Enhancing Crack Resistance in Flexible Pavement by Incorporating Lignin and Recycled Concrete Aggregate into Bitumen Mixes

Muskan[1], Er. Deepak Mathur[2]
[1]*M.Tech. Scholar, Kautilya Institute of Technology & Engineering, Jaipur*
[2]*Associate Professor, Kautilya Institute of Technology & Engineering, Jaipur*

***Abstract*—This research explores the incorporation of lignin into bitumen mixes as a sustainable approach to enhance crack resistance in flexible pavements. Lignin, a complex organic polymer derived from lignocellulosic biomass, is abundant and offers unique properties that can significantly enhance the performance of asphalt. By enhancing the mechanical characteristics of bitumen, lignin can increase ductility and elasticity, thus reducing brittleness and improving the material's ability to withstand deformation under load. This is particularly crucial for minimizing the risk of cracking, a common failure mode in flexible pavements. Furthermore, lignin improves the temperature susceptibility of asphalt binders, helping to maintain their performance under varying thermal conditions. This enhancement means that pavements are less likely to experience cracking in colder temperatures and are better equipped to handle deformation in hotter climates. The use of lignin not only contributes to improved mechanical properties but also aligns with global sustainability goals by reducing reliance on petroleum-based products. Its antioxidant properties enhance aging resistance, helping to maintain the integrity and performance of asphalt over time and reducing maintenance costs associated with pavement deterioration. However, the successful incorporation of lignin poses challenges, such as achieving uniform dispersion in bitumen and determining the optimal dosage to maximize benefits while maintaining workability. The study investigates the effects of lignin and recycled concrete aggregate (RCA) on bitumen and its mixtures. Lignin addition reduced penetration and ductility values while increasing softening point, specific gravity, and fire/flash points, enhancing stiffness and resistance to deformation. The inclusion of RCA slightly reduced aggregate strength, indicated by higher crushing, impact, and abrasion values. Lignin improved Marshall Stability, fracture energy, and flexibility index, with maximum stability of 11.05 kN and fracture energy of 1126.03 J/m². However, tensile strength ratio (TSR) decreased, highlighting moisture susceptibility. The combined use of lignin and RCA shows promise for sustainable, crack-resistant pavement applications.**

***Index Terms*—Lignin, Recycled Concrete Aggregate, Bitumen, Flexible Pavement, Crack Resistance, Sustainable Materials and Pavement Performance.**

I. INTRODUCTION

The increasing demand for sustainable construction practices has prompted a significant shift toward using waste materials in road construction in India. As urbanization accelerates and infrastructure development expands, the challenge of managing waste efficiently has become critical. Utilizing waste materials not only addresses the burgeoning waste problem but also enhances the sustainability of road construction by reducing the consumption of virgin materials, lowering greenhouse gas emissions, and promoting recycling and circular economy principles. In India, various waste materials, including industrial by-products like fly ash, slag, and quarry waste, as well as post-consumer materials such as plastic and rubber from used tires, are being explored for road construction. Incorporating these materials can improve mechanical properties, durability, and provide cost-effective alternatives. Using rubber in pavement surfaces also addresses disposal issues while enhancing flexibility and resilience. Government initiatives like the Swachh Bharat Mission support sustainable practices, promoting research and guidelines for integrating waste materials in infrastructure projects.

A. Pavement

Pavement is a crucial component of modern infrastructure, serving as the surface layer of roads, streets, and other transportation networks. It is designed to offer a durable, stable, and smooth surface for vehicles and pedestrians while also managing water drainage and reducing the environmental impact of roadways. There are several types of pavements, primarily categorized into flexible and rigid pavements.

• Flexible Pavement

• Rigid Pavement

B. Lignin in in Flexible Pavement

Lignin, an organic polymer found in plant cell walls and a by-product of the pulping and paper industries, offers a promising additive for enhancing the performance and sustainability of asphalt mixtures in road construction. Its incorporation into bitumen provides several benefits, contributing to more environmentally friendly and durable pavement solutions.

