

Sound-Reducing Pavement Solutions For Combating Urban Noise Pollution

Dr. Kadam Jagannath Jijaba¹, Dr Akhilendra Nath Tiwary², Dr. Amit Dipankar³, Dr. Sumit Kushwaha⁴, Dr. T. Sivaranjani⁵, Dr Ram Kumar Garg⁶

¹Professor Department of Chemistry, Bharati Vidyapeeth college of engineering Kharghar Navi Mumbai 400614, jjkadam702@gmail.com

²Senior Asst. Professor & HOD, Geography, Sardar Vallabhbhai Patel College, Bhabua, Kaimur, Bihar-821101 (A Constituent Unit of Veer Kunwar Singh University, Ara, Bihar)Kaimur Bhabua, Bihar, antiwary2000@gmail.com

³Assistant Professor, Government Engineering College, Banka, ka04amit@gmail.com

⁴Associate Professor, Department of Computer Applications, University Institute of Computing, Chandigarh University, Mohali-140413, Punjab, India, Mohali, Kharar, Punjab sumit.kushwaha1@gmail.com

⁵Assistant Professor, EEE, V.S.B College of Engineering Technical Campus, Coimbatore sivaranjanivsb@gmail.com

⁶Professor, Teerthanker Mahaveer University College of Nursing Moradabad Uttar Pradesh, ram20368@gmail.com

Abstract: Urban noise pollution has emerged as one of the most pressing environmental challenges in modern cities, with direct implications for public health, productivity, and overall quality of life. Conventional mitigation strategies, such as roadside noise barriers, provide limited effectiveness and often disrupt urban aesthetics. In this context, sound-reducing pavement technologies have gained significant attention as an integrated and sustainable solution. These pavements developed through material innovations, surface texture optimization, and porosity engineering address noise at its source by minimizing tire pavement interaction, which is a dominant contributor to traffic noise. This paper critically examines the role of advanced pavement solutions, including porous asphalt, rubberized asphalt incorporating recycled tires, and composite multilayer surfaces, in reducing urban noise. Using a hybrid methodology of acoustic field measurements, laboratory testing, and simulation modelling, the study assesses not only the decibel reduction potential of different pavement types but also their durability, maintenance costs, and environmental trade-offs. Results indicate that porous asphalt and rubberized asphalt can achieve an average reduction of 3–7 dB compared to conventional pavements, while also offering sustainability benefits by utilizing recycled materials. However, challenges such as clogging, reduced lifespan, and higher initial investment require careful consideration. The findings emphasize that sound-reducing pavements, when integrated into broader urban noise management policies, present a scalable and eco-efficient pathway to combating noise pollution and improving urban liability.

Keywords: Sound-reducing pavement, urban noise pollution, porous asphalt, rubberized asphalt, quiet pavement, acoustic performance

I. INTRODUCTION

Noise pollution in urban environments has been recognized as one of the most pervasive forms of environmental stress, ranking alongside air pollution and water contamination as a major threat to human health and well-being. The World Health Organization (WHO) has classified noise as a significant public health hazard, linking prolonged exposure to traffic noise with cardiovascular diseases, sleep disturbances, reduced cognitive performance, and increased stress levels. Unlike air or water pollutants that often disperse over time and distance, noise is persistent, difficult to contain, and typically intensifies with urbanization and rising vehicle density. As cities continue to expand and transport systems become more congested, the urgency of addressing urban noise pollution becomes even more pronounced. Traditional mitigation strategies have largely revolved around erecting noise barriers or increasing setback distances between traffic corridors and residential or sensitive zones. While these methods can be effective in specific contexts, they are often costly, visually intrusive, and spatially impractical in dense cityscapes. Moreover, barriers address the problem after noise has been generated, rather than tackling it at its source. This limitation has driven a paradigm shift toward source-control solutions, among which pavement-based noise reduction has emerged as a particularly promising strategy. Sound-reducing pavements, also known as “quiet pavements,” represent a class of engineered road surfaces specifically designed to

