softening point is due to the PVLNR particles well dispersed into the asphalt liquid.

According to Table 4, the Rediset LQ on PVLNR modified asphalt reduces penetration and is followed by lowering softening points. Compared with the original Rediset LQ additive asphalt, the modified PVLNR asphalt has a lower penetration value and higher softening points. The high softening point value illustrates better resistance to temperature changes when compared to the original Rediset LQ additive asphalt. Meanwhile, the decrease in viscosity contributes to a decrease in the mixing temperature.

From Table 3 and Table 4, PVLNR modified asphalt has an increasing Elastic Recovery. The Rediset LQ additive further enhances the Elastic Recovery of the PVLNR modified asphalt. The increase in elastic recovery is influenced by the presence rubber particles that absorb the asphalt liquid (solvent) so that these rubber particles expand. Therefore, PVLNR contributes to increasing the elastic recovery of modified asphalt. Rediset LQ additive increases asphalt absorption into rubber particles by reducing the viscosity of PVLNR modified asphalt.

2.4. Volumetric properties

Volumetric properties were by analyzing the Marshall sample against a mixture of HMA, HAR, WMA, WAR with a range of variations in the use of asphalt from 4.5% to 6.5%. In order to obtain the Optimum Binder Content (OBC) percentage and the optimum Volumetric value, as shown in Table 5.

Figure 8 shows the PVLNR in hot mix asphalt, increasing the Optimum Binder Content (OBC) 5.5% (for HMA) to 5.58% (for HAR) with a significant increase of 1.45%. For warm mix asphalt, the percentage of asphalt use increased from 5.45% (for WMA) to 5.52% (for WAR), with a significant increase of 1.28%. The magnitude of the increase in asphalt used for both hot mix and warm mix asphalt is almost equal. The percentage of asphalt used is

Table 5. Volumetric properties of all mixtures

No	Properties	HMA	HAR	WMA	WAR
1	OBC (%)	5.5	5.58	5.45	5.52
2	Density (gr/ml)	2.364	2.359	2.363	2.365
3	VIM (%)	3.97	4.15	3.89	3.94
4	VFA (%)	73.59	72.80	73.51	73.76
5	VMA (%)	15.02	15.26	15.00	14.99

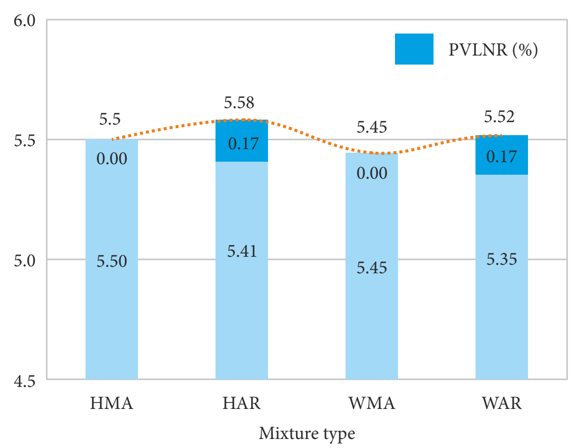

Figure 8. Asphalt needs variant mix

sensitive to the percentage of PVLNR content. So with the same PVLNR percentage (3% of the asphalt weight), the increase in asphalt use is almost equivalent.

Especially for the HAR mixture, the total asphalt requirement (OBC) will increase with an increase in the percentage of PVLNR. The higher the percentage of PVLNR, the more PVLNR particles are distributed. These PVLNR particles will absorb the asphalt liquid (solvent), making the asphalt thicker and more complex, so more asphalt is needed to cover the aggregate. Although the OBC increased, there has been a saving in the use of asphalt; because PVLNR can substitute asphalt in the mixture, there is a saving in asphalt use 0.17%.

Rediset LQ is more influential in equalizing the use of asphalt in the WAR mixture so that the OBC WAR value becomes equivalent to HMA and WMA, with equal volumetric values. By considering the substitution of the use PVLNR, then for the WAR mixture, the asphalt saving is increased by 2 (two) times, to around 0.34%.

2.5. Resilient Modulus

Resilient Modulus is the ability of the asphalt mixture to accept loading with conditions that remain elastic measured by the ratio of the size of loading and recoverable stress. The modulus test results are shown in Figures from 9a to 9d.

