Civil Engineering and Architecture 13(3): 1647-1655, 2025 http://www.hrpub.org
DOI: 10.13189/cea.2025.130315

Rutting Resistance of Agricultural-Waste-Plastic Based Modified Bitumen

Tri Sudibyo[1,2,*], Sutoyo[1], Chusnul Arif[1], Erizal[1], Fardzanela Suwarto[3]

[1]Department of Civil and Environmental Engineering, IPB University, Indonesia
[2]Professional Engineer Program, IPB University, Indonesia
[3]Department of Civil and Planning, Diponegoro University, Indonesia

Received December 10, 2024; Revised February 10, 2025; Accepted March 17, 2025

Cite This Paper in the Following Citation Styles

(a): *[1] Tri Sudibyo, Sutoyo, Chusnul Arif, Erizal, Fardzanela Suwarto , "Rutting Resistance of Agricultural-Waste-Plastic Based Modified Bitumen," Civil Engineering and Architecture, Vol. 13, No. 3, pp. 1647 - 1655, 2025. DOI: 10.13189/cea.2025.130315.*

(b): *Tri Sudibyo, Sutoyo, Chusnul Arif, Erizal, Fardzanela Suwarto (2025). Rutting Resistance of Agricultural-Waste-Plastic Based Modified Bitumen. Civil Engineering and Architecture, 13(3), 1647 - 1655. DOI: 10.13189/cea.2025.130315.*

Abstract Rutting is a common issue in heavily trafficked roads, which can lead to further unrecoverable permanent deformation. This distress commonly occurs on roads with low-speed traffic and high-temperature environments. A better rutting resistance pavement is favorable because it will require lower maintenance and thus be more economical and ecologically friendly. The utilization of agricultural waste plastic (AWP) as a modifier for bitumen in road construction presents a sustainable solution for both plastic waste management and road durability enhancement. This study investigated the effect of incorporating agricultural waste plastics into bitumen using a low shear mixing method. The primary objective of this study is to assess the impact of agricultural plastic waste on the rutting resistance of modified bitumen. The modification process was carried out at a temperature of 160-180 ℃ and a mixing speed of 500 rpm. Four types of bitumen were used in this study: standard 60/70 pen bitumen and 6% AWP-modified bitumen at three different shear mixing durations. Standard test results indicated that the inclusion of agricultural waste plastic dramatically changed the rheological properties of bitumen in terms of penetration number and R&B softening point. A further in-depth observation of the rheological properties of bitumen shows its enhanced capability in preventing potential rutting damage compared to conventional bitumen. The modified bitumen exhibited a higher complex modulus (G*) and lower phase angle (δ) at reduced frequency. The master curves explain the changes in the modification effect with temperature. The improved performance under higher temperatures and stress conditions or increased stiffness and elastic recovery can be attributed to the successful modification by agricultural waste plastic.

Keywords Polymer-Modified Bitumen, Polyethylene, Agricultural Waste Plastic, Low Shear Mixing

1. Introduction

Pavement deterioration is a widespread issue that affects the durability and performance of road infrastructure globally. Roads are subject to various forms of damage, such as cracking, rutting, and potholing, which are often exacerbated by extreme weather conditions and heavy traffic loads. In regions with fluctuating temperatures, roads may suffer from thermal cracking, whereas in hot climates, rutting due to permanent deformation under load is common. Additionally, heavy traffic, especially from large vehicles, accelerates these damages, leading to frequent and expensive maintenance. Ensuring long-lasting pavements under such conditions requires innovative solutions that can enhance asphalt properties and mitigate these common forms of failure.

The global plastic waste crisis is a pressing environmental challenge, with millions of tons of plastics generated annually. Agricultural industries contribute significantly to this problem, as they rely heavily on plastic products for packaging, mulching, and irrigation systems. These plastics, once discarded, contribute to long-lasting pollution owing to their non-biodegradable nature. Addressing this issue requires sustainable methods for plastic waste disposal and reuse. Recycling agricultural plastic waste into value-added products presents a promising approach to mitigating environmental pollution while providing new functionalities in other industries, such as construction [1].

The use of polymer modification in asphalt has emerged as an effective strategy for enhancing the performance of pavement materials. Polymers, particularly those derived from plastic waste, have been shown to improve the rheological properties of bitumen, resulting in enhanced resistance to deformation and cracking. By incorporating polymers of waste plastics into bitumen, bitumen can become more resilient to both temperature variations and heavy traffic stresses [2], [3], [4]. Polymer-modified bitumen not only improves the durability and lifespan of pavements, but also provides a practical solution for managing plastic waste, creating a win-win scenario for both infrastructure and environmental sustainability. This study tends to use various waste plastics from agricultural operations as a novel material in bitumen modification. This approach offers both environmental and economic benefits by enhancing bitumen properties while reducing agricultural waste plastic.