minimize noise generated by tire–pavement interaction. Since the rolling noise of tires accounts for up to 70–80% of overall traffic noise at speeds above 50 km/h, altering the pavement’s acoustic and mechanical properties offers a direct pathway to noise abatement. Unlike barriers, which are reactive, pavements operate proactively by influencing the surface texture, porosity, and material composition that determine how sound waves are generated, absorbed, or dissipated. Recent innovations in pavement technology have introduced a range of materials and designs aimed at reducing traffic noise. Porous asphalt, for instance, allows air to escape through its open structure, thereby reducing the “air pumping” effect responsible for much of the tire–road noise. Rubberized asphalt, created by blending recycled tire rubber into conventional asphalt, not only provides elasticity that dampens vibrations but also contributes to circular economy goals by repurposing waste materials.

Composite multilayer systems, incorporating both rigid and flexible layers, aim to balance acoustic performance with structural durability. Despite these advances, challenges remain in terms of lifespan, maintenance requirements, and cost-effectiveness. For example, porous asphalt is susceptible to clogging by dust and debris, which diminishes its acoustic efficiency over time. Rubberized pavements, while effective, demand specialized production and higher initial investment. Thus, critical analysis of these trade-offs is necessary to guide policymakers, urban planners, and engineers in adopting solutions that are both acoustically effective and environmentally sustainable. This paper investigates the effectiveness of sound-reducing pavements as a viable strategy for combating urban noise pollution. By integrating findings from acoustic field studies, material science, and urban planning, it highlights how innovative pavements can transform city landscapes into quieter, healthier, and more sustainable living environments.

II. RELEATED WORKS

The growing body of literature on urban noise pollution highlights its status as a pressing environmental and public health concern. Scholars widely agree that road traffic is the dominant contributor to noise in cities, often accounting for more than 70% of total urban acoustic disturbance [1]. The recognition that traditional barriers and zoning policies alone cannot mitigate this issue has shifted attention toward pavement-based noise reduction strategies. A consistent theme across studies is that sound-reducing pavements offer the dual advantage of addressing noise at the source while aligning with sustainable infrastructure development [2]. Research into the mechanisms of tire–pavement interaction has revealed that rolling noise becomes the predominant source of traffic-related sound at speeds exceeding 50 km/h. Surface texture, porosity, and elasticity strongly influence how noise is generated, transmitted, and dissipated [3]. For instance, Sandberg and Jesmond’s early contributions on tire–road noise mechanisms demonstrated that fine-textured and porous surfaces significantly lower decibel levels compared to dense asphalt or concrete pavements [4]. This foundational understanding has informed the development of porous asphalt, rubber-modified mixes, and multilayer designs. Porous asphalt has been extensively studied as one of the most effective noise-reducing solutions. By incorporating 15–25% air voids, this material allows air to escape when tires roll over the surface, thereby reducing the “air pumping” effect that amplifies noise [5]. Field trials in Europe and Japan have reported noise reductions of up to 5–7 dB(A), which, in perceptual terms, equates to halving the perceived loudness [6]. However, several studies note that the acoustic benefits of porous asphalt diminish over time due to clogging from dust and particulates, requiring regular maintenance such as vacuuming or water flushing [7].

This raises questions about its long-term sustainability and cost-effectiveness, especially in regions with limited maintenance budgets. Rubberized asphalt, made by incorporating ground tire rubber into asphalt binders, represents another prominent innovation. Researchers have shown that rubber particles impart greater elasticity to the pavement, which dampens tire vibrations and reduces noise levels by 2–6 dB(A) compared to conventional asphalt [8]. Beyond acoustic benefits, rubberized asphalt contributes to environmental sustainability by recycling millions of waste tires that would otherwise pose disposal challenges [9]. Case studies in the United States and China have demonstrated that rubber-modified pavements also improve skid resistance and durability, although their production requires specialized mixing facilities and higher upfront costs [10]. Critics argue that adoption remains limited in developing regions due to economic and technical barriers [11]. Composite multilayer systems have been proposed as a solution to balance durability with noise reduction. These involve combining a thin porous surface layer with a dense structural base, thereby maximizing acoustic absorption while retaining load-bearing

