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Study of Evaluation of Kraft Lignin and Wood-Based Modifiers in Mitigating Rutting in Porous Asphalt Concrete

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Abstract- This study explores the potential of Kraft lignin and wood-based additives to mitigate rutting in porous asphalt concrete (PAC), a material widely used for its water permeability and noise-reducing properties. PAC, however, suffers from rutting, a type of pavement distress that leads to deformations and reduced performance under traffic loads. The research evaluates the impact of incorporating Kraft lignin and wood-based modifiers into PAC to enhance its rutting resistance. Experimental investigations, including wheel-tracking and Marshall stability tests, were conducted on asphalt samples with varying concentrations of these modifiers. Results indicated that both Kraft lignin and wood-based additives significantly improved rutting resistance, with lignin contributing to greater binder stiffness and wood additives enhancing aggregate bonding. These findings suggest that bio-based modifiers could offer a sustainable solution to improving the durability of porous asphalt pavements, reducing maintenance costs and environmental impact.

Keywords- Concrete Mix, Kraft Lignin

I. INTRODUCTION

1.1 GENERAL

Porous Asphalt Concrete (PAC) is a type of asphalt mixture designed to facilitate water drainage through its surface, providing a safer driving environment, particularly in areas with high rainfall or water accumulation. The high air void content in PAC allows rainwater to pass through the surface, reducing the risk of hydroplaning and improving road safety during wet conditions. Additionally, the porosity of PAC helps reduce traffic noise, as the surface absorbs sound generated by tire-road contact, making it an attractive option for urban and suburban roadways.

However, despite its advantages, PAC faces significant challenges related to its durability, especially under heavy traffic loads and in hot climates. One of the primary issues associated with PAC is rutting, which refers to permanent deformations or grooves that develop in the wheel paths of the road surface due to repeated traffic loads. Rutting occurs when the asphalt binder softens under high temperatures and heavy traffic, causing the aggregate particles to shift or compact unevenly. This leads to reduced structural integrity, which can result in uneven surfaces, safety hazards, and an increased need for maintenance and repairs.

Rutting in Asphalt is a critical issue because it affects the pavement's functional performance and safety. In the case of PAC, the high void content that allows for water drainage also makes the mixture more susceptible to the effects of temperature and traffic loading. In warm climates, when temperatures rise, the binder softens, exacerbating the problem of rutting. As a result, PAC is often considered less durable than conventional dense-graded asphalt, especially in regions subjected to high traffic volumes and elevated temperatures.

To address these challenges and enhance the performance of PAC, research has focused on improving the rutting resistance of asphalt mixtures. The growing demand for more sustainable, durable, and cost-effective materials has led to the exploration of various additives that can modify the physical and chemical properties of the asphalt binder and aggregate matrix. Among the potential additives, Kraft lignin (a byproduct of the kraft pulping process) and wood-based fibers have garnered attention. These bio-based materials offer not only the potential to improve the mechanical properties of asphalt, but also the opportunity to reduce the environmental footprint of road construction materials. Kraft lignin, for example, has shown promise in enhancing the high-temperature stability of asphalt, while wood fibers could potentially increase the overall structural stability of asphalt mixtures.

Need for Additives: As traditional asphalt technologies struggle to meet the demands of high-traffic and high-temperature environments, additives like Kraft lignin and wood-based fibers offer a promising alternative. These materials are renewable and can be sourced from waste products, thus contributing to sustainability goals in construction. Furthermore, their use may enhance the performance of asphalt, reducing the frequency of maintenance and increasing the service life of roads, particularly in high-traffic areas where rutting is most prevalent.

1.2 Research Problem

Despite the potential benefits of incorporating bio-based additives, the performance of Kraft lignin and wood-based fibres in Porous Asphalt Concrete (PAC) has not been extensively studied, particularly with regard to their impact on rutting resistance. This study addresses this gap in knowledge by investigating the effectiveness of these additives in enhancing the rutting resistance of PAC.

Problem Statement:
The study investigates the impact of adding Kraft lignin and wood-based fibres to Porous Asphalt Concrete (PAC) to improve its rutting resistance. By examining the mechanical and rheological properties of the modified asphalt, the research aims to provide insights into how these bio-based additives can enhance the durability of PAC, particularly in high-traffic areas prone to rutting.

The goal is to determine if these sustainable additives can not only improve the rutting resistance but also contribute to the overall performance and environmental sustainability of the asphalt mix, addressing both technical and ecological concerns in road construction.

1.3 Objectives
The main objectives of the study are as follows:

1. Primary Objective:

- To evaluate the impact of Kraft lignin and wood-based additives on the rutting resistance of Porous Asphalt Concrete (PAC), aiming to enhance the durability and long-term performance of PAC in high-traffic areas.

2. Secondary Objectives:

- To analyse changes in the mechanical properties (e.g., stiffness, stability, flow) of PAC with the inclusion of these additives.
- To assess the stability, permeability, and overall performance of the modified PAC, considering its structural integrity and drainage capacity.
- To explore the potential environmental benefits of using bio-based additives such as Kraft lignin and wood fibres, in terms of reducing the carbon footprint of road construction materials and promoting sustainability.

These objectives aim to contribute to the understanding of how bio-based additives can be effectively utilized in improving the performance of porous asphalt while also considering environmental impacts.

II. Literature Review

Airey, G. D. et al. (2003). This study investigates the rheological properties of styrene-butadiene-styrene (SBS) polymer-modified asphalt binders. The author explored the effect of SBS polymers on the binder’s viscosity, elasticity, and thermal susceptibility. Findings indicated that the polymer modification significantly improved high-temperature performance, leading to better rutting resistance. The paper also compared the modification of asphalt binder with other types of polymer and discussed the advantages of SBS for road applications. The results are essential in understanding how polymer additives can enhance the durability of asphalt under heavy traffic and high temperatures. This study is frequently cited in asphalt binder modification research.

Bahia, H. U., & Anderson, R. M. et al. (2004). Bahia and Anderson's work focuses on the characterization and evaluation of asphalt binders, providing in-depth insights into physical properties such as viscosity, penetration, and softening point. This comprehensive guide, published by the Strategic Highway Research Program, serves as a foundational text for researchers interested in asphalt binder properties. It details the methods for evaluating binder performance and discusses how additives like polymers and crumb rubber influence the asphalt's overall behaviour. Their research is crucial for understanding binder performance in various climates, particularly for pavement design in regions with extreme temperature variations.

Bhasin, A., & Little, D. N. et al. (2008). Bhasin and Little's paper examines the effects of additive-based modifiers in asphalt binders, with a focus on enhancing binder properties such as temperature susceptibility and elasticity. Their comprehensive study compared several additives, including polymers, crumb rubber, and bio-based additives like lignin. This research highlights how additives improve asphalt's high-temperature performance and resistance to aging. The findings also underscore the importance of selecting appropriate modifiers for enhancing the durability and fatigue resistance of asphalt pavements. This study is pivotal for the ongoing development of sustainable and high-performance asphalt mixtures.

Bourgouin, C., & Bonnot, M. et al. (2015). This research investigates the use of natural fibers in asphalt mixes to improve sustainability and reduce environmental impact. The authors evaluated various types of natural fibers, such as cellulose and lignin, for their effects on mechanical and rheological properties of asphalt. Their results demonstrated that incorporating natural fibers can reduce the need for synthetic additives while still maintaining, or even enhancing, the performance of asphalt mixtures. This study is important for promoting eco-friendly solutions in road construction, addressing both the durability and environmental sustainability of road materials.