2. Materials and Methods

This study utilized standard bitumen and various agricultural waste plastics as primary materials. The laboratory tests included standard bitumen testing, bitumen modification using a shear mixer, and rheological analysis with a dynamic shear rheometer. The detailed material and experimental procedures are outlined in the following subsections.

2.1. Materials and Equipment

This study used a standard 60/70 penetration grade bitumen from Pertamina. Agricultural waste plastics for bitumen modification were gathered from the IPB University educational farm in Bogor, Indonesia. The collected agricultural waste plastics include polybags, seeding trays, and plant pots. Before being used as bitumen modifier, the agricultural waste plastics were thoroughly cleaned with water, dried at room temperature, and cut into small pieces approximately 5 mm × 5 mm × 0.1 mm in size. Figure 1 shows the AWP source and the cleaned and prepared AWP for bitumen modification.

(a) (b)

Figure 1. Pictures of the (a) AWP source and (b) the cleaned and prepared AWP

This study used a multipurpose mixer for bitumen low shear modification, Penetrometer for standard penetration test, Ring and Ball apparatus for softening point test, oven for various heating purposes, and Anton Paar SmartPave 92 Dynamic Shear Rheometer (DSR) for dynamic mechanical analysis of the bitumen.

2.2. Procedure

Following material preparation, the bitumen was modified using the low shear mixing method. The modified bitumen, that is, PMB from agricultural waste plastic or AWP modified bitumen, underwent standard testing for penetration and softening point. Subsequently, dynamic mechanical analysis was performed using a DSR to further evaluate the rheological properties of the modified bitumen.

2.2.1. Modification Process

The modification process was initiated by heating the unmodified bitumen to 160°C. Following the heating, 600 grams of bitumen were measured and poured into the blending container. In this study, 6% of bitumen weight modification by using AWP was chosen based on recent studies in plastic-based bitumen modification [5], [6], [7]. Based on the amount of bitumen poured, 6%wt or approximately 36 grams of AWP were prepared for each mixing batch.

The process of AWP pouring to the bitumen was done gradually at a rate of 20 grams per minute while the shearing speed was set at maximum of 250 rpm and the bitumen temperature was maintained at 170 ℃. Once the AWP was added to the bitumen, the shear mixings were started at 170±10°C, 500 rpm speed, for duration variation of 60, 90 and 120 minutes. The AWP based polymer modified bitumen products were labelled as AWP60, AWP90 and AWP120 for 60, 90 and 120 minutes low shear mixing process, respectively. As a control, the unmodified bitumen was also tested similar to the modified bitumen. Figure 2 shows the low shear mixing method of the AWP-PMB, and Figure 3 shows the mixing process by using the mixer equipment.

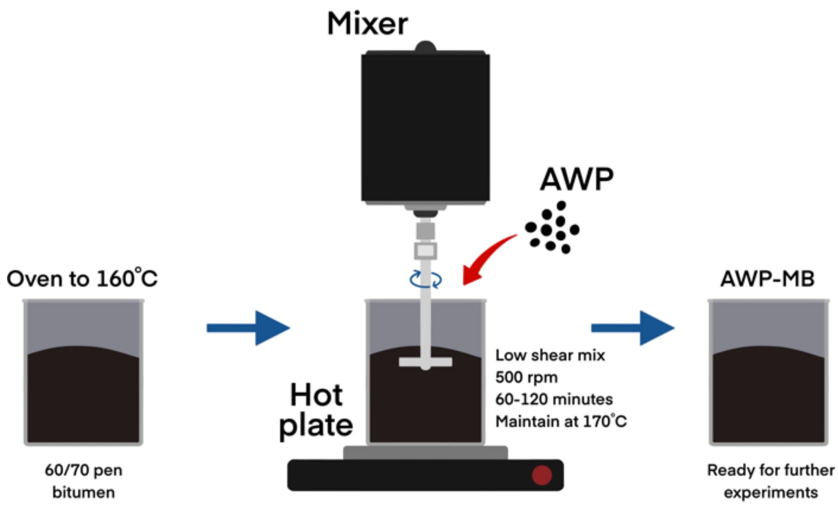

Figure 2. The modification method

Figure 3. The low shear mixing process

2.2.2. Standard Penetration and Softening Point Test

Standard tests of penetration number based on BS EN 1426-2015 and softening point based on BS EN 1427-2015 for unmodified bitumen (unmod) and agricultural waste plastic AWP-modified bitumen (AWP60, AWP90 and AWP120) were conducted. These tests were conducted to initially understand the unmodified and AWP-modified bitumen's basic rheological properties. Studies have stated the general agreement of lower penetration number and higher softening point in the presence of polymeric plastic in modified bitumen [3], [6], [7], [8]. Additionally, in polyethylene-modified bitumen, a common softening point higher results believed as a reflection of the successful modification process [9].