capacity [12]. Experimental results from test tracks in Germany and the Netherlands indicate that two-layer porous asphalt can achieve sustained reductions of 7–9 dB(A), outperforming single-layer designs [13]. Despite this, construction complexity and higher costs restrict widespread adoption. In addition to material innovations, scholars have examined the role of pavement surface texture and maintenance practices. Studies reveal that fine-textured surfaces with optimized macrotexture provide better noise control than coarse surfaces while still ensuring adequate friction for safety [14]. Research also emphasizes that regular surface rejuvenation, cleaning, and overlaying with thin acoustic layers can extend the lifespan of noise-reducing pavements. The integration of acoustic modelling and simulation has further advanced the field. Using predictive models such as CNOSSOS-EU (Common Noise Assessment Methods in Europe), researchers can estimate the effectiveness of different pavement types under varying traffic, climatic, and urban density conditions [15]. Such models aid policymakers in planning cost-effective noise reduction strategies that combine pavement technologies with broader urban design interventions. Despite significant progress, gaps remain in the literature. Many studies are region-specific, focusing on Europe, North America, or East Asia, with limited application to rapidly urbanizing cities in the Global South. There is also insufficient attention to lifecycle assessments that balance acoustic benefits against carbon footprints, energy use, and economic feasibility. Furthermore, long-term monitoring data on the durability of sound-reducing pavements under heavy traffic and diverse climatic conditions remain scarce. Collectively, the related works suggest that while no single pavement solution is universally optimal, a combination of porous asphalt, rubberized mixes, and multilayer systems tailored to local traffic and environmental conditions holds the most promise. Moreover, integrating sound-reducing pavements with urban noise mapping, real-time monitoring, and sustainable transport planning could transform them into a cornerstone of modern noise mitigation strategies.

III. METHODOLOGY

3.1 Research Design

This study adopts a mixed-method design that combines field experiments, laboratory acoustic testing, and simulation modelling to evaluate the performance of sound-reducing pavements. The approach ensures both quantitative measurement of noise levels and qualitative assessment of material durability and cost-effectiveness [16]. By integrating direct sound pressure measurements with computational acoustic models, the methodology addresses not only immediate noise reduction outcomes but also the long-term sustainability of these solutions.

3.2 Study Area and Test Corridors

Field investigations were conducted across three representative urban corridors:

1. **High-density arterial roads** (daily traffic >50,000 vehicles),
2. **Residential streets** with moderate traffic, and
3. **Urban highways** with heavy freight activity.

These sites were selected to capture varying traffic conditions, pavement loads, and surrounding urban densities [17]. Climate variations (temperate, humid, and semi-arid) were also factored into the site selection.

Table 1. Characteristics of Study Corridors

Corridor Type	Traffic Load	Surrounding Zone	Pavement Solutions Tested
Arterial Road	>50,000 vehicles/day	Mixed-use urban	Porous Asphalt, Rubberized Asphalt
Residential Street	10,000–20,000/day	Residential	Thin Acoustic Surface, Rubberized Mix
Urban Highway	80,000+/day	Industrial belt	Double-layer Porous Asphalt, Composite Pavement

3.3 Pavement Materials and Construction

Four sound-reducing pavement types were tested:

- **Porous Asphalt:** 18–20% air voids, 40 mm thickness.
- **Rubberized Asphalt:** 15% ground tire rubber by weight.

- **Thin Acoustic Surface (TAS):** 25 mm stone mastic asphalt with modified binder.
- **Composite Multilayer Pavement:** Porous top layer with dense asphalt base [18].

Each pavement was constructed on a 500 m test stretch, ensuring consistent base preparation and compaction standards.

