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Mechanical and Thermal Properties Analysis on Bitumen Mixture with Additives: HDPE, PP, and Lignin

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Abstract: This study focuses on enhancing the performance and sustainability of asphalt materials in road construction by recycling High-Density Polyethylene (HDPE). Polypropylene (PP) and lignin as additives in bitumen. The Hot Melt Mixing method is employed to investigate the impact of different concentrations of HDPE, PP, and lignin on bitumen properties. Key properties such as ductility, penetration, softening point, and thermal behavior are analyzed, providing valuable insights into the potential of these additives to enhance bitumen performance. The findings demonstrate that higher concentrations of HDPE and PP result in reduced penetration depth, indicating increased hardness. The addition of lignin enhances penetration depth, contributing to the flexibility and performance of the bitumen mixture. Moreover, thermal analysis offers valuable information about the thermal behavior and stability of the bitumen-plastic-lignin blends, shedding light on their compatibility and interactions. This research contributes to the ongoing efforts in road construction and pavement engineering by exploring sustainable solutions that not only address plastic waste challenges but also improve the performance and durability of bituminous materials, making it a crucial step towards environmentally responsible and long-lasting asphalt pavements.

Keywords: Bitumen Modification; Plastic Waste Recycling; Hot Melt Mixing; Asphalt Performance; Biopolymers.

Abstrak: *Penelitian ini berfokus pada peningkatan kinerja dan keberlanjutan material aspal dalam konstruksi jalan dengan mendaur ulang plastik High-Density Polyethylene (HDPE) dan Polypropylene (PP) sebagai bahan tambahan berbasis bio dalam bitumen. Metode Hot Melt Mixing digunakan untuk menginvestigasi dampak konsentrasi yang berbeda dari HDPE, PP, dan lignin terhadap sifat-sifat bitumen. Sifat-sifat kunci seperti ketangguhan, penetrasi, titik lunak, dan perilaku termal dianalisis, memberikan wawasan berharga tentang potensi bahan tambahan ini untuk meningkatkan kinerja bitumen. Temuan menunjukkan bahwa konsentrasi yang lebih tinggi dari HDPE dan PP mengakibatkan penurunan kedalaman penetrasi, menandakan peningkatan kekerasan. Penambahan lignin meningkatkan kedalaman penetrasi, berkontribusi pada fleksibilitas dan kinerja campuran bitumen. Selain itu, analisis termal memberikan informasi berharga tentang perilaku termal dan stabilitas campuran bitumen-plastik-lignin, memberikan pencerahan tentang kompatibilitas dan interaksinya. Penelitian ini berkontribusi pada upaya berkelanjutan dalam konstruksi jalan dan rekayasa perkerasan dengan menjelajahi solusi berkelanjutan yang tidak hanya mengatasi masalah limbah plastik tetapi juga meningkatkan kinerja dan ketahanan material bitumen, menjadikannya langkah penting menuju pembangunan jalan aspal yang bertanggung jawab secara lingkungan dan tahan lama.*

Kata kunci: *Modifikasi Bitumen; Daur Ulang Limbah Plastik; Hot Melt Mixing; Kinerja Aspal; Biopolimer.*

INTRODUCTION

The field of road construction and pavement engineering continually seeks innovative solutions to enhance the durability, performance, and sustainability of asphalt materials. Bitumen, a crucial component in asphalt mixtures, offers excellent adhesive and binding properties but faces challenges such as susceptibility to temperature-induced deformations, moisture, and fatigue cracking [1]. To address these challenges, researchers have been exploring various additives and modification techniques aimed at improving the overall performance of bituminous materials.

On the other hand, there is an escalating concern over the mounting volume of plastic waste, particularly High-Density Polyethylene (HDPE) and Polypropylene (PP). As the global population grows exponentially and economies advance, the production and disposal of plastics have reached unprecedented levels [2]. These synthetic polymers, ubiquitous in various industries, contribute significantly to environmental degradation and pose a formidable challenge for waste management.

The recycling of HDPE and PP as bio-based additives for bitumen aligns with the principles of a circular economy, wherein waste materials are repurposed to fulfill new functions. This not only mitigates the adverse environmental impacts associated with plastic disposal but also harnesses the beneficial attributes of these polymers to enhance the functional capabilities of bituminous materials [3], [4].

Our previous studies has investigated a preliminary analysis of PP mixed with bitumen using lignin as the compabilitizer, which resulted the mixture to have better ability to agglomerate; but poorer distribution [5]. Additionally, our study previously has investigated the addition of HDPE to bitumen, that showed the higher the composition level of multilayer plastic waste, the higher the dispersion properties of the mixture and the lower the thermal stability of the mixture [6].