2.2.3. Dynamic Shear Rheometer Tests

Frequency sweep test was carried out to observe a deeper understanding of bitumen rheological properties. The test was done by using 1 mm gap, 25 mm spindle of Anton Paar MCR 92 Dynamic Shear Rheometer, as shown in Figure 4, from 30°C to 70°C with 10°C increments. The test incorporates eleven frequencies at equal log spaces from 0.1 – 10 Hz. Prior to this test, amplitude sweep test was done to ensure the frequency sweep test was conducted within bitumen's linear viscoelastic region. Following this procedure, dynamic mechanical analysis was done to construct complex modulus and phase angle master curves for unmodified and AWP-modified bitumen.

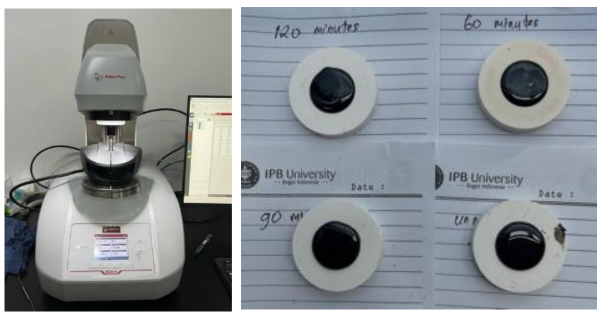

Figure 4. MCR 92 DSR and the 25 mm bitumen samples

3. Results and Discussions

3.1. Penetration Number

There were noticeable differences in penetration number between the unmodified and AWP-modified bitumen as shown in Figure 5. This phenomenon occurs for all modified bitumen regardless the selected mixing duration. The penetration number for the base, unmodified bitumen is 68, while the modified samples exhibit a significant reduction: AWP60 records a penetration number of 25, AWP90 further reduces to 24, and AWP120 achieves the lowest value of 23. In all cases of AWP modified bitumen, a low penetration number explains that the incorporation of AWP into bitumen resulted in stiffer modified bitumen. This condition is attributed to the polymer's ability to form stronger molecular bonds within the asphalt binder. This phenomenon is expected as stated in many previous PMB studies that a plastomeric plastic always tends to harden the modified bitumen product [7], [9], [10].

The modification of bitumen was found to cause polymer particles to swell and disperse, depending on the compatibility between the two materials [11], [12]. The lower penetration numbers of the modified bitumen at room temperature indicated the influence of modifier (AWP's) physical properties on the attributes of the bitumen-polymer system. However, the duration of blending did not significantly affect the physical properties or penetration numbers of the modified product. This suggests that, compared to unmodified bitumen, AWP achieved a superior modification due to its enhanced dispersion and swelling in the bitumen matrix.

This result also indicated that the modified condition can be achieved with AWP modifier in 60 minutes of 500 rpm low shear mixing. Similar condition occurs on the rest modified bitumen, AWP90 and AWP120. These lower penetration numbers indicate the ability of AWP polymer phase's to affect the modified bitumen phase's properties at room temperature 25 ℃.

However, the polymer's effect on the modified bitumen should be more evident at higher temperatures [11], [13]. The relatively similar pen number of AWP60, AWP90 and AWP120 can also explain this statement because the tests were conducted at room temperature. In other words, the room temperature's pen numbers were unable to clearly differentiate the AWP's effects on the polymer and bitumen system. Meanwhile, at elevated temperatures the polymer's mechanical properties become more dominant than those of the bitumen, making their effects easier to observe. As a result, the softening point is regarded as a crucial parameter for gaining a deeper understanding of the impact of this modification.

3.2. Softening Point

As shown in Figure 6, the AWP-modified bitumen's R&B test demonstrates an increase in softening point compared to the original bitumen (unmod). The softening point of the unmodified bitumen was recorded at 52 ℃, whereas the modified bitumen samples demonstrated significant improvements, with AWP60 reaching 76.5 ℃, AWP90 at 69.5 ℃, and AWP120 achieving the highest value of 93 ℃. Figures 5 and 6 clearly illustrate that, as the penetration number decreased, the softening points increased, showing an inverse relationship as expected. Studies have consistently reported a strong correlation between the degree of modification and the softening point in PMB [5], [6], [9]. A higher softening point in AWP modified bitumen, compared to unmodified bitumen, indicates an effective modification blend [9]. This correlation allows the compatibility of polymer blends to be evaluated based on the trend in ring-and-ball softening point results.