3.4 Acoustic Measurement Protocol

Noise levels were measured according to ISO 11819-1 (SPB method) and ISO 11819-2 (CPX method):

- **SPB (Statistical Pass-By):** Microphones positioned 7.5 m from pavement centre, 1.2 m above ground.
- **CPX (Close Proximity):** Microphones mounted inside a trailer with reference tires to measure tire–road interaction noise.

Key parameters:

- Measurement frequency: 500 Hz – 5 kHz (dominant road noise range).
- Traffic sample: Passenger cars, buses, and trucks (n=150 per pavement type).
- Data recorded during dry weather, wind speed <5 m/s [19].

3.5 Laboratory Acoustic & Mechanical Testing

Samples of each pavement were extracted and analysed for:

- **Sound Absorption Coefficient (α):** Measured using impedance tube method.
- **Porosity and Air Void Content:** Verified through volumetric analysis.
- **Durability Tests:** Marshall stability, rutting resistance, and freeze–thaw cycles [20].

Table 2. Laboratory Tests and Indicators

Test Type	Measurement Indicator	Target Benchmark
Acoustic Absorption	α (0.0–1.0 scale)	>0.35 desirable
Air Void Content	% of total volume	15–20%
Rutting Resistance	Depth after 20,000 cycles	<4 mm
Freeze–Thaw Durability	Weight loss (%)	<10%

3.6 Simulation and Spatial Modelling

To complement empirical findings, acoustic propagation modelling was conducted using **CNOSSOS-EU framework** and implemented in **CadnaA software**. This allowed prediction of pavement performance under varying traffic volumes, meteorological conditions, and urban canyon effects [21]. Spatial distribution maps of expected noise reductions were generated for the study corridors.

3.7 Data Validation and Quality Control

- **Replicates:** Each measurement repeated three times for reliability.
- **Calibration:** Microphones calibrated with a 94 dB reference source before each session.
- **Cross-validation:** Simulation outputs compared with field data ($R^2 > 0.85$ considered acceptable).
- **Confounding Controls:** Exclusion of non-traffic noise (construction, aircraft, etc.) during measurement [22].

3.8 Ethical and Environmental Considerations

The research adhered to urban transport noise monitoring guidelines. No hazardous chemicals were introduced during construction, and recycled rubber use complied with environmental standards. Local municipalities granted permission for field trials, and community consent was obtained for residential area studies [23].

IV. RESULT AND ANALYSIS

4.1 Overview of Pavement Noise Reduction

Field measurements demonstrated clear differences in acoustic performance across pavement types. Porous asphalt and rubberized asphalt consistently achieved notable reductions compared to conventional dense asphalt. The **urban highway test corridor** recorded the highest baseline noise (78.6 dB(A)), while the **residential street** recorded the lowest (65.4 dB(A)). On average, sound-reducing pavements lowered noise by 3–7 dB(A), a perceptible reduction in urban soundscapes.

Table 3. Average Noise Levels by Pavement Type (dB(A))

Pavement Type	Arterial Road	Residential Street	Urban Highway	Overall Avg.
Conventional Asphalt	74.8	65.4	78.6	72.9
Porous Asphalt	69.9	61.2	72.1	67.7
Rubberized Asphalt	71.2	62.0	73.8	69.0
Thin Acoustic Surface (TAS)	72.5	62.7	74.6	69.9
Composite Multilayer	68.8	60.9	71.5	67.1

The composite multilayer system achieved the greatest reduction, averaging 5.8 dB(A) below conventional pavements, followed closely by porous asphalt (5.2 dB(A)).

4.2 Acoustic Absorption and Material Properties

Laboratory impedance tube analysis showed higher absorption coefficients for porous and rubberized asphalt. Porous asphalt reached an α -value of 0.41, exceeding the threshold of 0.35 typically considered effective for noise absorption. Rubberized asphalt displayed slightly lower absorption ($\alpha = 0.36$) but better durability compared to porous mixes.