This paper investigates the effects of incorporating HDPE, PP, and lignin into bitumen using the Hot Melt Mixing method. HDPE and PP are fillers that functioned to improve the asphalt mixture resistance to water presence. The coupling agent, lignin, is added to improve the compability between the plastics and asphalt [5]. Various concentrations of HDPE, PP and lignin was applied in this paper to examine the effect of each substance within the bitumen mixtures.

METHODS

Bitumen with penetration grade 60/70 from the Pertamina, tested properties from Yuanita et al., 2017 [7], was used as the main asphalt mixture. Fresh polypropylene (PP) plastic bag and high-density polyethylene (HDPE) were obtained through local commercial market. A modified lignin by polyutrethanization was used as the coupling agent and prepared with the same method as Dwijaya et al., 2020 [8].

The hot melt mixing bitumen modification was performed at 180 °C in 30 min using hot melt mixer with stirring speed of 60 rpm. For each sample, 1000 gram of bitumen was used as matrix of the mixture. Bitumen, lignin, PP and HDPE was added simultaneously to the hot melt mixer once the container has reached 180 °C. The mixing process will start once all materials are properly added to the mixer. Table 1 shows the weight variation in relation with the bitumen weight as well as the sample code that will be used in this paper.

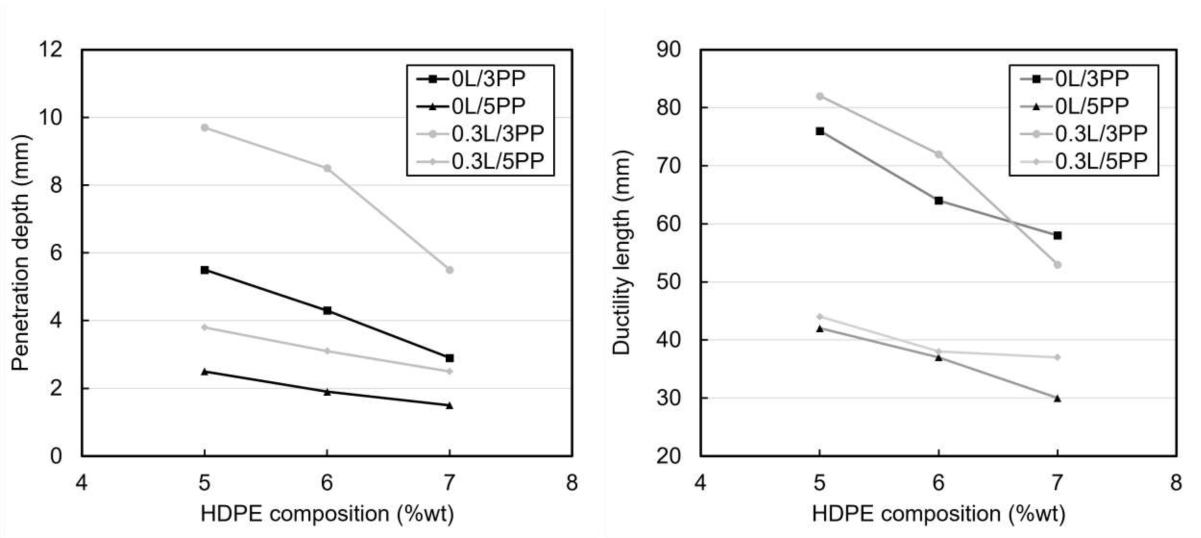
Table 1. Sample code

Sample name	Lignin concentration (%wt)	PP concentration (%wt)	HDPE concentration (%wt)
0L/3PP	0	3	varied
0L/5PP	0	5	varied
0.3L/3PP	0.3	3	varied
0.3L/5PP	0.3	5	varied
0L/3PP/7HDPE	0	3	7
0.3L/3PP/7HDPE	0.3	3	7
0L/5PP/7HDPE	0	5	7
0.3L/5PP/7HDPE	0.3	5	7

Simultaneous Thermal Analysis (STA), that combines the thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), was conducted using a Perkin-Elmer STA 6000. The ductility test assesses the capacity of bitumen to stretch or elongate without breaking. This procedure entails elongating a typical bitumen briquette until it reaches a point of fracture and quantifying the extent to which it elongates prior to breaking. This examination aids in the assessment of bitumen's flexibility and its resistance to deformation, especially when exposed to fluctuating temperature conditions. The penetration test assesses the consistency or hardness of bitumen It establishes the depth, measured in tenths of a millimeter, to which a standard needle vertically enters a bitumen sample, following specific temperature and loading conditions. The penetration value reflects the bitumen's level of hardness or softness. A ductility test, penetration test, and softening point test were conducted according to SNI-06-2432-1991, SNI 06-2456-1996, and SNI-06-2434-1991.