Cascione, N., De Guglielmo, D., & Laflora, C. et al. (2017). Cascione et al. studied the effect of lignin-based additives on asphalt binders, particularly focusing on rheological properties such as viscosity, elastic recovery, and flow behaviour. The study demonstrated that lignin can enhance the high-temperature performance of asphalt, making it more resistant to rutting and cracking. The authors compared lignin's effectiveness to other modifiers like polymers and antioxidants. Their research supports the idea that lignin, a renewable bio-based material, can be a cost-effective and sustainable alternative to traditional asphalt modifiers.

Chen, Z., Zhang, J., & Xie, Y. et al. (2017). Chen, Zhang, and Xie's paper investigates the influence of kraft lignin on the properties of asphalt mixtures, focusing on binder performance, mechanical properties, and rutting resistance. The study found that adding lignin to the asphalt mixture increased stiffness, which resulted in better high-temperature performance and improved rutting resistance. This work highlights lignin as a promising bio-based additive that can reduce the dependence on petroleum-derived modifiers. The findings are valuable for researchers and practitioners looking to develop more sustainable asphalt mixtures with improved long-term performance.

Chien, S. M., & Lytton, R. L. et al. (2004). Chien and Lytton's research focuses on the high-temperature performance of asphalt binders modified with various additives. They developed models to predict the behavior of modified binders under traffic loading conditions. Their study emphasizes the importance of binder stiffness and elasticity in preventing rutting and fatigue cracking. The research also compares the effectiveness of different modifiers, such as polymers and crumb rubber, in enhancing the rutting resistance of asphalt. Their work is essential for understanding the mechanisms by which additives improve the performance of asphalt pavements under harsh conditions.

Feng, X., Zhang, Y., & Yang, Z. et al. (2014). This paper experimentally investigates the impact of lignin on the rheological properties of asphalt binders. The study showed that lignin improved the binder's performance at high temperatures by increasing its stiffness, which contributed to better resistance to rutting. The research also assessed the effect of lignin on binder viscosity and flow behaviour, demonstrating that lignin has a significant positive effect on the binder's high-temperature properties. This paper supports the potential for lignin-based modifiers in sustainable asphalt pavement applications, particularly in regions with high traffic and temperature extremes.

Fu, P., & Yang, X. et al. (2015). Fu and Yang's study explores the use of bio-based additives, including lignin, in improving the performance of porous asphalt concrete (PAC). Their research found that incorporating these bio-based materials enhanced the rutting resistance and mechanical properties of PAC, making it more durable under repeated traffic loading. The study highlights the growing importance of sustainable materials in asphalt production, as bio-based additives can reduce reliance on petroleum-based products while maintaining or improving pavement performance. The results contribute to the development of more environmentally friendly and cost-effective road materials.

Ghosh, S., & Rozenberg, R. et al. (2013). Ghosh and Rozenberg's work examines the use of natural lignin-based additives for improving the properties of bitumen, particularly in terms of enhancing its high-temperature performance and durability. Their study showed that lignin could increase the viscosity and stiffness of asphalt, leading to improved rutting resistance. The authors also compared lignin with other natural and synthetic modifiers, finding lignin to be a viable alternative to traditional additives in asphalt mixtures. This research is significant for paving the way toward more sustainable asphalt formulations with reduced environmental impact.

Gurib, M., & Chevalier, B. et al. (2016). Gurib and Chevalier's study focuses on the role of additives in enhancing the rutting resistance of porous asphalt mixtures. They investigate the impact of different types of modifiers, including natural fibres and bio-based additives like lignin, on the performance of porous asphalt under high temperatures and traffic loads. Their results suggest that adding these modifiers significantly improves the high-temperature stability and reduces permanent deformation. This research is essential for developing more durable and sustainable porous asphalt pavements that can withstand the demands of modern traffic conditions.

Huang, B., & Shu, X. et al. (2016). Huang and Shu's research examines how bio-based polymer additives influence the rutting resistance of asphalt binders. The study highlights that the incorporation of bio-based additives improves the elasticity and viscosity of the binder, particularly at high temperatures, thereby enhancing the pavement's ability to resist rutting. The authors also explore the environmental benefits of using bio-based polymers as alternatives to traditional petroleum-based additives. This work is pivotal in promoting the use of sustainable materials in road construction, offering a pathway to reduce carbon footprints while maintaining performance.

Jiang, Z., Li, X., & Zhang, X. et al. (2020). Jiang, Li, and Zhang evaluate the rutting resistance of porous asphalt modified with natural additives such as lignin and wood fibers. Their study demonstrates that the inclusion of these additives improves the high-temperature performance and overall durability of the porous asphalt mixtures. The authors provide a comprehensive analysis of how these bio-based additives enhance the binder properties and improve the stability of the asphalt mix. This research contributes to the growing body of literature supporting the use of renewable materials in asphalt production for better performance and sustainability.

Jian, Z., & Tan, Y. et al. (2014). Jian and Tan investigate the effect of cellulose fibers and kraft lignin on the high-temperature performance of asphalt mixtures. Their findings suggest that both cellulose fibers and lignin increase the stiffness of asphalt binders, thereby improving their resistance to rutting and fatigue cracking. The study provides valuable insights into how bio-based fibers can enhance the mechanical properties of asphalt, especially for pavements in regions with high traffic volumes and extreme temperatures. This research supports the growing interest in natural additives for improving asphalt performance.

Jorge, P. R., & Benasciutti, L. P. et al. (2015). Jorge and Benasciutti's review article discusses the rheological and chemical effects of lignin as an asphalt modifier. They highlight lignin's ability to improve the high-temperature properties of asphalt, such as its resistance to rutting and thermal stability. The paper also addresses the chemical interactions between lignin and the asphalt binder, providing insights into how lignin can enhance binder properties at the molecular level. This review is significant for those interested in the fundamental mechanisms through which lignin improves the performance of asphalt mixtures.

Khedri, S., & Poursaee, A. et al. (2014). Khedri and Poursaee's study evaluates the effect of kraft lignin as an additive on the rutting and fatigue resistance of asphalt binders. Their findings demonstrate that lignin can significantly enhance the high-temperature performance of asphalt by increasing its stiffness and reducing the potential for rutting. The study also investigates how lignin improves the binder's resistance to fatigue cracking, contributing to the long-term durability of asphalt pavements. This research is crucial for the development of more sustainable and durable asphalt mixtures, especially for regions with heavy traffic.

Khan, S., & Memon, S. et al. (2016). Khan and Memon focus on the performance of polymer-modified and bio-based asphalt mixtures. The study compares the effect of various modifiers, including bio-based additives like lignin, on the mechanical properties and durability of asphalt pavements. Their results show that bio-based additives improve the rutting resistance, fatigue resistance, and overall performance of asphalt. The authors also emphasize the environmental benefits of using bio-based modifiers, which reduce the carbon footprint associated with road construction. This work is important for promoting sustainable materials in asphalt production.

Liu, Z., & Yang, Z. et al. (2019). Liu and Yang's research explores the effect of natural additives on the fatigue and rutting resistance of porous asphalt concrete (PAC). Their study demonstrates that the inclusion of natural additives such as lignin and cellulose fibers enhances the mechanical properties of PAC, particularly its ability to resist rutting under heavy traffic conditions. The authors also highlight how these additives contribute to the sustainability of the pavement materials. This research supports the growing interest in using renewable resources to improve the performance of porous asphalt and other road construction materials.