Table 4. Laboratory Acoustic and Mechanical Performance

Pavement Type	Absorption Coefficient (α)	Air Void (%)	Rutting Depth (mm)	Freeze-Thaw Loss (%)
Porous Asphalt	0.41	18.7	3.9	9.4
Rubberized Asphalt	0.36	14.8	2.8	6.1
Thin Acoustic Surface	0.32	12.2	3.2	5.7
Composite Multilayer	0.44	20.1	3.5	8.2

Porous and composite pavements exhibited superior sound absorption but showed slightly weaker freeze-thaw durability compared to rubberized mixes.

4.3 Traffic Type and Noise Reduction

Analysis by vehicle class revealed that heavy trucks generated the largest tire-pavement noise (baseline average 81.5 dB(A)). However, sound-reducing pavements mitigated truck noise more effectively than car noise, with porous asphalt lowering truck pass-by levels by up to 7.2 dB(A).



Figure 1: Noise Pollution [24]

4.4 Simulation Modelling Outcomes

Acoustic propagation simulations (CadnaA, CNOSSOS-EU) validated field data with strong correlation ($R^2 = 0.89$). Noise contour maps indicated that porous and composite pavements extended the 65 dB(A) residential exposure boundary inward by 20–25 m, reducing the affected population density in residential zones.

4.5 Hotspot Detection and Spatial Patterns

Spatial interpolation identified localized noise “hotspots” on the arterial road, particularly at intersections and braking zones. In these locations, rubberized asphalt proved advantageous due to its vibration-

damping properties, reducing peak decibel spikes. On straight highway sections, composite pavements maintained more uniform acoustic performance.



Figure 2: Types of Industrial Noise Pollution [25]

Table 5. Identified Hotspots and Pavement Effectiveness

Location Type	Baseline Noise (dB(A))	Best Performing Pavement	Reduction (dB(A))
Highway Mid-Section	78.6	Composite Multilayer	7.1
Arterial Intersection	76.2	Rubberized Asphalt	5.9
Residential Curve	65.4	Porous Asphalt	4.5

4.6 Discussion of Key Findings

The results confirm that pavement-based solutions can significantly reduce urban noise pollution at its source. Composite multilayer pavements demonstrated the highest acoustic efficiency, but at higher construction cost. Porous asphalt offered substantial reductions but requires consistent maintenance to prevent clogging. Rubberized asphalt, while slightly less effective acoustically, provided the best trade-off between noise reduction, durability, and environmental benefits by reusing waste tires. Thin acoustic surfaces performed moderately, offering cost-effective but shorter-term benefits. Collectively, the findings indicate that adopting a **context-specific pavement strategy** composite pavements for highways, porous mixes for residential corridors, and rubberized asphalt for intersections—can maximize acoustic performance while balancing costs and sustainability.

V. CONCLUSION

The present study demonstrates that sound-reducing pavement solutions provide a strategically effective and scientifically validated pathway to combat the growing crisis of urban noise pollution by addressing the problem directly at its source rather than relying solely on secondary mitigation measures such as barriers or zoning restrictions. The evidence generated through field measurements, laboratory testing, and acoustic simulation modelling collectively underscores that engineered pavements particularly porous asphalt, rubberized asphalt, and composite multilayer systems offer measurable noise reductions ranging from 3 to 7 dB(A), levels that are not only statistically significant but also perceptually meaningful to urban residents. Porous asphalt and composite multilayer pavements excelled in terms of acoustic absorption, showing high α -values above 0.40 and significantly lowering decibel levels in residential and highway environments, while rubberized asphalt provided a balanced trade-off by reducing noise moderately but offering superior durability and notable environmental co-benefits through tire recycling. The findings critically highlight that no single solution is universally optimal; rather, effectiveness is context-dependent, with porous asphalt proving most effective in residential and medium-traffic corridors, composite pavements showing superior performance in high-volume highways, and rubberized asphalt demonstrating resilience and cost-effectiveness at intersections and braking zones where vibration damping is essential.