C. Recycled Concrete Aggregate (RCA) in Flexible Pavement

Recycled Concrete Aggregate (RCA) has emerged as an affordable and ecologically conscious option for flexible pavements. As the demand for construction materials continues to rise, the use of RCA helps address environmental concerns related to the disposal of concrete waste and the depletion of natural aggregate resources. Incorporating RCA into flexible pavement systems not only promotes recycling but also enhances the mechanical and durability properties of asphalt mixtures.

II. LITERATURE REVIEW

In this study by Albayati and Albayati (2025) explored the application of soda lignin powder in enhancing the durability of asphalt concrete. It focused on the material's mechanical and rheological properties, demonstrating that lignin incorporation significantly improved stiffness and resistance to rutting and cracking. The research highlighted soda lignin's ability to interact synergistically with asphalt components, reducing fatigue and thermal cracking. The authors suggested that soda lignin powder could serve as an economical and eco-friendly alternative to conventional modifiers in asphalt mixtures. Ashteyat et al., 2024 studied flexibility of reinforced concrete (RC) beams containing reused concrete aggregate (RCA) and reclaimed asphalt pavement (RAP) under high temperatures. It aimed to evaluate the performance of these sustainable materials in extreme conditions, which is important for structural applications in thermally exposed regions. The research highlighted sustainability and structural integrity but had a limitation in testing a narrow range of temperatures. RC beams with varying RCA and RAP percentages were subjected to flexural tests under controlled heating. The results showed that RCA and RAP could maintain sufficient flexural strength at moderate temperatures, suggesting their potential for use in fire-prone environments while supporting recycling in construction. **Coelho et al.** (2024) explored the impact of curing time on the mechanical properties of cold recycled bituminous mixes in flexible pavement base layers. It found that longer curing times improved stiffness and strength, with optimal performance achieved after a specific duration. However, the study also noted diminishing returns beyond a certain curing period, emphasizing the need to balance curing time with cost-effectiveness for sustainable pavement construction. The paper by Khadim and Ahmad (2024) examines the effect of paper waste lignin as a binder modifier in hot mix asphalt. The study evaluates the impact of lignin on the mechanical properties, performance, and durability of asphalt mixtures. Results indicate that incorporating paper waste lignin improves the stiffness and rutting resistance of the asphalt. The research highlights lignin's potential as a sustainable and cost-effective alternative binder modifier in asphalt production.

Manjima et al. (2023) investigated the partial replacement of bitumen with plant polymer lignin in bituminous pavements, aiming to reduce reliance on fossil fuels. It demonstrated lignin's potential to improve asphalt performance, including enhanced mechanical properties and resistance to aging. While the focus on eco-friendly alternatives was a strength, the lack of extensive field testing was a limitation. Experimental tests showed that lignin could be a sustainable modifier for bituminous pavements. Xu et al. (2021) examined how lignin as a modifier affects bituminous binder performance, aiming to optimize asphalt properties. A key strength was its systematic approach to understanding lignin's impact, though a limitation was the narrow range of binder types tested. Asphalt binders with varying lignin percentages were prepared, and performance tests like the bending beam rheometer and dynamic shear rheometer were conducted. The results showed that lignin improved the binder's viscosity and temperature susceptibility, enhancing the overall asphalt mix performance.

III. OBJECTIVES

1. To assess how varying lignin content affects the stability and flow of bitumen mixes to identify the optimal dosage for enhanced performance.
2. To evaluate the tensile properties of lignin-modified bitumen mixes to determine their ability to resist cracking under tensile loads.
3. Analyze energy discharge rate and fracturing patterns to evaluate crack resistance in modified bitumen combinations.
4. Analyze the resilience of lignin-modified asphalt mixes to repeated loading and estimate its impact on endurance life under cyclic stress.
5. To evaluate the impact of lignin on the moisture resistance of bitumen mixes, focusing on adhesion properties in wet conditions.

IV. METHODOLOGY

In this research work choose lignin and Recycled Concrete Aggregate as replacement of bitumen and natural aggregates in bitumen mix. For this study percentage of lignin used in bitumen mix is 0%, 10%, 20% and 30%. Utilization of natural aggregate with Recycled Concrete Aggregate (RCA) at 0%, 5%, 10%, 15%, 20% and 25%. To enhancing crack resistance in flexible pavement by incorporating lignin and 20% recycled concrete aggregate into bitumen mixes is major concern of this study.