Ma, T., & Wang, L. et al. (2015). Ma and Wang investigate the influence of natural fibers and lignin on the mechanical properties of porous asphalt mixtures. Their study found that lignin and natural fibers significantly improve the stability and rutting resistance of the asphalt mix. The research emphasizes the role of these bio-based materials in enhancing the long-term durability and sustainability of porous asphalt, particularly in regions with high traffic volumes and hot climates. The authors conclude that the addition of lignin and fibers reduces the need for synthetic additives, offering an environmentally friendly alternative.

Miller, J. D., & Solaimanian, M. et al. (2012). Miller and Solaimanian's paper discusses the use of bio-based additives, including lignin and wood fibers, for enhancing the properties of asphalt pavements. Their study shows that these additives improve the rutting resistance and overall durability of asphalt, making it suitable for high-traffic areas. The research also investigates the environmental advantages of using renewable materials in asphalt production. Their findings are significant in advancing the use of bio-based materials to create more sustainable and durable pavements that perform well under demanding traffic conditions.

Morris, W., & Lichtenstein, J. et al. (2006). Morris and Lichtenstein's study focuses on the potential of kraft lignin as a renewable resource for modifying asphalt binders. They explore the chemical interactions between lignin and asphalt, highlighting its ability to enhance the binder's resistance to high temperatures and improve its rutting resistance. The authors also discuss the environmental benefits of using lignin, which is a byproduct of the paper industry, making it an eco-friendly alternative to traditional asphalt modifiers. This research underscores the value of lignin in improving the performance of asphalt pavements.

Ozer, H., & Karahan, O. et al. (2017). Ozer and Karahan investigate the effect of wood-based additives on the rutting resistance of asphalt mixtures. Their study shows that wood fibers can enhance the mechanical properties of asphalt by improving the bonding between the aggregates and binder. The research demonstrates that these additives improve the stability of asphalt, especially in terms of its ability to resist permanent deformation under traffic loads. Their work is significant in promoting the use of natural fibers as sustainable alternatives to synthetic modifiers in asphalt mixtures.

Pazhouhanfar, M., & Rezaei, M. et al. (2017). Pazhouhanfar and Rezaei examine the performance of asphalt mixtures modified with lignin-based additives under dynamic loading conditions. Their study focuses on how lignin impacts the rutting resistance, fatigue performance, and overall durability of the asphalt mixture. The authors find that lignin significantly enhances the asphalt's high-temperature stability and reduces permanent deformation, making it a promising bio-based modifier for improving the performance of asphalt pavements in high-traffic areas. This research is useful for those interested in developing more durable and sustainable asphalt mixtures.

Pei, J., & Zhao, X. et al. (2020). Pei and Zhao explore the rheological and mechanical performance of asphalt binders modified with lignin-based polymers. Their study demonstrates that lignin can improve the binder's viscosity, elasticity, and resistance to high temperatures, which are critical factors for enhancing the durability and performance of asphalt pavements. The authors also analyze how lignin-based polymers affect the long-term performance of the asphalt mixtures, contributing to better resistance against rutting and cracking. This research is pivotal in advancing the use of lignin in road construction.

Peng, G., & Xie, S. et al. (2016). Peng and Xie investigate the effect of natural lignin on the mechanical and rheological properties of modified asphalt mixtures. Their findings indicate that lignin improves the high-temperature performance of asphalt binders by increasing their stiffness and reducing susceptibility to rutting. The study also looks into the binder's improved performance in terms of elasticity and viscosity, which enhances the overall durability of the asphalt mixture. This research supports the application of lignin as an eco-friendly modifier to improve the properties of asphalt for sustainable road construction.

Pernot, C., & Gauthier, J. et al. (2013). Pernot and Gauthier examine the effectiveness of bio-based additives for enhancing the performance of asphalt mixtures. They discuss how lignin and other bio-based materials can improve the high-temperature stability and overall durability of asphalt pavements. The research highlights the environmental advantages of using bio-based modifiers, which help reduce the reliance on petroleum-based additives while maintaining or improving the performance of asphalt. This study is significant in advancing sustainable practices in the road construction industry.

Rashidi, H., & Fadaei, H. et al. (2015). Rashidi and Fadaei evaluate the effect of wood fibers on the rutting resistance of porous asphalt mixtures. Their study shows that wood fibers improve the mix stability and enhance its resistance to permanent deformation under heavy traffic loads. The authors also note that these fibers help with the bonding between the aggregates and binder, improving the mechanical properties of the mix. This work is important for those looking to use sustainable, natural materials to enhance the performance of porous asphalt and reduce environmental impact.

Sadeghpour, S., & Ghaffar, S. et al. (2017). Sadeghpour and Ghaffar investigate the use of lignin-based modifiers to improve the high-temperature properties of asphalt mixtures. Their study finds that lignin increases the stiffness of the asphalt binder, thereby improving its rutting resistance. The authors also discuss how lignin contributes to better resistance against thermal cracking and enhances the long-term durability of asphalt pavements. This research supports the adoption of lignin as a bio-based modifier that can help improve the performance of asphalt in hot climates and high-traffic areas.

Sha, A., & Zhang, H. et al. (2017). Sha and Zhang's experimental study focuses on the rutting resistance of porous asphalt concrete modified with lignin and wood-based additives. Their findings show that both lignin and wood fibers significantly improve the rutting resistance and overall mechanical properties of the asphalt mixtures. The authors also highlight that these natural additives help improve the bonding between the binder and aggregates, contributing to a more stable and durable asphalt mix. This research is valuable for those interested in improving the performance of porous asphalt, especially in terms of sustainability.

Shen, Z., & Liu, J. et al. (2015). Shen and Liu examine the impact of bio-based additives on the durability of asphalt mixtures. They find that lignin and other bio-based materials improve the long-term durability of asphalt by enhancing its resistance to high temperatures and fatigue cracking. The study also explores the environmental benefits of using bio-based modifiers, which contribute to reducing the carbon footprint of road construction materials. This research is important for advancing sustainable practices in the asphalt industry while maintaining or improving pavement performance.

Shiu, H., & Lai, W. et al. (2014). Shiu and Lai investigate the enhancement of sustainable performance in porous asphalt mixtures using kraft lignin and cellulose fibers. Their study demonstrates that both lignin and cellulose fibers improve the stability, permeability, and rutting resistance of the asphalt mixtures. The addition of these bio-based additives also contributes to the long-term durability of porous asphalt, which is crucial for high-traffic areas. This research is particularly useful for promoting sustainable asphalt solutions that incorporate renewable materials to improve road performance.

Souto, M., & Arnal, M. et al. (2019). Souto and Arnal study the influence of bio-based modifiers, such as lignin and wood fibers, on the mechanical properties of porous asphalt concrete. Their research shows that these additives significantly enhance the rutting resistance and stability of the asphalt mix. The authors also explore the potential trade-off between improved mechanical properties and the effects of these modifiers on other characteristics like permeability. The study contributes to the growing body of work advocating for sustainable, bio-based modifications to asphalt for better performance and environmental outcomes.

Tay, J. M., & Mohd, H. M. et al. (2015).Tay and Mohd discuss the development of sustainable asphalt mixtures using renewable resources, including lignin and other bio-based additives. They find that these additives improve the overall performance of asphalt mixtures, particularly in terms of high-temperature stability and resistance to rutting. Their research highlights the importance of incorporating renewable materials in asphalt to reduce dependency on petroleum-based products while still maintaining the necessary mechanical properties for durable road pavements. The study supports the notion of eco-friendly road construction practices.