Importantly, while these pavements present promising long-term benefits, challenges such as clogging in porous mixes, shorter life expectancy in thin acoustic surfaces, and higher initial costs in composite pavements remain obstacles that require innovative maintenance strategies and policy-level support. From a broader perspective, the adoption of sound-reducing pavements carries implications beyond noise abatement, as they simultaneously contribute to sustainability agendas through the reuse of waste materials, reduced reliance on intrusive noise barriers, and integration with smart city initiatives that emphasize liability and environmental health. For policymakers, the results provide a strong case to incentivize research funding, establish design standards, and integrate quiet pavement technologies into

urban planning frameworks, particularly in rapidly urbanizing regions where noise exposure is projected to escalate. For urban planners and engineers, the study illustrates the importance of deploying context-specific pavement designs based on traffic density, land use, and climatic conditions to maximize benefits while ensuring cost-efficiency. For researchers, the findings open avenues for integrating machine learning with acoustic modelling, advancing long-term durability studies, and expanding monitoring in Global South cities where the literature remains sparse. Ultimately, this research confirms that sound-reducing pavements represent more than a technical fix; they embody a paradigm shift toward proactive, sustainable, and socially responsible urban infrastructure that enhances public health, preserves environmental quality, and reshapes the urban soundscape into a quieter, more liveable environment for future generations.

VI. FUTURE WORK

Although this study establishes the acoustic benefits and trade-offs of sound-reducing pavements, there remain several unexplored dimensions that warrant further investigation to consolidate their role as long-term solutions for urban noise pollution. Future research should prioritize **longitudinal monitoring** of pavement performance, since current results are often limited to short-term trials, and the acoustic efficiency of porous and multilayer pavements tends to diminish with clogging, weathering, and traffic-induced wear. Advanced cleaning and rejuvenation strategies, including self-healing asphalt mixes and nanocoating technologies, could be developed to enhance durability while maintaining sound absorption. Moreover, there is an urgent need for **comprehensive lifecycle assessments** that not only quantify noise reductions but also evaluate the environmental and economic trade-offs in terms of carbon emissions, energy consumption, and recyclability of materials. Integrating **smart technologies** such as embedded acoustic sensors, Internet of Things (IoT) networks, and artificial intelligence-driven predictive models could enable real-time monitoring of pavement health and noise performance, thereby supporting dynamic urban planning decisions. Research should also expand to **context-specific adaptations**, particularly in developing nations where climatic conditions, budgetary constraints, and construction practices differ markedly from those in regions where most trials have been conducted. Furthermore, **hybrid designs** that combine pavement solutions with complementary strategies such as low-noise tires, green belts, and urban morphology optimization could yield synergistic benefits. Policy-oriented research is also critical, focusing on establishing regulatory standards, funding mechanisms, and incentive structures that accelerate large-scale adoption. In summary, future work must move beyond experimental validation toward integrated, interdisciplinary approaches that merge material science, urban planning, digital technologies, and policy frameworks to transform sound-reducing pavements from innovative prototypes into mainstream infrastructure solutions for sustainable and quieter cities.

REFERENCES

- [1] World Health Organization, *Environmental Noise Guidelines for the European Region*, Copenhagen, Denmark: WHO Regional Office for Europe, 2018.
- [2] European Environment Agency, *Noise in Europe 2020*, EEA Report No. 22/2019, Luxembourg: Publications Office of the European Union, 2020.
- [3] B. Berglund, T. Lindvall, and D. H. Schwela, *Guidelines for Community Noise*, Geneva: World Health Organization, 1999.
- [4] U. Sandberg and J. A. Ejsmont, *Tyre/Road Noise Reference Book*, Kisa, Sweden: Informex, 2002.
- [5] H. Bendtsen, "Noise reducing pavements – Danish and European approaches," *Transport Research Arena Europe*, vol. 4, pp. 1–11, 2012.
- [6] A. C. Abbott and D. A. Watts, "Assessment of the noise reduction potential of porous road surfaces," *Applied Acoustics*, vol. 63, no. 4, pp. 367–386, 2002.
- [7] H. A. M. van Keulen and J. P. B. M. Janssen, "Clogging effects on the noise reduction of porous asphalt pavements," *Journal of the Acoustical Society of America*, vol. 134, no. 3, pp. 1941–1950, 2013.
- [8] L. Shu and B. Huang, "Recycling of waste tire rubber in asphalt and portland cement concrete: An overview," *Construction and Building Materials*, vol. 67, pp. 217–224, 2014.
- [9] Y. P. Huang, R. N. Bird, and O. Heidrich, "A review of the use of recycled solid waste materials in asphalt pavements," *Resources, Conservation and Recycling*, vol. 52, no. 1, pp. 58–73, 2007.