A. Natural Aggregate

Natural aggregates are widely used in flexible pavement construction due to their durability, strength, and availability. Natural aggregates, such as crushed stone, sand, and gravel, are essential in forming the base, sub-base, and surface layers of flexible pavements. They ensure structural stability, load distribution, and surface resilience, crucial for accommodating dynamic traffic loads and providing a stable foundation.

B. Bitumen

Bitumen is a critical component in flexible pavement, acting as a binding agent that holds aggregates together, creating a cohesive, durable, and flexible surface. Bitumen, a viscous, dark-colored hydrocarbon derived from crude oil, is known for its adhesive and waterproofing properties, making it ideal for pavement applications that must withstand dynamic loads and weather extremes.

C. Recycled Concrete Aggregate

Recycled Concrete Aggregate (RCA) is gaining attention as an eco-friendly alternative to natural aggregates in flexible pavement construction. RCA is derived from crushing demolished concrete structures, such as old buildings, roads, and other infrastructure, allowing for the repurposing of construction waste that would otherwise contribute to landfill volume. This sustainable approach offers several benefits and some challenges, making RCA a promising yet complex option in flexible pavement.

D. Waste Lignin

Waste lignin, a renewable by-product of the paper and pulp industry, has promising applications in sustainable construction and materials science. Traditionally burned for energy, its potential is underutilized, but its structural complexity and phenolic composition make it valuable for bio-based materials. In flexible pavement, lignin can replace bitumen, improving durability and flexibility while reducing reliance on petroleum. Its hydrophobic and UV-resistant properties also enhance composite materials, reinforcing structural integrity and extending product lifespan.

E. Mix Formulation of Bitumen Composition

Table 1. Replacement of Bitumen

Mix	Replacement of bitumen with Lignin	Bitumen %	Lignin%
1	0%	5.5	0
2	10%	4.95	0.55
3	20%	4.4	1.1
4	30%	3.85	1.65

Table 2. Replacement of aggregate

Mix	Aggregate Replacement with RCA	RCA 19-13.2 mm	Aggregate 19-13.2 mm	Aggregate 13.2-6.3 mm	Aggregate 6.3 mm to less
1	0%	0%	14%	15%	63.5%
2	5%	0.7%	13.3%	15%	63.5%
3	10%	1.4%	12.6%	15%	63.5%
4	15%	2.1%	11.9%	15%	63.5%
5	20%	2.8%	11.2%	15%	63.5%
6	25%	3.5%	10.5%	15%	63.5%

Table 3. Prepared Samples with Varying % of Lignin and with and without RCA

Name of Sample	Lignin	RCA
STD	0%	0%
L10RCA0	10%	0%
L20RCA0	20%	0%
L30RCA0	30%	0%
L10RCA20	10%	20%
L20RCA20	20%	20%
L30RCA20	30%	20%