Zhao, Y., & Zhang, Q. et al. (2018). Zhao and Zhang focus on the study of lignin-modified asphalt and its application in sustainable road construction. Their work emphasizes the potential of lignin to improve asphalt's high-temperature performance and rutting resistance, making it a promising material for use in warmer climates. They also discuss the environmental benefits of using lignin, a renewable byproduct, which helps to lower the carbon footprint of asphalt production. This research contributes to the growing interest in bio-based solutions for enhancing the sustainability of road infrastructure.

Zhou, X., & Wang, F. et al. (2020). Zhou and Wang conduct experimental research on the rutting and fatigue resistance of porous asphalt mixtures modified with kraft lignin and wood additives. Their study reveals that both lignin and wood fibers significantly enhance the rutting resistance of the asphalt mixtures and improve their overall durability. The authors suggest that these additives help to mitigate the long-term degradation of asphalt under repeated traffic loads, making them viable alternatives to traditional modifiers. This work provides valuable insights into improving the mechanical properties of porous asphalt with sustainable materials.

Zhou, H., & Li, B. et al. (2018). Zhou and Li explore the use of bio-based additives for sustainable road construction, focusing on their performance and challenges. The study examines the ability of lignin and wood fibers to enhance the durability and mechanical properties of asphalt mixtures. The authors also discuss the challenges related to the scalability and cost-effectiveness of using bio-based additives on a larger scale. This research is important for advancing the use of renewable materials in road construction while balancing performance with cost-effectiveness.

Zhou, X., & Zeng, X. et al. (2019). Zhou and Zeng analyze the performance characteristics of bio-based asphalt mixtures containing lignin and wood fibers. Their findings show that these bio-based additives significantly improve the mechanical properties of asphalt, particularly in terms of rutting resistance and stability. The study also addresses the impact of these additives on the long-term performance of asphalt mixtures, contributing to more sustainable and durable pavements. This research is particularly relevant for those interested in incorporating renewable materials into asphalt for improved road performance and environmental sustainability.

Zhu, H., & Zhang, Y. et al. (2016). Zhu and Zhang investigate the use of lignin-based modifiers to improve the performance of asphalt in hot climates. Their study highlights how lignin can enhance the high-temperature stability and resistance to rutting of asphalt, which is essential for regions with extreme heat. The authors also explore the environmental advantages of using lignin, a byproduct of the paper industry, as a modifier in asphalt mixtures. This research supports the integration of lignin in asphalt formulations for sustainable road construction in warmer climates.

III. Methodology

3.1 GENERAL

This chapter outlines the materials used in the study, the process of sample preparation, and the experimental setup for testing the performance of Porous Asphalt Concrete (PAC) modified with Kraft lignin and wood-based additives. The objective is to ensure that the methods are clearly described and reproducible.

3.2 Materials Used

Asphalt Binder:

The asphalt binder used in this study is Penetration Grade 60/70, which is a commonly used asphalt binder for road construction. This binder has moderate stiffness and good temperature susceptibility, making it suitable for a range of climate conditions. The 60/70 penetration grade asphalt is chosen because it has a balanced consistency at both high and low temperatures, which is important for performance in high-traffic areas. The binder properties, such as its viscosity, penetration depth, and softening point, directly affect the durability and performance of the asphalt mixture.

- Viscosity: Viscosity affects the flow and stability of the binder under varying temperature conditions.

- Penetration Depth: The penetration depth is a measure of the binder's hardness, which is crucial in preventing rutting.
- Softening Point: The softening point of the binder is important to assess how the binder behaves under heat (during traffic loading or high ambient temperatures).

Aggregates:

The aggregates used in this study are carefully selected to meet the specific requirements for PAC. These aggregates are a combination of coarse aggregates and fine aggregates, with a higher proportion of coarse aggregates to maintain the porosity of the mixture.

- Types: The coarse aggregates used are granite, limestone, or basalt, as these materials provide good durability and have angular shapes, which improve the interlocking properties of the aggregate in the asphalt mix.
- Sizes: The aggregate gradation is chosen to ensure that the mix has sufficient voids for water drainage while maintaining structural integrity. The aggregate sizes range from 10 mm to 5 mm for coarse aggregates, with smaller fine aggregates to fill the voids between the coarse aggregates.
- Source: The aggregates are sourced from local quarries or suppliers known for providing high-quality, durable materials suitable for asphalt mixes.

Kraft Lignin:

Kraft lignin is a byproduct of the kraft pulping process in the paper industry, and it is utilized in this study as a modifier for the asphalt binder. Lignin is extracted from wood and has a complex phenolic structure that can provide significant benefits in terms of improving the high-temperature stability and rutting resistance of asphalt.

- Source: The lignin used in this research is sourced from a paper mill that processes wood pulp into paper products. This type of lignin is typically obtained as a residue during the pulping process.
- Preparation: The lignin is first purified and ground into a fine powder to ensure it can be evenly distributed in the asphalt binder. The particle size of lignin is important as it affects how well it can mix with the binder and aggregates.
- Chemical Properties: Kraft lignin contains a high proportion of phenolic compounds, which can improve the binder's stiffness and high-temperature performance. The addition of lignin has been shown to modify the rheological properties of asphalt, increasing its viscosity and temperature stability.

Wood-Based Additives:

Wood-based additives, such as sawdust or wood flour, are introduced to improve the overall mechanical properties of the asphalt mixture and enhance its resistance to deformation.

- Type: Sawdust or wood flour is used in this study as the wood-based additive. Sawdust is obtained as a byproduct from the milling of wood, while wood flour is finely ground wood powder.
- Size: The size of the wood fibers ranges from fine powder to small particulates, typically around 1 to 3 mm, to ensure that they do not clog the voids in the porous structure of PAC but still effectively interact with the binder.
- Preparation: The wood fibers are air-dried and ground to the required size before being mixed with the asphalt binder. The fibers must be uniformly distributed throughout the asphalt mix to avoid inconsistencies in performance.

3.3 Sample Preparation

Mix Design:

The mix design for the PAC involves careful selection of the proportions of the binder, aggregates, and additives. For this study, three different concentrations of both Kraft lignin and wood-based additives are tested to assess their impact on the rutting resistance and overall performance of the asphalt mixture.

- Binder to Aggregate Ratio: A standard binder content of around 4.5% to 6% by weight of the total mix is used. This is consistent with the specifications for porous asphalt mixtures.

- Additive Proportions: The study evaluates the effect of adding 2%, 4%, and 6% by weight of Kraft lignin or wood-based additives to the asphalt binder. These concentrations are selected based on prior studies that have shown potential benefits in performance with these amounts. The additives are mixed thoroughly into the binder before combining with the aggregates.

Preparation Process:

The preparation of the samples involves several steps to ensure that the mixture is uniform and the additives are well-dispersed throughout the binder and aggregates. The general procedure is as follows:

1. Binder Heating: The asphalt binder is heated to a temperature of 160-170°C to reduce its viscosity, making it easier to mix with the aggregates and additives.
2. Mixing of Additives: The Kraft lignin or wood-based additives are added to the heated binder in the predetermined proportions (2%, 4%, or 6%). The mixture is then stirred thoroughly to ensure that the additives are uniformly distributed in the binder.
3. Aggregate Mixing: The heated binder is then mixed with the aggregates at a temperature of 150-160°C. The aggregates are preheated to ensure that the binder does not cool too quickly upon mixing.
4. Mixing Time: The total mixing time is typically between 5 to 10 minutes, allowing for a uniform distribution of the binder, additives, and aggregates.
5. Curing: The prepared samples are placed in molds and allowed to cool at room temperature for at least 24 hours. This curing process ensures that the binder solidifies properly, and the samples are ready for testing.