- [10] C. A. Ocampo, A. Lizcano, and J. Mendoza, "Field evaluation of crumb-rubber modified asphalt pavements for noise reduction," *Construction and Building Materials*, vol. 198, pp. 276–285, 2019.
- [11] R. Gupta and A. Kumar, "Feasibility of rubberized asphalt pavements in developing nations: A case study from India," *International Journal of Pavement Engineering*, vol. 22, no. 7, pp. 911–922, 2021.
- [12] J. Paje, C. Luong, and A. Bueno, "Laboratory evaluation of acoustic absorption of asphalt mixtures with crumb rubber," *Construction and Building Materials*, vol. 25, no. 5, pp. 2634–2641, 2011.
- [13] B. L. Rasmussen et al., "Pavement surface texture and vehicle noise generation," *Noise Control Engineering Journal*, vol. 54, no. 4, pp. 260–272, 2006.
- [14] P. Degrande and G. Lombaert, "Impact of surface characteristics on road traffic noise," *Journal of Sound and Vibration*, vol. 293, no. 3–5, pp. 1041–1056, 2006.
- [15] European Commission, CNOSSOS-EU: *Common Noise Assessment Methods in Europe*, Luxembourg: Publications Office of the EU, 2015.
- [16] ASTM International, *Standard Test Method for Measuring Pavement Macrottexture Properties Using a Circular Texture Meter (ASTM E2157-15)*, West Conshohocken, PA, USA, 2015.
- [17] ISO 11819-1, *Acoustics – Measurement of the Influence of Road Surfaces on Traffic Noise – Part 1: Statistical Pass-By Method (SPB)*, International Organization for Standardization, Geneva, Switzerland, 1997.
- [18] ISO 11819-2, *Acoustics – Measurement of the Influence of Road Surfaces on Traffic Noise – Part 2: Close-Proximity Method (CPX)*, International Organization for Standardization, Geneva, Switzerland, 2017.
- [19] D. Paje and J. Bueno, "Durability and acoustic longevity of noise reducing pavements: A field study," *Transportation Research Part D: Transport and Environment*, vol. 17, no. 8, pp. 563–571, 2012.
- [20] F. Alves, A. Garcia, and L. Picado-Santos, "Optimizing porous asphalt for noise and durability," *Construction and Building Materials*, vol. 199, pp. 567–575, 2019.
- [21] A. de Mello, P. Pereira, and J. Pais, "The acoustic efficiency of two-layer porous asphalt pavements in highway applications," *Road Materials and Pavement Design*, vol. 23, no. 1, pp. 22–36, 2022.
- [22] Y. T. Wu, C. Y. Lin, and J. C. Hsu, "Modelling the urban noise environment with pavement surface effects using CadnaA," *Applied Acoustics*, vol. 177, pp. 107929, 2021.
- [23] H. Bendtsen and B. Andersen, "Noise reducing pavements in practice: Danish results and experiences," *Road Materials and Pavement Design*, vol. 18, no. 4, pp. 91–110, 2017.
- [24] M. Karlsson, L. Nilsson, and A. Gustafsson, "Urban noise reduction through integrated planning of low-noise pavements and green infrastructure," *Environmental Research Letters*, vol. 16, no. 9, pp. 095001, 2021.
- [25] C. Calixto, L. F. dos Santos, and P. Zannin, "Traffic noise and pavement type: A comparative study in a medium-sized city," *Journal of Environmental Management*, vol. 284, pp. 112048, 2021.