The rise in the softening point is primarily attributed to the AWP's physical properties that being inherently resistant to heat [14], thus adding thermal stability to the modified bitumen. However, the variety of modification duration of 60, 90 or 120 minutes has resulted in unclear differences between the modified products. This indicated that 60 minutes of blending duration is sufficient in resulting in the expected PE-based modified bitumen. A longer duration of blending produces insignificant differences in the ability of dispersion between the modifiers to the bitumen. With this modification process, the AWP polymer in the bitumen blend enhances its stiffness and stability to withstand higher temperatures, resulting in a higher softening point.

This result reflected typical characteristics of significantly modified bitumen and indicates the potential advantageous of AWP-modified bitumen for application in high-temperature climates. AWP-modified bitumen results in a more durable material for road paving, as it is less likely to deform under hot conditions compared to unmodified bitumen. This result is in line with conclusions from previous studies in thermoplastic-based modified bitumen [2], [3], [7], [15], [16], [17] that are also supported by changes in the high-temperature complex modulus.

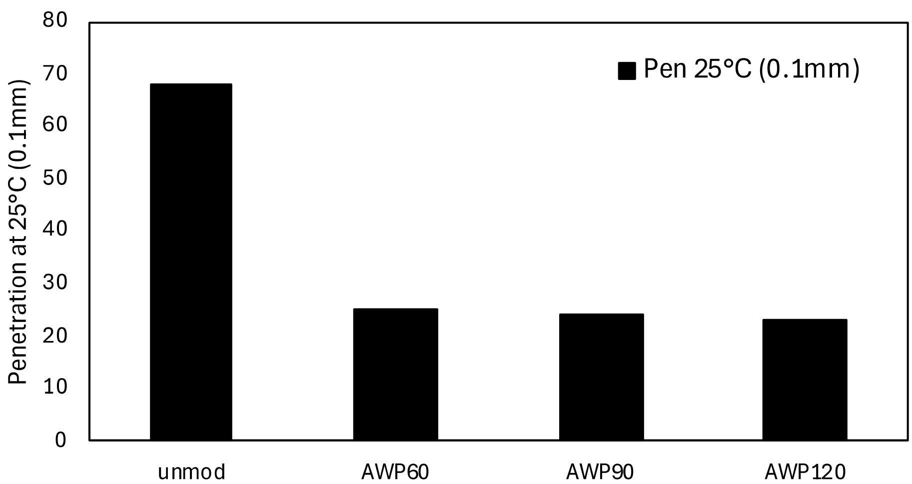

Figure 5. Bitumen's standard penetration test result

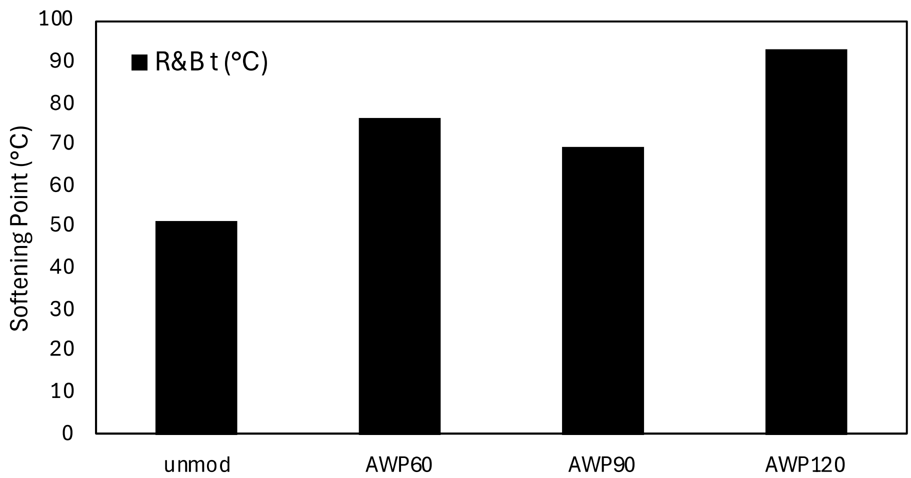

Figure 6. Bitumen's ring and ball softening point test result

3.3. Complex Modulus (G*) Master Curves

The DSR's frequency sweep analysis to unmodified and AWP modified bitumen resulted in the presented rheological data. With time-temperature superposition principles, using 40℃ as shifting factor, the complex modulus and phase angle master curve were constructed as presented in Figure 7 and Figure 8. At reduced frequencies that represent elevated temperatures, the AWP-modified bitumen demonstrates a notably higher G* complex modulus compared to unmodified bitumen. Generally, a higher G* value indicates that the asphalt binder is stiffer and more resistant to deformation, whereas a lower G* value signifies less stiffness and a greater susceptibility to deformation under applied stress [11].