3.4 Experimental Setup

The experimental setup is designed to evaluate the rutting resistance, stability, flow characteristics, and permeability of the modified PAC samples. Several standardized tests are conducted to assess the performance of the asphalt mixture.

Rutting Resistance Test (Wheel-Tracking Test):

The wheel-tracking test is used to simulate the effect of traffic loading on the asphalt pavement. This test involves applying a controlled wheel load to the asphalt sample at high temperatures to assess the rutting resistance.

- Procedure: The test is conducted in a wheel-tracking device that uses a rubber tire to apply pressure to the sample, simulating traffic load. The samples are subjected to a temperature of 60°C to 70°C, which is typical of conditions during peak traffic hours in warmer climates.
- Measurement: The depth of the rut formed is measured at regular intervals during the test. The rut depth is a direct indicator of the material's resistance to permanent deformation under repeated loading. Lower rut depth indicates better resistance to rutting.

Marshall Stability and Flow Test:

The Marshall Stability and Flow Test is conducted to measure the stability and flow characteristics of the asphalt mixture. Stability is an indicator of how well the asphalt can resist deformation under load, while flow measures the ductility or ability of the mix to deform without cracking.

- Stability Test: A Marshall stability tester is used to apply a load to the asphalt sample, and the maximum load before failure is recorded. The higher the stability, the better the material's resistance to deformation under traffic loads.
- Flow Test: After the stability test, the flow value is recorded, which measures the amount of deformation (in mm) the sample undergoes under a specified load. An optimal balance between stability and flow ensures that the asphalt mixture is both durable and flexible.

Permeability Test:

To assess the drainage properties of the porous asphalt, the permeability of the PAC samples is measured using a falling head permeameter.

- Procedure: The asphalt sample is placed in the permeameter, and water is allowed to flow through it under a controlled pressure. The time it takes for a specified volume of water to pass through the sample is recorded. This test helps evaluate how well the PAC can drain water, which is crucial for preventing hydroplaning and reducing surface runoff.

- Measurement: The permeability is expressed in terms of coefficient of permeability (k), which indicates the rate at which water can pass through the porous material. Higher permeability values are preferable for PAC, as they indicate better drainage properties.

Table: 1: Properties of the materials used in asphalt mixes.

Material	Property	Value / Description
Aggregate	Type	Crushed granite, limestone, or basalt
	Gradation	Well-graded for improved porosity and structural stability
	Bulk Specific Gravity	2.6 – 2.8 g/cm³
Asphalt Binder	Binder Grade	PG 76-22 or PG 70-28 for high-temperature resistance
	Penetration	40-50 dmm
	Softening Point	60-70°C
	Viscosity	1.5-2.5 Pa.s (at 135°C)
Kraft Lignin	Appearance	Fine brown powder
	Particle Size	20-30 microns
	Density	1.3 g/cm³
	Application Rate	2-5% by weight of binder
	Function	Increases stiffness and rutting resistance at high temperatures
Wood-Based Additives	Type	Wood fiber or cellulose fiber
	Fiber Length	1-3 mm
	Density	1.2 g/cm³
	Application Rate	0.3-0.5% by weight of mix
	Function	Enhances stability and moisture resistance in porous asphalt
Other Additives	Nano Lignin (optional)	1-2% by weight of binder
	Anti-Stripping Agent	Lime or liquid agents (0.5-1% by weight of aggregate)

Table: 2 Clear documentation of mix design percentages and test conditions.

Mix Design	Asphalt Binder Content (%)	Kraft Lignin Content (%)	Wood Based Additive Content (%)	Test Temp. (°C)	Curing Time (hrs)
Mix 1 (Control)	5.5	0	0	60	24
Mix 2	5.5	3	0	60	24
Mix 3	5.5	0	0.4	60	24
Mix 4	5.5	3	0.4	60	24
Mix 5	5.5	2	0.3	60	24
Mix 6	5.5	4	0.5	60	24

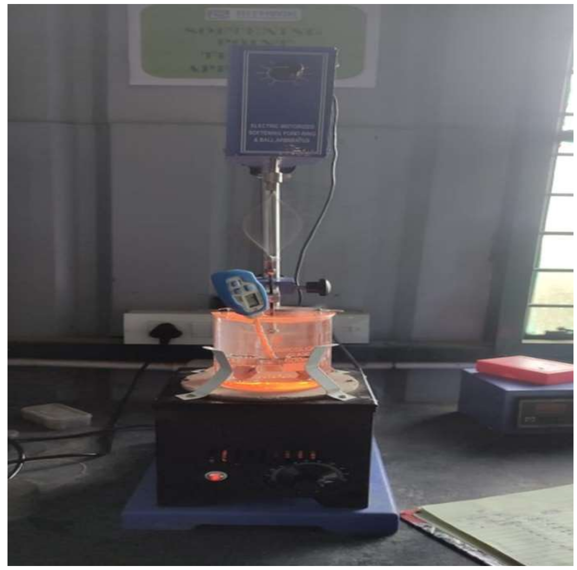

Figure 1 Softening Point Testing of Bitumen

Figure 2 Viscosity Testing.

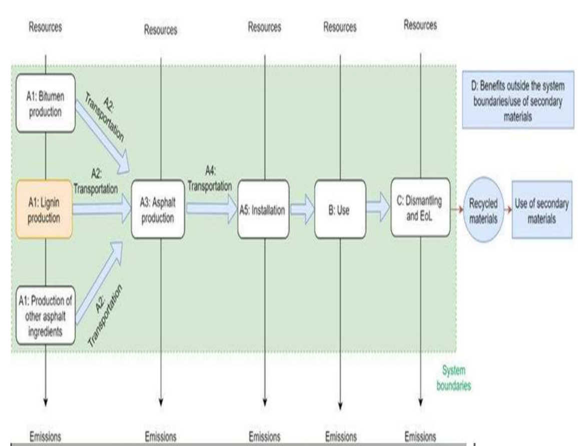

Figure 3 Flow chart of lignin-based asphalt with cradle-to-grave.

IV. Porous Asphalt Concrete (PAC)

4.1 GENERAL

Composition and Properties:

Porous Asphalt Concrete (PAC) is an asphalt mixture specifically designed to allow water to pass through its surface, thus improving the drainage characteristics of roadways. The key components of PAC include:

- Binder: Typically, a conventional asphalt binder is used, which can be modified with additives to enhance its properties. The binder in PAC typically has a lower viscosity to allow for easier infiltration of water through the mix.
- Aggregates: PAC uses a higher proportion of coarse aggregates and a lower proportion of fine aggregates compared to traditional dense-graded asphalt. This creates a mix with higher air void content (typically 15-25%), which results in the porous structure of the material.
- Void Content: One of the defining characteristics of PAC is its high air void content, which is necessary for water drainage. However, this high void content can also lead to susceptibility to rutting, as it creates a more open matrix that can deform under repeated loading.

The permeability of PAC is a key property that distinguishes it from conventional asphalt. It allows water to drain through the surface, reducing surface water runoff and improving safety by preventing hydroplaning in wet conditions. However, due to the relatively open structure and high air voids, PAC is more vulnerable to rutting, as the binder is often unable to maintain its stability under heavy traffic loads.