Percentage of PVLNR increases the resilient modulus hot mix asphalt (HMA and HAR) and warm mix asphalt (WMA and WAR) (Figure 9).

For hot mix asphalt (HMA and HAR), the Resilient Modulus increases by 8.2%, 19%, 22.2%, 69%, and 107%, at temperatures test 20 °C, 30 °C, 41 °C, and 50 °C, respectively. This Resilient Modulus increase by rubber particles content of which are well dispersed in the asphalt, thereby increasing the adhesion of asphalt and increasing the stiffness of the mixture. The Resilient Modulus increases at low, medium, and high temperatures.

The Resilient Modulus increase for each temperature is 2.4%, 18%, 34%, 48%, and 87% for warm mix asphalt (WMA and WAR). The Resilient Modulus WAR is lower compared to HAR. Resilient Modulus WAR is influenced by Rediset LQ, which reduces the softening points and viscosity of the asphalt to become more sensitive to temperature changes. Resilient Modulus WAR is better than the HMA control, evidence that PVLNR affects the WAR mixture's stiffness. The Resilient Modulus WAR increase for each test temperature was 6%, 13%, 8%, 29%, and 45.7% compared to the HMA control.

The increased percentage of PVLNR in the mixture of HAR and WAR makes the modified asphalt harder, thicker, and more elastic; this can be seen from the penetration value, softening point, and viscosity modified asphalt. This thicker rubber modified asphalt produces a thick asphalt film; this thick asphalt film can help better increase the adhesion between aggregates with asphalt and between asphalt. In addition, the release of grains in the asphalt mixture can be reduced, thereby increasing the stiffness of the mixture.