This enhancement is primarily due to the improved viscoelastic characteristics introduced by the polymer of AWP. At high temperature, when the bitumen's structural integrity loosens due to its viscoelastic nature, the polymer's physical properties' effect becomes dominant [11] allowing the increasing complex modulus of the AWP polymer-bitumen matrix system. The polymer increases the stiffness of the bitumen by restricting the mobility of its molecular components. Furthermore, the polymer forms a network within the bitumen matrix, which strengthens the material and improves its ability to resist deformation and dissipate energy. This consistently stable network structure at high temperature provides additional reinforcement. These combined effects enhance the bitumen's capacity to withstand stress, reduce permanent deformation, and maintain performance under various environmental and load conditions.

Meanwhile, at higher reduced frequencies that correspond to low temperatures, the complex modulus curve of all bitumen tends to converge. This condition is due to the fact at the low temperature, the bitumen structure becomes the dominant factor in affecting the bitumen and polymer blend [11], [18]. However, at this point the AWP polymer still also provides factor in the stiffness of the bitumen that can be seen from the decreasing pen number. However, the fundamental dynamic mechanical analysis as presented in the master curves provides insightful explanation that the stiffness observed in AWP at low temperatures does not necessarily indicate a superior complex modulus.

3.4. Phase Angle (δ) Master Curves

The bitumen phase angle represents the time lag between the applied stress and the resulting strain caused by traffic loads. This parameter is significantly influenced by loading frequency and temperature and serves as an indicator of the bitumen's viscosity and elasticity [19]. A lower phase angle indicates higher elasticity in the asphalt binder, whereas a higher phase angle suggests reduced elastic properties.

As shown in Figure 8, the phase angle of AWP modified bitumen decreases at reduced frequencies that correspond to high temperatures compared to unmodified bitumen, indicating a shift towards more elastic behaviour. This result suggests that the incorporation of AWP polymers enhances the bitumen's viscosity and elastic response, resulting in a more elastic and durable material compared to unmodified bitumen. These phenomenon often occurs on thermoplastic based modified bitumen, for example polyethylene [5], [6].

Thus, similar to the commonly known PE-based modified bitumen, the phase angle reduction can be attributed to the AWP polymer's ability to form a more structured and interconnected network within the bitumen matrix. At high temperatures, this network helps maintain structural integrity by resisting viscous deformation, leading to a lower phase angle. Additionally, the interaction between the polymer and bitumen components stabilizes the binder, improves elasticity, making it less prone to deformation under long-term loading or elevated temperatures.