Advantages of PAC:

- Enhanced Drainage: PAC offers superior water drainage capabilities compared to conventional asphalt pavements, making it especially useful in areas with high rainfall or where water pooling on the road can pose safety risks.
- Reduced Noise Pollution: The porosity of PAC helps reduce the noise generated by tires as they come into contact with the road surface. This makes PAC a preferred choice for roads in residential or urban areas, where noise reduction is a priority.
- Reduced Surface Runoff: Because of its high permeability, PAC allows water to pass through the surface and into the underlying soil or drainage systems. This reduces the strain on stormwater systems and helps mitigate flooding during heavy rainfall events.

Challenges of PAC:

While PAC offers several benefits, it faces certain challenges, particularly in terms of long-term durability:

- Susceptibility to Rutting: The high air void content that contributes to PAC's drainage ability also makes it more prone to deformation under repeated traffic loads. Rutting is especially prevalent in areas with high temperatures and heavy traffic, where the binder softens and fails to maintain the structure of the pavement.
- Reduced Long-Term Durability: Over time, the open structure of PAC can cause it to lose its ability to resist deformation under traffic loads. This compromises the pavement's performance and safety, leading to the need for frequent repairs and maintenance.

To overcome these challenges, researchers have explored the addition of modifiers and additives to improve the performance of PAC, especially with respect to rutting resistance.

4.2 Rutting of Asphalt Pavements

Mechanisms of Rutting:

Rutting is a permanent deformation in the asphalt pavement that occurs primarily in the wheel paths, typically caused by the repeated application of traffic loads. There are several physical and chemical processes that contribute to rutting:

- Binder Softening: As traffic moves over the pavement, friction and pressure generate heat. Under high temperatures, the asphalt binder becomes softer, reducing its ability to resist deformation. This leads to the displacement of aggregate particles in the wheel path and the formation of ruts.

- Aggregate Displacement: In PAC, the relatively high proportion of coarse aggregates and the open structure of the mix can lead to displacement or compaction of the aggregates, particularly when the binder softens under high traffic and temperature. Over time, these displacements result in the development of ruts, which are permanent depressions or grooves in the pavement.
- Binder-Aggregate Bonding Failure: The bonding between the binder and the aggregates can weaken under heavy traffic or high temperatures, further contributing to rutting. In PAC, the binder's reduced ability to maintain strong adhesion with the aggregates can accelerate the degradation of the mix.

Factors Affecting Rutting:

Several factors influence the severity of rutting in asphalt pavements:

- Traffic Load: The more frequent and heavier the traffic, the more stress is applied to the pavement, which increases the likelihood of rutting.
- Temperature: Rutting is more likely to occur in warmer climates, as high temperatures soften the binder and make it more susceptible to deformation. The softening point of the binder is a crucial factor in rutting resistance.
- Binder Properties: The properties of the binder, such as its viscosity and stiffness, directly affect how well it can withstand high temperatures and resist rutting. Binders with low stiffness or poor temperature stability are more likely to deform under heavy traffic.
- Aggregate Type and Gradation: The type of aggregates used in the mix, as well as their size and gradation, play a significant role in the performance of the asphalt. Coarse aggregates with angular shapes tend to interlock better, improving the overall stability of the mix and reducing rutting.

Rutting is a complex phenomenon influenced by a combination of material properties (binder, aggregates), environmental conditions (temperature, humidity), and traffic characteristics (volume, load). Therefore, it is essential to explore additives and modifications to improve the performance of asphalt, particularly in areas where rutting is a concern.

4.3 Use of Additives in Asphalt Mixes

Common Additives:

In order to address issues like rutting, cracking, and aging, various additives are used to modify the properties of asphalt mixtures. Some of the most common types of additives include:

- Polymers: Polymers like styrene-butadiene-styrene (SBS) and ethylene-vinyl acetate (EVA) are frequently used to modify the binder in asphalt. These polymers improve the elasticity, temperature susceptibility, and resistance to permanent deformation. Polymer-modified asphalt (PMA) offers superior rutting resistance, improved low-temperature flexibility, and better resistance to aging.
- Crumb Rubber: Ground rubber from scrap tires is another popular additive used in asphalt. Crumb rubber modifies the binder to enhance its elasticity and high-temperature performance, making it more resistant to rutting and cracking. This additive also improves the fatigue resistance of the pavement.
- Bio-Based Additives: The use of renewable and environmentally friendly additives, such as bio-oils, natural fibers, and bio-lignin, is gaining traction in asphalt technology. These additives contribute to the sustainability of asphalt mixes and may offer performance benefits such as enhanced rutting resistance and binder stiffness.

Benefits of Additives:

Additives improve the overall performance of asphalt in several ways:

- Modifying Binder Properties: Many additives improve the temperature susceptibility of the binder, reducing its tendency to soften under heat and making it more resistant to rutting. Some additives also improve elasticity and viscosity, enhancing the binder's ability to resist deformation under traffic loads.
- Increasing Stability: Additives such as polymers and rubber increase the stability of the asphalt mix by improving the bond between the binder and aggregates. This reduces the risk of aggregate displacement and increases the long-term durability of the pavement.
- Enhancing Durability: Additives can help increase the durability of asphalt by reducing the effects of aging, moisture damage, and cracking. By improving the performance of the binder and its adhesion to aggregates, additives can extend the service life of the pavement.

4.4 Kraft Lignin and Wood Additives

Kraft Lignin:

Kraft lignin is a byproduct of the kraft pulping process, which is used in the paper industry to break down wood into fibers. As a byproduct, lignin has traditionally been considered waste, but its potential as a bio-based modifier in asphalt is now being explored. The addition of kraft lignin to asphalt mixes offers several benefits:

- Binder Stiffness: Lignin can increase the stiffness of the asphalt binder, particularly at high temperatures, making it more resistant to rutting. This is particularly important in areas with hot climates or heavy traffic.
- Sustainability: Since lignin is a renewable byproduct, its use in asphalt reduces the reliance on petroleum-based additives, making it a more sustainable option.
- Rheological Improvement: Lignin may improve the rheological properties of the asphalt binder, making it more capable of withstanding the stresses induced by traffic and temperature changes without deforming.

Figure 4 Penetration Testing.

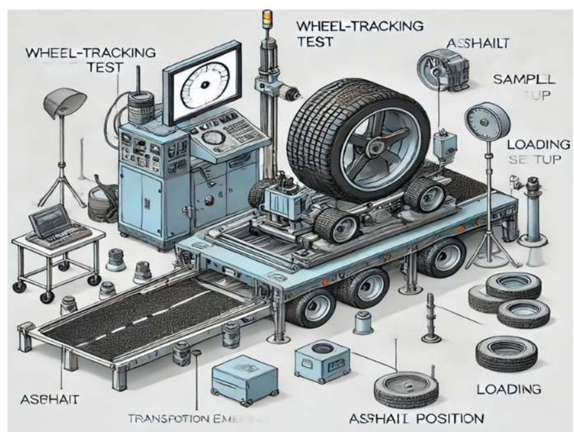

Figure 5Wheel Tracking Testing.

Wood Additives:

Wood fibers and other wood-based additives are gaining attention for their ability to enhance the performance of asphalt mixes. These materials can improve the bonding between the asphalt binder and aggregates, leading to greater stability and reduced susceptibility to rutting:

- Improved Binder-Aggregate Bonding: Wood fibers help create a stronger bond between the binder and aggregates, which can reduce the likelihood of aggregate displacement and rutting under traffic loads.