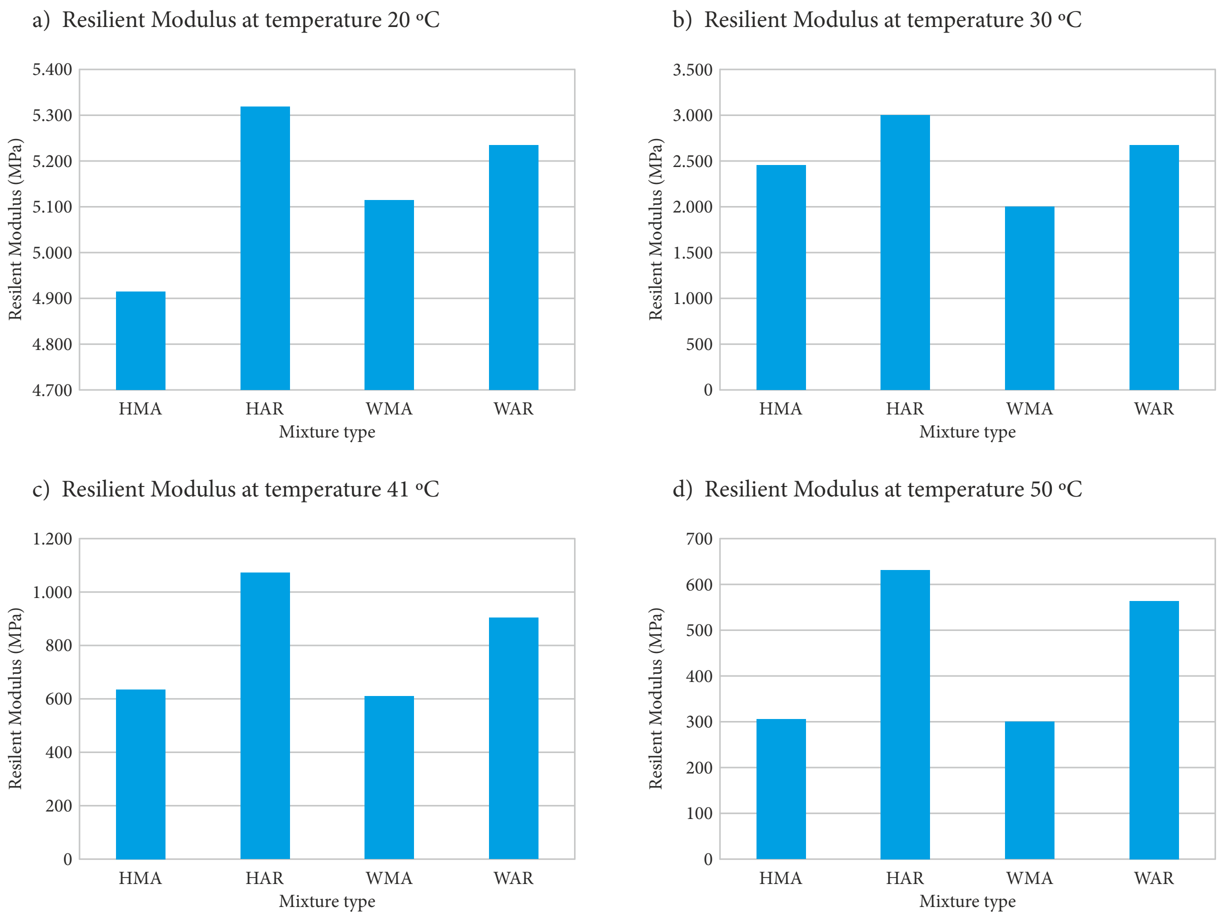

Figure 9. Modulus resilient HMA, WMA, WAR at temperature 20 °C, 30 °C, 41 °C and 50 °C

2.6. Hamburg Wheel Tracking Test

The Rutting test used the Hamburg Wheel Tracking (HWT) machine. This test can detect the resistance to premature failure of asphalt mixtures caused by weak aggregate structure, insufficient binder stiffness, moisture damage, and inadequate adhesion between aggregate and binder (Al-Khateeb & Basheer, 2009; Zhou et al., 2004; Yin et al., 2014; Du et al., 2018). The Rutting test using the Hamburg Wheel Tracking (HWT) can be seen in Figure 10.

As it can be seen from Figure 10, PVLNR increases the rutting resistance of hot mix asphalt (HMA and HAR) and warm mix asphalt (WMA and WAR).

For hot mix asphalt (HMA and HAR), the number of passes increased by 35% (passed/mm) to reach the Stripping Inflection Point (SIP). The maximum number of passes (striping phase) increased 28%, with Rutting resistance increased by 5.4%. PVLNR modified asphalt in warm asphalt mixes increases the Rutting resistance of the mixture. This condition indicates that the content of rubber particles is well dispersed into the asphalt, increasing adhesion and better cohesion. The increase in asphalt adhesion is related to the asphalt's ability to bind aggregates, resulting in a good bond between the aggregates and asphalt. In contrast, the increase in asphalt cohesion is related to the bonds between asphalt molecules to hold the aggregates in place after binding.

The percentage of PVLNR increases the Rutting resistance for warm mix asphalt (WMA and WAR). To reach the Stripping Inflexion Point (SIP), the number of passes increased by 25% (passed/mm) to reach the Stripping Inflection Point (SIP). The maximum number of passes (striping phase) increased 20%, with a Rutting resistance of 6.2%. The increased Rutting resistance of the WMA and WAR mixture (at a lower mixing temperature of 30 °C), influenced by the Rediset LQ additives, effectively increased the volumetric mixture of WMA and WAR has an optimal density. In addition to the rheological characteristics of asphalt, this good density can increase the mixture's resistance to Rutting.

The Rutting resistance of the WAR mixture is smaller than that of HAR, influenced by the Rediset LQ, which reduces the softening points and viscosity of the asphalt so that the asphalt is more sensitive to high temperatures. However, when compared to the control HMA, the Rutting resistance was. In addition, the number of passes to reach the Stripping Inflection Point (SIP) increased 18% (passed/mm), and the maximum number of passes (striping phase) increased 13% with resistance to Rutting of 4.3% compared to HMA control.

PVLNR modified asphalt can improve thermal stability at low temperatures. Because the molecular structure of natural rubber functions as a membrane in rubber asphalt, it can resist the propagation of cracks. Meanwhile,