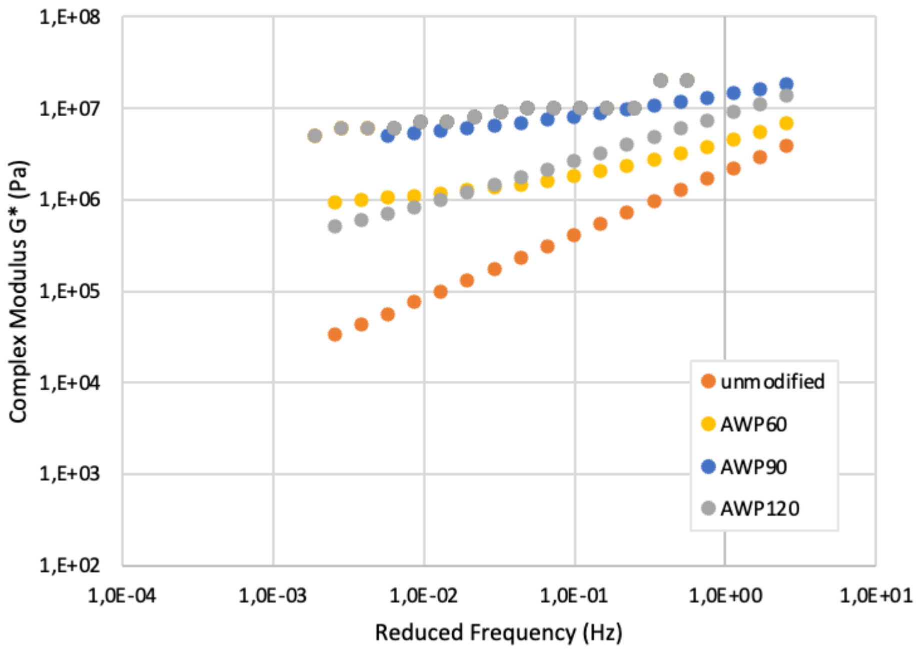

Figure 7. Complex modulus master curves

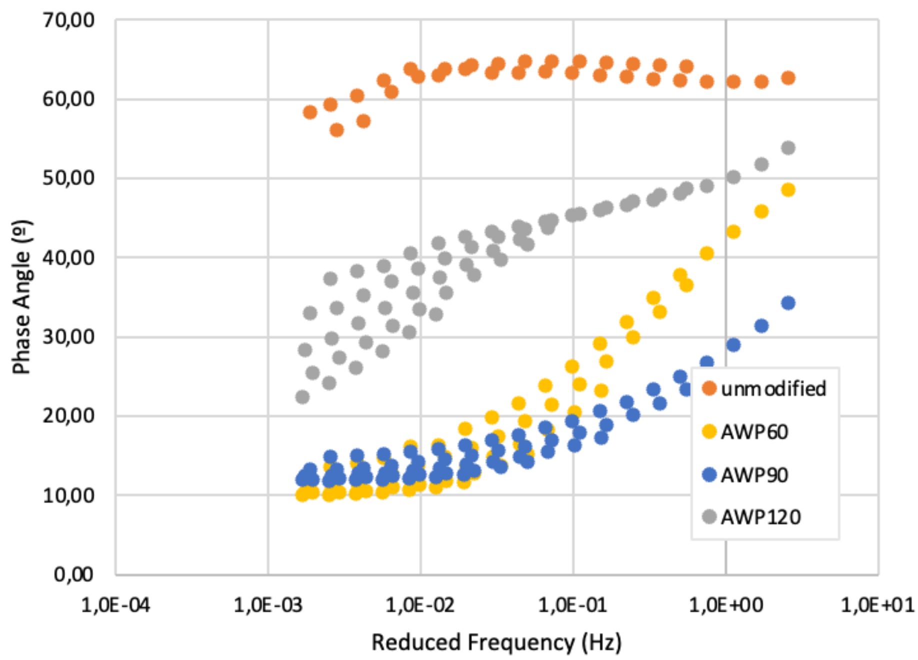

Figure 8. Phase angle master curves

Similar to tendencies to the complex modulus master curves, at lower temperatures or higher reduced frequencies the phase angle of AWP modified bitumen approaches that of unmodified bitumen. This occurs because the polymer's elastic network becomes less dominant under these conditions. At lower temperatures, both modified and unmodified bitumen stiffen, and the behaviour of the binder is primarily governed by its base bitumen properties rather than the polymer. Additionally, under higher frequencies, the short timescale of deformation minimizes the influence of polymer-induced elasticity. This leads to less observable distinctions of the viscoelasticity between the two materials, leading to a convergence in their phase angles.

3.5. Mixing Duration Effect on the Bitumen Performance

This study incorporates agricultural waste plastic at 6% of bitumen weight as modifier through 500 rpm low shear mixing duration of 60 (AWP60), 90 (AWP90), and 120 minutes (AWP120) at 170℃. With these similar mixing speed, temperature, and modifier content, the effect of the mixing duration on the modified bitumen's properties was evaluated.

In regard to standard penetration test, as shown in Figure 5, extending the blending duration from 60 to 120 minutes has minimal impact on the penetration value. The changes in penetration are minor and statistically negligible, indicating that blending time does not significantly influence this property. Similarly, the softening point (R&B value) remains largely unaffected by the mixing duration. The data show that variations in blending time have little to no effect on the softening point of the AWP modified bitumen. Overall, it is evident that blending time has a negligible impact on the rheological properties of the AWP binder, as indicated by the consistent penetration and R&B values over extended interaction periods. These findings are consistent with previous research. Cao, et al. [20] reported no substantial impact of extended blending time on the elastic recovery of rubber based modified asphalt binders, regardless of the amount of rubber used.

The effect of mixing duration on the complex modulus (G*) values was also evaluated. In general, extending the blending duration up to 120 minutes appears to have an insignificant impact on the G* values of the asphalt binder. This is evidenced by the irregular trend observed in G* values as blending time increases, with no clear or consistent pattern emerging. The results suggest that mixing durations up to 120 minutes do not substantially change the binder's properties or enhance its stiffness. The negligible effect of blending time on the binder's complex modulus implies that other factors may play a more significant role in influencing this property.

The mixing duration's effect was also evaluated towards phase angle. The results, as shown in Figure 8, indicate that mixing duration does not exhibit a consistent trend in phase angle values, suggesting that blending time has a minimal impact on this property of the asphalt binder. The phase angle values of the modified binder show a fluctuating trend and remain relatively unchanged with varying mixing durations. Specifically, AWP binders with 60 and 90 minutes of blending time exhibited similar phase angle values, while AWP120, with a blending time of 120 minutes, showed a slightly higher phase angle compared to AWP60 and AWP90. Therefore, the findings demonstrate that mixing duration has little to no impact on the phase angle, highlighting its limited influence on binder elasticity. This result aligns with the study conducted by Jeong, et al. [21] which shows that polymer mixing time has minimal influence on the viscoelastic properties of asphalt binders, as indicated by stable viscosity values recorded throughout a mixing period ranging from 0 to 480 minutes.