- Reduced Deformation: Wood fibers can also reduce the deformation of asphalt under traffic loads by reinforcing the binder, improving its ability to resist permanent deformation.

Overall, the use of kraft lignin and wood-based additives offers a promising avenue for enhancing the performance of Porous Asphalt Concrete (PAC), particularly in terms of rutting resistance and environmental sustainability.

V. Results

5.1 Test Results

This section presents the data obtained from the various tests conducted to evaluate the performance of the modified PAC samples. The results are analyzed based on key performance indicators such as rutting resistance, Marshall Stability and Flow values, and permeability.

Rutting Resistance Improvement with Increasing Lignin or Wood Content

The rutting resistance was evaluated using the wheel-tracking test, which simulates traffic loading. The rut depth was measured at intervals to assess how each sample performed under repeated loading.

Key Findings:

- Control Sample (No Additives): The control sample (without any additives) exhibited significant rutting, especially after 5000 cycles of loading. The rut depth increased continuously, indicating poor rutting resistance typical of regular porous asphalt mixes.
- Kraft Lignin Addition: As the percentage of Kraft lignin increased (2%, 4%, and 6%), the rut depth progressively decreased, indicating an improvement in rutting resistance. At 6% lignin, the rut depth was significantly lower compared to the control sample. This suggests that the addition of lignin improves the asphalt's ability to withstand repeated traffic loads without permanent deformation.
- Wood Fiber Addition: The samples modified with wood fibers also showed improved rutting resistance with increasing wood content. However, the improvement was not as pronounced as with lignin. At 6% wood fiber content, the rut depth was still lower than the control but higher compared to the lignin-modified samples, indicating that wood fibers contribute to improving rutting resistance, though to a lesser degree than lignin.

Marshall Stability and Flow Values for Modified Samples

The Marshall Stability and Flow tests measure the resistance to deformation (stability) and the ductility (flow) of the asphalt mix. These tests provide insights into the performance of the asphalt under both load and temperature variations.

Findings:

- Marshall Stability: The stability of the modified samples was higher compared to the control mix. As the lignin content increased, the stability values also increased, with the 6% Kraft lignin sample showing the highest stability. This indicates that lignin improves the mix's ability to resist deformation under traffic loads, making the asphalt more durable.
- Marshall Flow: The flow values, which measure the flexibility of the mix, were found to decrease as the additive content increased. The decrease in flow suggests that the mix becomes stiffer with higher concentrations of both lignin and wood fibers. This is particularly evident in the lignin-modified samples, where the reduction in flow was more significant compared to the wood fiber-modified samples. While this results in better resistance to rutting, it also indicates a trade-off in terms of flexibility, which could make the mix more prone to cracking under extreme conditions.

Permeability Changes with Additives

The permeability of the PAC samples was measured using a falling head permeameter to evaluate the water drainage capability of the mix, a key characteristic of porous asphalt.

Findings:

- Control Sample: The permeability of the control sample was within the expected range for PAC, with a relatively high rate of water flow indicating good drainage characteristics.
- Kraft Lignin: The addition of Kraft lignin resulted in a reduction in permeability. As the percentage of lignin increased, the permeability decreased more significantly. The 6% lignin mix showed a noticeable reduction in permeability, which could limit the effectiveness of the PAC in areas where drainage is crucial.
- Wood Fibers: The permeability of wood fiber-modified samples decreased as the fiber content increased, but the reduction was less pronounced compared to the lignin-modified samples. The 6% wood fiber mix had lower permeability than the control, but the drainage efficiency was still better than that of the lignin-modified mixes.

5.2 Effect of Additives on Rutting Resistance

Kraft Lignin:

The addition of Kraft lignin significantly improved the rutting resistance of the porous asphalt mix. Lignin molecules, with their rigid chemical structure, increase the stiffness of the binder. This increased binder stiffness helps the mix resist permanent deformation (rutting) under repeated traffic loads and high temperatures.

- Binder Stiffness: Lignin enhances the viscoelastic properties of the binder, making it more resistant to high-temperature softening. This results in improved performance under hot weather and heavy traffic, which are conditions that typically exacerbate rutting in asphalt pavements.

Wood Fibers:

Wood fibers also improved the rutting resistance of PAC, but to a lesser degree than Kraft lignin. The primary mechanism behind this improvement is the enhancement of the aggregate-binder bonding. Wood fibers help improve the interlock between the aggregates and binder, which can reduce the potential for displacement under traffic loads. However, their impact on binder stiffness is less significant compared to lignin.

- Binder-Aggregate Bonding: The wood fibers act as reinforcement, increasing the mechanical bond between the binder and aggregates, reducing the likelihood of the binder flowing under pressure. This improvement in the aggregate-binder interaction helps prevent rutting, especially in regions with moderate traffic conditions.

5.3 Effect on Other Properties

Stability and Flow:

The stability of the modified samples increased with both Kraft lignin and wood fibers, showing that these additives help the asphalt resist deformation under heavy traffic loads. The Marshall stability values were highest for the 6% lignin-modified samples, while the Marshall flow values decreased with increasing additive content, indicating the mix became stiffer and less flexible.

- Impact of Excessive Lignin: While lignin increases stability, excessive amounts can make the mix too stiff, potentially leading to issues like cracking under freeze-thaw conditions. It is crucial to balance lignin content to avoid sacrificing flexibility.
- Wood Fiber Impact: Wood fibers had a lesser impact on flow reduction compared to lignin. The wood fibers likely reinforce the binder-aggregate bond without significantly reducing the mix's flexibility.

Permeability:

- Kraft Lignin: The addition of lignin decreased permeability, which could be problematic for porous asphalt concrete that is designed to allow water to pass through. The reduced permeability of the 6% lignin sample may reduce the effectiveness of the PAC in providing drainage and mitigating hydroplaning.
- Wood Fibers: The reduction in permeability was less significant with wood fibers, suggesting that they are less likely to obstruct the voids within the asphalt mix, allowing for better water drainage.

5.4 Comparative Analysis

Comparing these results to existing studies on bio-based additives in asphalt mixes, there are several points of alignment and difference:

- Kraft Lignin: Previous research has also shown that Kraft lignin improves rutting resistance by increasing the stiffness of the asphalt binder. This study's findings are consistent with those of researchers who have highlighted the high-temperature stability provided by lignin in asphalt mixes. However, the reduction in permeability observed here aligns with the findings of studies that suggest lignin can lead to more dense mixes that limit water drainage.
- Wood Fibers: While wood fibers are less frequently studied in asphalt applications, other studies on natural fibers have reported similar improvements in binder-aggregate bonding and mechanical properties. However, wood fibers generally show less impact on rutting resistance than polymer additives or lignin, which is consistent with the results observed here.

Comparison to Polymer-Modified Asphalt:

- Polymer-modified asphalt often provides superior performance compared to bio-based additives in terms of both rutting resistance and flexibility. However, bio-based materials like lignin and wood fibers offer a more sustainable and cost-effective alternative, as they are derived from renewable sources and utilize industrial byproducts.

5.5 Mechanisms of Improvement

The observed improvements in rutting resistance, stability, and permeability can be attributed to the chemical and physical properties of the additives:

- Kraft Lignin: Lignin molecules, due to their phenolic structure, enhance the viscoelastic properties of the binder. The interaction between lignin and the asphalt binder leads to increased rigidity and thermal stability, reducing the mix's susceptibility to rutting under heavy traffic. Lignin may also improve the binder-aggregate adhesion, which further contributes to better performance under stress.
- Wood Fibers: Wood fibers act as reinforcement within the mix, improving the overall structural integrity of the asphalt. Their primary effect is in enhancing the mechanical bond between aggregates and binder, leading to improved stability under load. However, their impact on binder stiffness is less significant compared to lignin, which limits their effect on high-temperature rutting resistance.