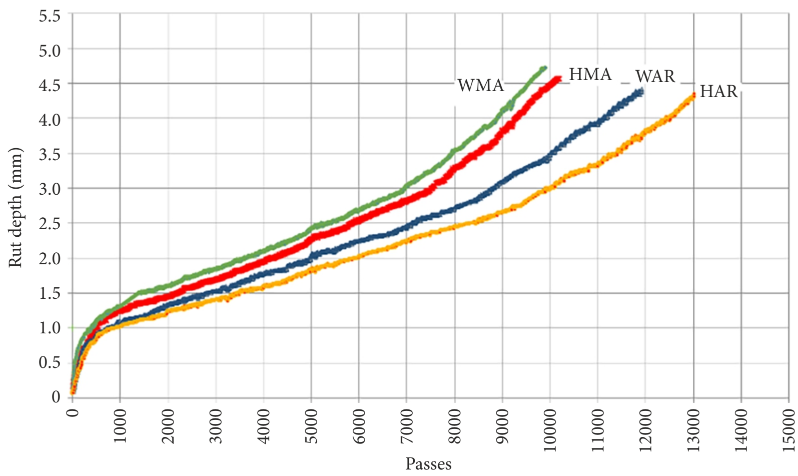

Figure 10. Hamburg Wheel Tracking Test for HMA, WMA, HAR, and WAR

at high temperatures, the properties of the asphalt become more dilute. Still, the polymeric properties of the rubber asphalt inhibit the flow of asphalt, thereby increasing the resistance of the asphalt mixture to deformation.

2.7. Statistical analysis

Statistical analysis of the test results was conducted to determine the most influencing factors for Permanent Deformation. An ANOVA analysis with a significance level of 5% was performed using the SPSS program. The experimental parameters consisted of mixtures Resilient Modulus and Volumetric, VIM and VFA. Statistical analysis was performed to test the feasibility of the null hypothesis, which is the assumption that there is no difference in the value of the Resilience Modulus and the Volumetric to Permanent Deformation. Because the p-value < 0.05, the null hypothesis is rejected. Anova results are shown in Table 6, Table 7 and Table 8. The S_{mix} (Modulus Resilient Mix) variables significantly affect permanent deformation assuming p-value < 0.05, then H0 (zero hypotheses) is rejected. The S_{mix} variable has more effect on deformation compared to volumetric properties. VIM and VMA have no impact on mixtures deformation, which means that p-value > 0.05, Ho is accepted. From this ANOVA analysis, a model equation for the Permanent Deformation of the asphalt mixture can later be developed using the mixed Resilient Modulus (S_{mix}) parameter.

Table 6. Anova – Resilient modulus mix

ANOVA					
	Sum of Sq	df	Mean Square	F	Sig.
Smix	1678040.380	1	1678040.380	190.413	0.000
Residual	52875.800	6	8812.633		
Total	1730916.180	7			

Table 7. Anova – VIM

ANOVA					
	Sum of Sq	df	Mean Square	F	Sig.
VIM	201131.101	1	201132.101	0.789	0.409
Residual	1529784.079	6	254964.013		
Total	1730916.180	7			

Table 8. Anova – VMA

ANOVA					
	Sum of Sq	df	Mean Square	F	Sig.
VMA	146359.789	1	146359.789	0.554	0.485
Residual	1584556.391	6	264092.732		
Total	1730916.180	7			

Conclusions

The use of PVLNR in the original 60/70 Pen makes the asphalt harder and viscous. As a result, the softening point and viscosity increase, increasing the recovery elasticity, making the asphalt more resistant to temperature changes. Rediset LQ additive reduces softening point and viscosity and further enhances the elastic recovery of modified asphalt.

PVLNR can substitute asphalt so that asphalt can be saved by 0.17%. The use of the Rediset LQ additive increases the savings in asphalt usage approximately twofold.

The Resilient Modulus and Rutting resistance of the mixture of HAR and WAR is better than HMA and WMA, influenced by PVLNR and Rediset LQ additives.

The Modulus of elasticity and deformation resistance is influenced by the PVLNR content, which increases the elasticity of the asphalt, increases the adhesion and cohesion of the modified asphalt, thereby binding between the aggregates, thereby inhibiting the aggregate.

The use of WAR technology provides an advantage to reduce the risk of asphalt damage due to high mixing temperatures (up to 175 °C) and construction failure in the field due to high compaction temperatures (up to 165 °C). High temperatures are difficult to achieve in the field because of the transportation process.

The statistical analysis results show that the Smix variable has more effect on deformation than volumetric properties (VIM and VMA).

The right combination of the percentage of PVLNR usage and the Rediset LQ additive creates a new balance in the asphalt mix. PVLNR, which can increase the Resilient Modulus and resistance of the mixture to deformation but with the side effect of increasing the production temperature, can be covered by the Rediset LQ additive, which can reduce the production temperature of the mixture but with the effect of decreasing the performance of the mixture.

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