V. RESULTS AND DISCUSSION

Results of Bitumen test

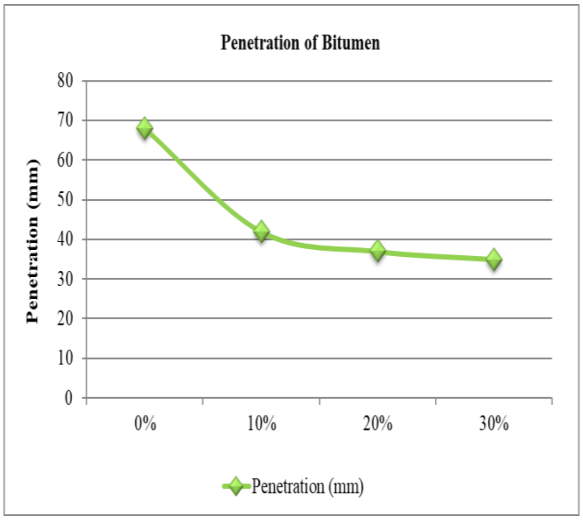

Figure 1. Penetration Value of Bitumen replacement with Lignin

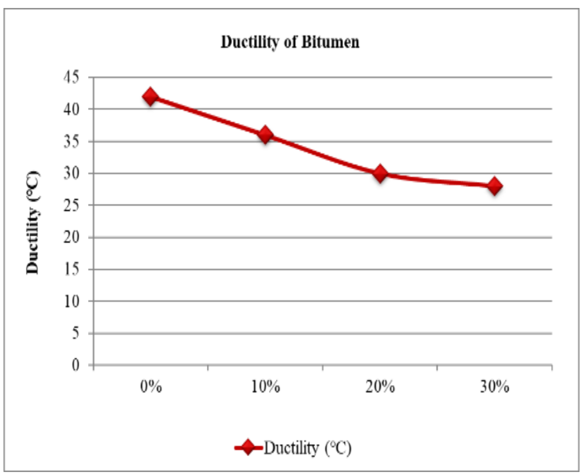

Figure 2. Ductility Value of Bitumen replacement with Lignin

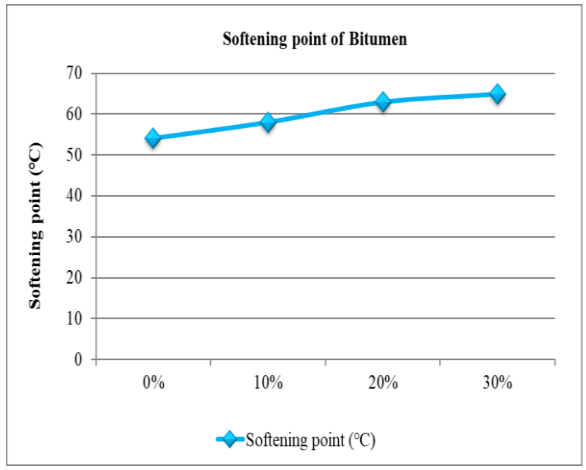

Figure 3. Softening point of Bitumen with varying percentage replacement of Lignin