3.6. Rutting Resistance Potential

The lower penetration number and higher softening point of AWP modified bitumen compared to unmodified bitumen indicate enhanced rutting resistance. A lower penetration number reflects increased stiffness, which reduces deformation under heavy traffic loads. Meanwhile, a higher softening point demonstrates better thermal stability, allowing the binder to maintain its structure and resist flow at elevated temperatures. Together, these properties suggest that AWP modified bitumen is better equipped to handle the stress and heat associated with rutting, making it more durable for pavement applications.

The higher complex modulus of AWP modified bitumen at reduced frequency further confirms its superior rutting resistance. A higher complex modulus signifies greater material stiffness and elastic response under prolonged loading conditions. At reduced frequencies, which simulate slow-moving traffic and high temperature, the enhanced stiffness minimizes permanent deformation. This, combined with the lower penetration number and higher softening point, underscores the modified bitumen's ability to withstand rutting by effectively resisting both thermal softening and mechanical stresses in demanding pavement environments.

The lower phase angle of AWP modified bitumen at reduced frequency provides additional evidence of its enhanced rutting resistance. A lower phase angle indicates a shift toward more elastic behaviour. This elastic response reduces the accumulation of permanent deformation or rutting. When combined with the higher complex modulus, lower penetration number, and higher softening point, the lower phase angle highlights the overall superior performance of AWP modified bitumen in preventing rutting.

4. Conclusions

Based on this study, several points can be concluded as follows:

- The penetration number and softening point of the AWP modified bitumen showed significant changes compared to the original bitumen, clearly indicating the success of the modification.
- The constructed complex modulus (G*) master curves suggest that the AWP modified bitumen demonstrates enhanced rigidity, particularly at low frequencies and high temperatures, making the material more resistant to deformation.
- The phase angle (δ) master curves explain the higher elastic behavior, especially at reduced frequencies that correspond to high temperature.
- In general, the AWP modified bitumen exhibits improved elasticity, stiffness, and thermal resistance compared to unmodified bitumen. Both master curves suggest that at high frequency or low temperature, the AWP modified bitumen behavior aligns more closely with unmodified bitumen due to reduced polymer influence.

- Among AWP60, AWP90, and AWP120, the improvement of G* and the lower δ were clearly presented. However, no consistent trend is observed in the changes of these parameter. This suggests that the 60-minute low shear mixing is sufficient for 6%wt in producing the expected enhancements.
- Finally, in terms of rutting resistance potential, the standard tests and dynamic mechanical analysis results suggest the AWP modifiers have similar effect in improving rutting resistance of modified bitumen compared to the general virgin/fresh polyethylene. This result can be used as foundation to further bitumen modification studies by using agricultural waste plastic (AWP) for feasible and sustainable approach in bitumen modification.

Acknowledgements

The authors express sincere gratitude to PT Equiva Ligand Indonesia as Anton Paar supplier for their kind support in this study by providing the DSR equipment for conducting the rheology tests. We also extend our deep appreciation for the funding provided by Dana Masyarakat IPB 2024, under contract number 23451/IT3/PT.01.03/P/B/2024.

REFERENCES

[1] E. Schettini, G. Scarascia-Mugnozza, I. Blanco, F. Convertino, and G. Vox, "12 - Agricultural plastic waste," in *Handbook of Sustainable Concrete and Industrial Waste Management*, F. Colangelo, R. Cioffi, and I. Farina, Eds., Woodhead Publishing, 2022, pp. 255–268. doi: 10.1016/B978-0-12-821730-6.00005-X.

[2] A. Almeida, S. Capitão, R. Bandeira, M. Fonseca, and L. Picado-Santos, "Performance of AC mixtures containing flakes of LDPE plastic film collected from urban waste considering ageing," *Constr Build Mater*, vol. 232, p. 117253, 2020, doi: 10.1016/j.conbuildmat.2019.117253.

[3] S. Haider, I. Hafeez, Jamal, and R. Ullah, "Sustainable use of waste plastic modifiers to strengthen the adhesion properties of asphalt mixtures," *Constr Build Mater*, vol. 235, p. 117496, 2020, doi: 10.1016/j.conbuildmat.2019.117496.

[4] M. Sasidharan, M. E. Torbaghan, and M. Burrow, "Using waste plastics in road construction," K4D Helpdesk Report, no. 2016, pp. 1–19, 2019. https://assets.publishing.service.gov.uk/media/5d41b34040f0b60a86a5e5dc/595_Use_of_Waste_Plastics_in_Road_Construction.pdf

[5] T. Sudibyo, F. Suwarto, M. Fauzan, and C. Arif, "The Basic Rheological Properties of LDPE Modified Bitumen," *Jurnal Teknik Sipil dan Lingkungan*, vol. 9, no. 2, pp. 275–282, Oct. 2024, doi: 10.29244/jsil.9.2.275-282.