RESULT AND DISCUSSION

The physical properties of bitumen play a pivotal role in determining the performance and durability of asphalt pavements. Among these properties, ductility, penetration, and softening point are paramount indicators that significantly influence the behavior of bitumen mixtures in asphalt applications [9]. Ductility reflects the extent of bitumen's ability to deform under tensile stress, providing insights into its flexibility and resistance to cracking [10]. Penetration measures the depth to which a standard needle penetrates a bitumen sample under specific conditions, offering crucial information about the bitumen's consistency and structural stability [11], [12]. Meanwhile, the softening point is a key parameter indicating the temperature at which bitumen undergoes a transition from a solid to a more viscous state, affecting its performance and susceptibility to deformation under traffic loads [12].



(a) (b)

Figure 1. Penetration test (a) and ductility test (b) performance for various PP, HDPE and Lignin variations.

Figure 1.a, shows that bitumen with the addition of 3% PP exhibits a deeper penetration compared to the addition of 5% PP. This implies that a higher concentration of PP in bitumen corresponds to increased hardness. It is clear from the observation that thermoplastics, in this case PP and HDPE, influence the penetration depth with the increase in the viscosity of the bitumen; where viscority directly proportional to the increase in concentration of polymer [13]. In addition, PP has a rigid and short methyl group attached to every second carbon atom of the polymer main chain, which restricts rotation of the chain producing a stronger but less flexible material [14]. Furthermore, when the mixture is supplemented with HDPE, further reduction in penetration depth was observed. As HDPE is a linear, contains very little branching, and stronger intermolecular forces [15], a more rigid polymer blend structure was developed when HDPE was added with PP. The penetration test graph of bitumen mixture with the addition of lignin also indicates an increase in penetration depth, ranging from 63% to 98%, for the bitumen and plastic mixture compared to without the addition of lignin. The role of lignin as an additive focuses on the high-temperature rheological properties of the asphalt mixture by increasing the hardness and consistency of base asphalt [16].

From Figure 1.b, it can be observed that bitumen with the addition of 3% PP exhibits higher ductility compared to the addition of 5% PP. This indicates that an increased PP content leads to a decrease in bitumen ductility or flexibility. Furthermore, when bitumen mixtures are supplemented with HDPE, an elevated percentage of added HDPE corresponds to a reduction in ductility. In other words, the addition of HDPE makes the bitumen mixture increasingly challenging to shape or form [17]. The addition of lignin to the bitumen mixture increases ductility compared to the mixture without lignin. This indicates that the incorporation of lignin into the bitumen mixture enhances its flexibility.