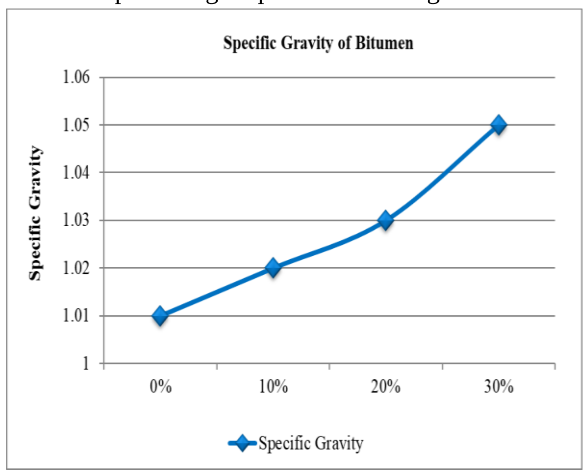

Figure 4. Specific Gravity of Bitumen replacement with Lignin

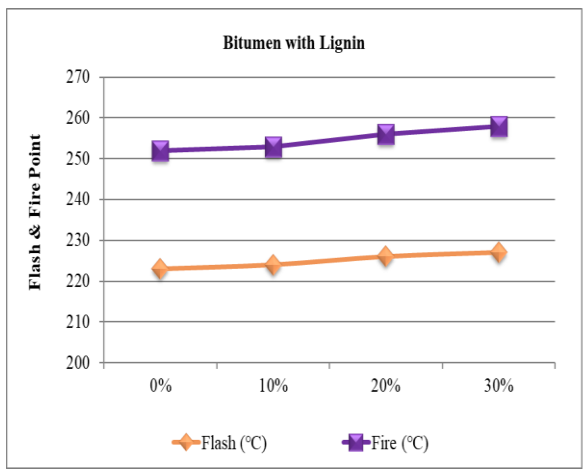

Figure 5. Flash and Fire point test of Bitumen replacement with Lignin

Results of Aggregate test

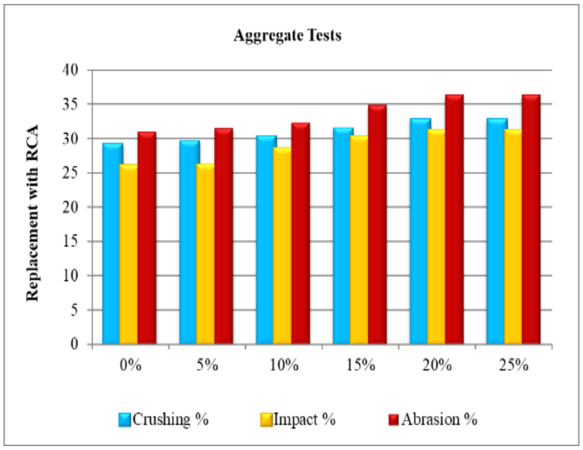

Figure 6. Test values of aggregate with percentage replacement of RCA

Results of Bitumen mix

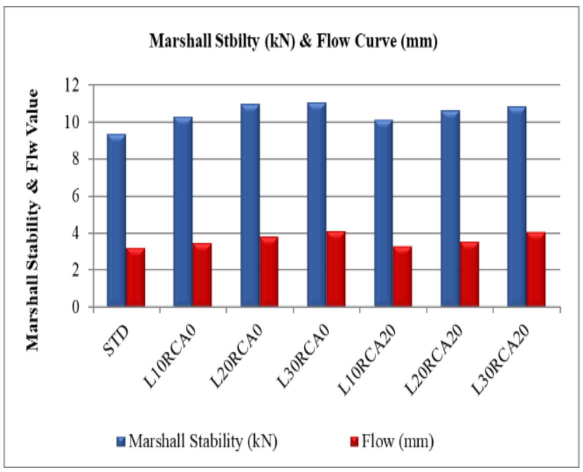

Figure 7. Marshall Stability of samples with varying % of lignin with or without RCA

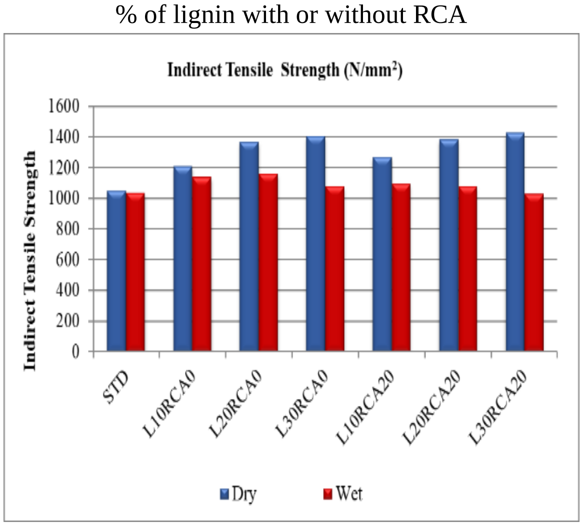

Figure 8. Indirect Tensile test for samples with varying % of lignin and with or without RCA

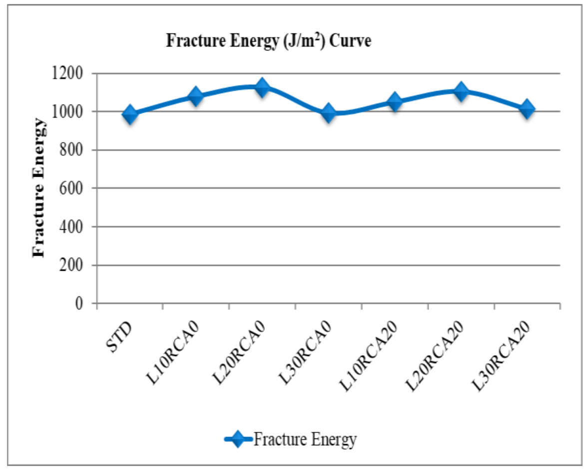

Figure 9. Fracture Energy of prepared samples with varying % of lignin and with or without RCA