[6] T. Sudibyo, H. Putra, and Sutoyo, "Utilization of Distilled Water to Observe Surface Contact Angle of Polymer-Modified Bitumen," *Civil Engineering and Architecture*, vol. 12, no. 2, pp. 1294–1302, Mar. 2024, doi: 10.13189/cea.2024.120244.

[7] M. A. Dalhat and H. I. Al-Abdul Wahhab, "Performance of recycled plastic waste modified asphalt binder in Saudi Arabia," *International Journal of Pavement Engineering*, vol. 18, no. 4, pp. 349–357, 2017, doi: 10.1080/10298436.2015.1088150.

[8] L. M. B. Costa, H. M. R. D. Silva, J. Peralta, and J. R. M. Oliveira, "Using waste polymers as a reliable alternative for asphalt binder modification – Performance and morphological assessment," *Constr Build Mater*, vol. 198, pp. 237–244, 2019, doi: 10.1016/j.conbuildmat.2018.11.279.

[9] G. Polacco, S. Berlincioni, D. Biondi, J. Stastna, and L. Zanzotto, "Asphalt modification with different polyethylene-based polymers," *Eur Polym J*, vol. 41, no. 12, pp. 2831–2844, 2005, doi: 10.1016/j.eurpolymj.2005.05.034.

[10] D. Movilla-Quesada, A. C. Raposeiras, L. T. Silva-Klein, P. Lastra-González, and D. Castro-Fresno, "Use of plastic scrap in asphalt mixtures added by dry method as a partial substitute for bitumen," *Waste Management*, vol. 87, pp. 751–760, 2019, doi: 10.1016/j.wasman.2019.03.018.

[11] G. D. Airey, "Rheological properties of styrene butadiene styrene polymer modified road bitumens," *Fuel*, vol. 82, no. 14, pp. 1709–1719, 2003, doi: 10.1016/S0016-2361(03)00146-7.

[12] S. M. Asgharzadeh and N. Tabatabaee, "Rheological master curves for modified asphalt binders," *Scientia Iranica*, vol. 20, no. 6, pp. 1654–1661, 2013.

[13] G. D. Airey, "Rheological characteristics of polymer modified and aged bitumens," PhD thesis, University of Nottingham, 1997.

[14] N. T.-H. Pham, "Characterization of Low-Density Polyethylene and," *Polymers (Basel)*, vol. 13, no. 14, p. 2352, 2021.

[15] M. T. Awwad and L. Shbeeb, "The use of polyethylene in hot asphalt mixtures," *Am J Appl Sci*, vol. 4, no. 6, pp. 390–396, 2007, doi: 10.3844/ajassp.2007.390.396.

[16] Z. N. Kalantar, M. R. Karim, and A. Mahrez, "A review of using waste and virgin polymer in pavement," *Constr Build Mater*, vol. 33, pp. 55–62, 2012, doi: 10.1016/j.conbuildmat.2012.01.009.

[17] I. M. Khan, S. Kabir, M. A. Alhussain, and F. F. Almansoor, "Asphalt Design Using Recycled Plastic and Crumb-rubber Waste for Sustainable Pavement Construction," *Procedia Eng*, vol. 145, pp. 1557–1564, 2016, doi: 10.1016/j.proeng.2016.04.196.

[18] G. D. Airey, "Use of Black Diagrams to Identify Inconsistencies in Rheological Data," *Road Materials and Pavement Design*, vol. 3, no. 4, pp. 403–424, 2002, doi: 10.1080/14680629.2002.9689933.

[19] F. Xiao, V. S. Punith, S. N. Amirkhanian, and B. J. Putman, "Rheological and chemical characteristics of warm mix asphalt binders at intermediate and low performance temperatures," *Canadian Journal of Civil Engineering*, vol. 40, no. 9, pp. 861–868, Aug. 2013, doi: 10.1139/cjce-2012-0363.

[20] W. D. Cao, S. T. Liu, X. Z. Cui, and X. Q. Yu, "Effect of crumb rubber particle size and content on properties of crumb rubber modified (CRM) asphalt," in *Applied Mechanics and Materials*, 2011, pp. 955–959. doi: 10.4028/www.scientific.net/AMM.99-100.955.

[21] K. D. Jeong, S. J. Lee, S. N. Amirkhanian, and K. W. Kim, "Interaction effects of crumb rubber modified asphalt binders," *Constr Build Mater*, vol. 24, no. 5, pp. 824–831, May 2010, doi: 10.1016/j.conbuildmat.2009.10.024.