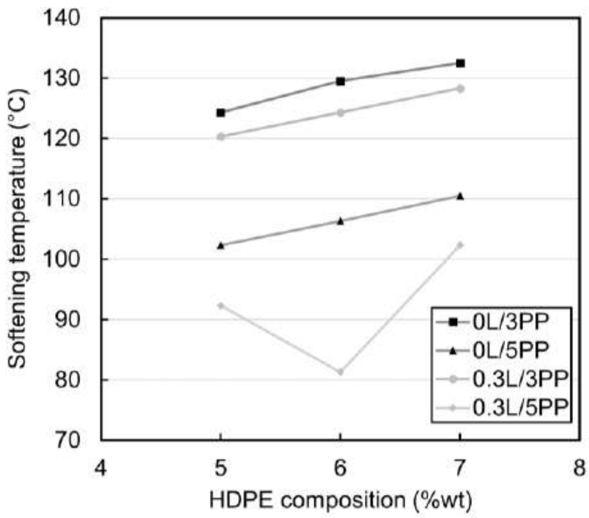
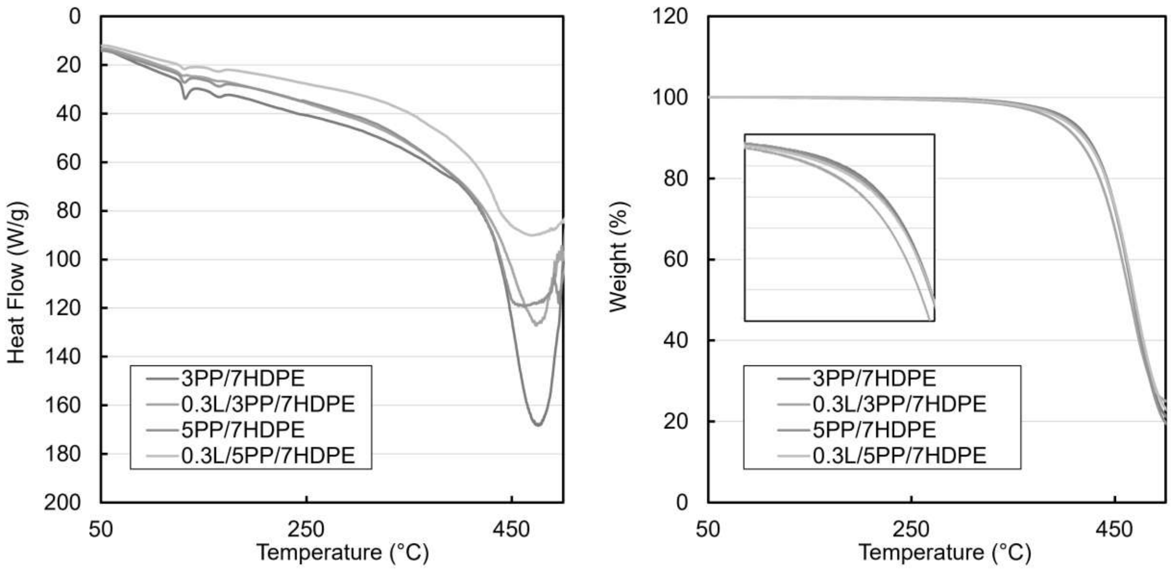


Figure 2. Softening point test performance for various PP, HDPE and Lignin variations.

Figure 2 depicts that the softening point of the bitumen mixture increases with the addition of 5% PP compared to the addition of 3% PP. This implies that a higher concentration of added PP results in an increased energy requirement for stretching the intermolecular bonds. Additionally, the incorporation of HDPE in the bitumen mixture also raises the softening point of the mixture; the higher the added HDPE, the higher the softening point of the mixture. In other words, an increased content of HDPE also escalates the energy required for stretching the intermolecular bonds. Data from Fig 2 indicate that the addition of lignin to the bitumen mixture decreases its softening point compared to the mixture without lignin. This suggests that the inclusion of lignin in the bitumen mixture reduces its processing temperature.

Thermal performance, DSC and TGA, provide invaluable insights into the thermal behaviour and stability of such complex combinations. DSC allows us to identify key temperature transitions, such as melting points and glass transition temperatures, helping to understand the interactions and compatibility of the components within the mixture [6], [18]. On the other hand, TGA assists in determining the degradation temperatures and mass loss profiles, shedding light on the thermal stability and decomposition kinetics of the constituents [18]. This information is crucial for optimizing the formulation of bituminous materials with enhanced performance and durability, as well as for ensuring the suitable use of lignin and polymer additives in these asphalt-related applications.



(a) (b)

Figure 3. DSC (a) and TGA (b) result for various PP, HDPE and Lignin variations.

Based on Fig 3.a, bitumen mixture generally has a melting point of 130 °C and at around 170 °C point another smaller curve was observed which, according to previous researches, indicates an impurity in bitumen [19], [20].

In addition, the DSC curve which opens upwards at the temperature point around 470 °C is the decomposition temperature of bitumen mixture. This statement is supported by the TGA results of bitumen which experienced a drastic decrease in mass. The heat flow profile within the decomposition temperature varied along with the composition; the trend shows higher heat flow is observed when lignin is added, and PP composition is reduced. Figure 3.b shows the TGA curve that indicates no chemical changes have occurred so that the two temperature points can be confirmed as the melting point of bitumen and the melting point of impurities.

CONCLUSIONS

In conclusion, this study highlights the promising potential of recycling HDPE, PP and lignin as additives for bitumen in the realm of road construction and pavement engineering. The utilization of the hot melt mixing method has offered valuable insights into the effects of different additive concentrations on bitumen properties. The results indicate that the inclusion of HDPE, PP, and lignin influences crucial properties such as ductility, penetration, and softening point, while thermal analysis provides insights into the thermal behavior and stability of the bitumen-plastic-lignin blends. These findings underscore the potential for sustainable and environmentally responsible advancements in asphalt technology, emphasizing the significance of further research and development in this innovative area of bitumen modification for improved road infrastructure.

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