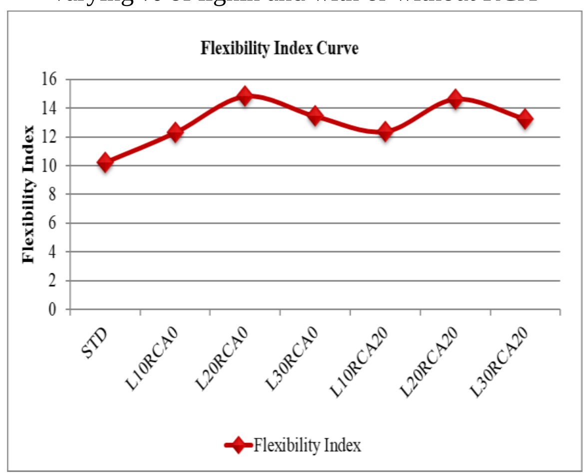

Figure 10. Flexibility Index of prepared samples with varying % of lignin and with or without RCA

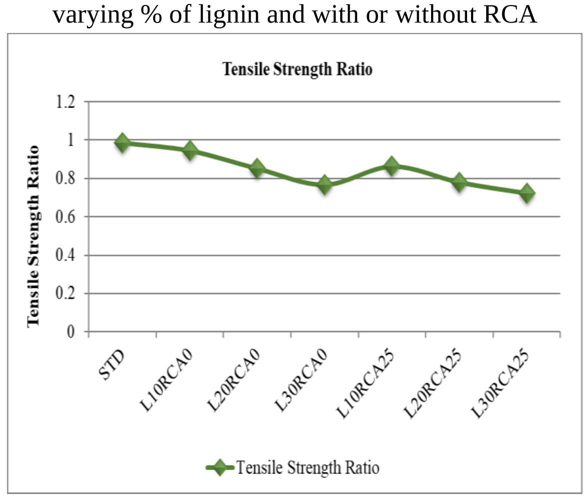

Figure 11. Tensile Strength Ratio for with varying % of lignin and with or without RCA

VI. CONCLUSIONS

- The addition of lignin to bitumen (VG-30) reduces its penetration value, indicating increased stiffness. A small amount of lignin causes a slight decrease, while 30% lignin reduces the value significantly to 35 mm, compared to the standard 68 mm. This modification enhances stiffness, making the bitumen suitable for high-performance, rut-resistant pavements, though adjustments may be required for optimal performance.
- Maximum ductility value of standard bitumen was 42 mm when no lignin content added. This value of ductility was reduced as addition of lignin material at various percentage. Maximum reduced value of ductility was 28 cm. The addition of lignin can reduce ductility significantly, making the binder less flexible.
- The addition of lignin to bitumen increases its softening point, with the standard bitumen having a softening point of 54°C. As lignin content rises, the softening point increases, reaching a maximum of 65°C. This enhancement is attributed to lignin's high melting point, which improves the bitumen's resistance to deformation at elevated temperatures.
- Maximum Specific Gravity value of standard bitumen was 1.01 when no lignin content added. This value of Specific Gravity was enhanced as addition of lignin material at various percentage. Maximum increased value of Specific Gravity was 1.05. The specific gravity may increase slightly, as lignin can contribute a minor density change in the binder.
- The addition of lignin to bitumen slightly increases both the flash point and fire point. The standard bitumen has a flash point of 223°C and a fire point of 252°C. With lignin, the flash point rises to 227°C and the fire point increases to 258°C. These changes are due to the altered chemical composition, with both points remaining stable but slightly elevated.
- The use of recycled concrete aggregate (RCA) in place of traditional aggregates slightly reduces the strength and durability of the mix. Crushing, impact, and abrasion values increase from 28.94%, 25.88%, and 30.85% to 32.62%, 31.08%, and 36.31%, respectively. While RCA provides sustainability benefits, it may compromise strength, necessitating adjustments in mix design or treatment methods to maintain performance standards in structural applications.
- Impart of lignin to standard bitumen mix improves Marshall Stability, increasing from 9.38kN to a maximum of 11.05kN without RCA. When combined with 20% RCA, the stability value also improves, reaching 10.84kN, though not as much as with lignin alone. These results suggest that lignin enhances stability, and while RCA has a moderate effect, the combination of both additives shows promise for creating sustainable pavement mixes.
- The ITS values for the standard bitumen mix were 1048 N/mm² (dry) and 1032 N/mm² (wet). With lignin addition (without RCA), the ITS values increased to 1401 N/mm² (dry) and 1074 N/mm² (wet). When lignin was combined with 20% RCA, the ITS values further rose to 1423 N/mm² (dry) and 1028 N/mm² (wet). The higher ITS and TSR values indicate improved moisture resistance.
- The fracture energy of the standard bitumen mix increased from 986.17 J/m² to 1126.03 J/m² with lignin, and to 1105.15 J/m² when combined with 20% RCA. The Flexibility Index rose from 10.2 to 14.81 with lignin alone, and 14.62 with lignin and RCA. These results indicate that lignin enhances both fracture energy and flexibility, while combining it with RCA provides moderate improvements in energy absorption and crack resistance.
- Tensile Strength Ratio (TSR) of standard bitumen mix was 0.985. This ratio reduced for bitumen mix with addition of various percentage of lignin without consideration of RCA was 0.767 and bitumen mix with addition of various percentage of lignin and 20% of RCA was 0.722.