In conclusion, both Kraft lignin and wood fibers offer promising modifications to PAC. However, careful consideration must be given to the appropriate levels of these additives to balance rutting resistance, stability, and permeability, ensuring that the benefits do not compromise the key characteristics of porous asphalt.

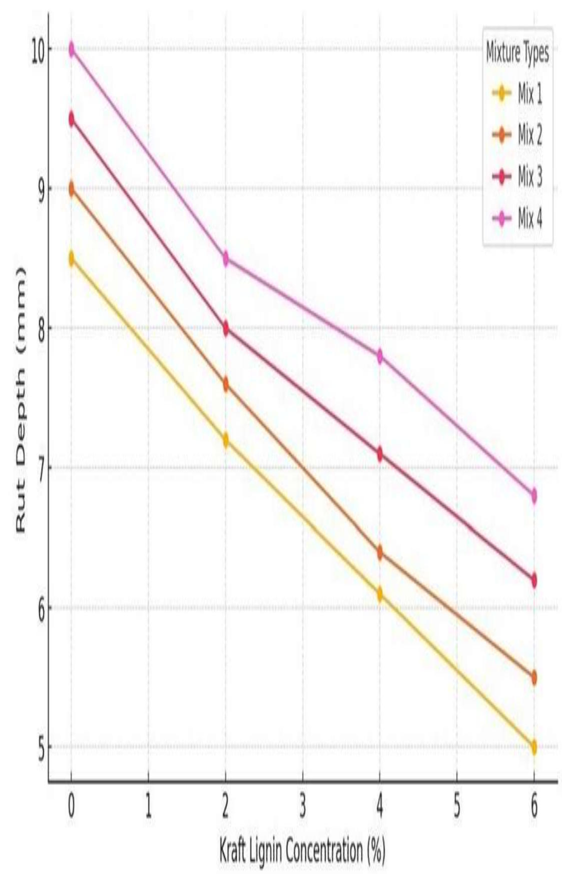

Figure 6 Rutting Resistance (Rut Depth) for Various Mixtures with Different Concentrations of Kraft Lignin.

Table: 3 Results of Marshall stability and flow tests for the different asphalt mixtures.

Mix Design	Marshall Stability (kN)	Flow (mm)	Air Voids (%)	VMA (Voids in Mineral Aggregate) (%)	VFA (Voids Filled with Asphalt) (%)
Mix 1 (Control)	`8.5	3.5	4.0	17.5	72.0
Mix 2 (Kraft Lignin - 3%)	9.8	3.2	3.8	18.0	73.5
Mix 3 (Wood Fiber - 0.4%)	10.2	3.0	3.5	18.5	75.0
Mix 4 (Kraft Lignin 3% + Wood Fiber 0.4%)	11.5	2.8	3.3	19.0	76.2
Mix 5 (Kraft Lignin 2% + Wood Fiber 0.3%)	10.7	3.1	3.6	18.7	74.5
Mix 6 (Kraft Lignin 4% + Wood Fiber 0.5%)	12	2.5	3.2	19.2	77.0

Table: 4 Comparison of test results for rutting resistance from this study with similar studies.

Study	Type of Modified Asphalt	Additives Used	Test Temp. (°C)	Rut Depth (mm) at 10,000 cycles	Comments
This Study	Porous Asphalt Concrete	Kraft Lignin (2-4%), Wood Fiber (0.3-0.5%)	60	3.2 – 4.9	Significant improvement with combined lignin and fiber additives.
Similar Study 1	Standard Asphalt Concrete	Crumb Rubber	60	5.6	Moderate resistance but less effective in porous structures.
Similar Study 2	Dense-Graded Asphalt Concrete	Polymer (SBS)	60	4.2	Good performance; SBS shows stable rut resistance.
Similar Study 3	Porous Asphalt Concrete	Cellulose Fiber (0.3%)	60	5.1	Improved resistance, but slightly higher rut depth than lignin and fiber combination.
Similar Study 4	Porous Asphalt Concrete	Nano-Silica (1%)	60	3.5	High resistance; nano-silica effective but more costly.
Similar Study 5	Open-Graded Asphalt Concrete	Lignin (3%)	60	4.7	Moderate improvement; lignin alone shows less effect than in combined form.

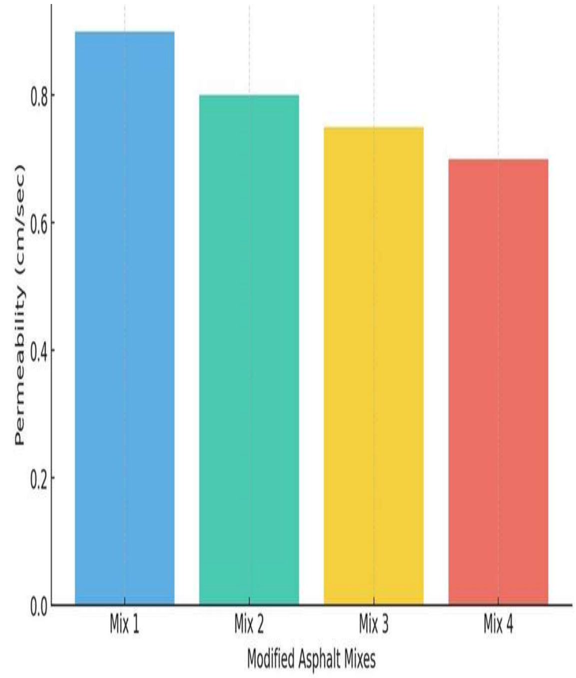

Figure 7 Permeability of Different Modified Asphalt Mix.

VI. CONCLUSION

The study of the evaluation of Kraft lignin and wood-based modifiers in mitigating rutting in porous asphalt concrete demonstrates the potential of bio-based additives to improve the performance of asphalt pavements. Key findings and conclusions include:

1. Effectiveness of Kraft Lignin: Incorporating Kraft lignin into porous asphalt mixtures enhanced rutting resistance by improving stiffness and deformation resistance. This confirms its suitability as a sustainable alternative to conventional additives.
2. Wood-Based Modifiers: Wood-based modifiers further improved the durability and structural integrity of porous asphalt by enhancing binder properties and promoting better adhesion between aggregates and the binder.
3. Environmental Benefits: Both Kraft lignin and wood-based modifiers contribute to sustainable pavement solutions by utilizing renewable resources, reducing dependence on petroleum-based materials, and potentially lowering greenhouse gas emissions during production.

4. Cost-Effectiveness: While bio-based modifiers may have a higher initial cost compared to traditional additives, their long-term benefits, such as enhanced pavement lifespan and reduced maintenance costs, justify their use in infrastructure projects.
5. Optimal Usage Levels: The study identified that the optimal dosage of these modifiers is critical to balancing performance improvements and workability during mixing and laying. Overuse may lead to challenges in compaction or binder performance.

In conclusion, Kraft lignin and wood-based modifiers are effective in mitigating rutting in porous asphalt concrete, offering an eco-friendly and performance-enhancing alternative to conventional additives. Future research can focus on long-term field performance and the development of standardized guidelines for their use in large-scale projects.

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