REFERENCES

[1] Ashteyat, Ahmed, et al. "Flexural Behavior of RC Beams Incorporating Recycled Concrete Aggregate and Reclaimed Asphalt Pavement Exposed to Elevated Temperatures." Results in Engineering (2024): 102309.

[2] Coelho, Lisley Madeira, et al. "Influence of Curing Time on the Mechanical Behavior of Cold Recycled Bituminous Mix in Flexible Pavement Base Layer." Applied Sciences 14.17 (2024): 7612.
[3] D'Addio, Giuseppe, et al. "Influence of Bio-Additives on Recycled Asphalt Pavements." Materials 17.14 (2024).
[4] Khadim, Adnan, and Naveed Ahmad. "Evaluating the effect of paper waste lignin in hot mix asphalt." Engineering Research Express 6.2 (2024): 025105.
[5] Ngii, Edward, et al. "Enhancing Crack Resistance in Concrete Overlays by Shredded Rubber in Stress Absorbing Membrane Interlayer (SAMI)." Nanotechnology Perceptions 20.4 (2024): 508-518.
[6] Riekstins, Arturs, et al. "Comparative environmental and economic assessment of a road pavement containing multiple sustainable materials and technologies. "Construction and Building Materials 432 (2024): 136522.
[7] Songqiang, Chen, et al. "Research on innovative preparation and performance of semi flexible pavement materials. "Case Studies in Construction Materials 20 (2024): e03050.
[8] Manjima, M. A., Nihal Nazar, and Maria Jose. "Partial Replacement of bitumen by Plant Polymer Lignin in Bituminous Pavement." (2023): 801253
[9] Pang, Yafeng, et al. "Performance evaluation of asphalt mixture reinforced by lignin and ceramic fiber." Journal of Engineering Research (2023).
[10] Wu, Jiantao, et al. "Investigation of lignin as an alternative extender of bitumen for asphalt pavements." Journal of Cleaner Production 283 (2021): 124663.
[11] Xu, Chi, et al. "Effect of lignin modifier on engineering performance of bituminous binder and mixture." Polymers 13.7 (2021): 1083.
[12] Zhang, Yi, et al. "Mechanical performance characterization of lignin-modified asphalt mixture." Applied sciences 10.9 (2020): 3324.
[13] Pérez, Ignacio, et al. "Feasibility of using a lignin-containing waste in asphalt binders." Waste and biomass valorization 11 (2020): 3021-3034
[14] Tokede, Olubukola O., et al. "Life cycle assessment of asphalt variants in infrastructures: The case of lignin in Australian road pavements." Structures. Vol. 25. Elsevier, 2020.
[15] Ren, Yanru, et al. "Improved aging properties of bio-bitumen coating sheets by using modified lignin." Journal of environmental management 274 (2020)
[16] Xie, Shangxian, et al. "Lignin as renewable and superior asphalt binder modifier." ACS sustainable chemistry & engineering 5.4 (2017): 2817-2823.
[17] Arafat, Shams, et al. "Sustainable lignin to enhance asphalt binder oxidative aging properties and mix properties." Journal of cleaner production 217 (2019): 456-468.