Journal of Civil Engineering and Construction 2024;13(2):59-66
https://doi.org/10.32732/jcec.2024.13.2.59

Performance Evaluation of an Asphalt Mix Containing Non-Metallic Fractions of Recycled Printed Circuit Boards

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Received: 23 January 2024; Accepted: 16 April 2024; Available online: 20 May 2024

Abstract: The growing volume of non-metallic fractions extracted from recycled printed circuit boards necessitates sustainable solutions. Integrating these fractions into road paving asphalt mix presents potential opportunities to bolster environmental sustainability and resource conservation. While previous studies have predominantly focused on the wet process of incorporating electronic waste into asphalt binder, challenges persist, including but not limited to the requirement for specialized machinery and concerns regarding the storage stability of the modified binder. In contrast, this paper explored designing a Superpave mix via the dry process followed by execution of fundamental performance tests including Hamburg wheel-tracking and the Illinois flexibility index test. The results highlighted that the asphalt mix substantially surpassed the minimum requirement of 80% for Tensile Strength Ratio (TSR), indicating excellent moisture resistance. Additionally, its resistance to rutting and fatigue cracking remained well within acceptable limits, underscoring the overall durability of the mix. Finally, structural analysis of four pavement models was conducted using AASHTOWare Pavement M-E Design (PMED). The findings indicated that predicted distresses consistently remained below the failure threshold, even when faced with varying subgrade conditions, traffic volumes, and climate factors.

Keywords: Asphalt mix performance; E-waste; Recycling non-metallic fraction; Sustainability.

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1. Introduction

Every year, roughly 50 million tonnes of electronic and electrical waste (e-waste) are produced globally. This volume of waste is anticipated to more than double by 2050, reaching an annual total of 120 million tonnes [1]. In Canada, it is estimated that a substantial 757 kilo tonnes of e-waste were generated in 2019 [2,3]. Printed circuit boards (PCBs), essential components of many modern devices, are present in e-waste in various amount, with an average proportion of 3% [4]. The recovery of valuable metallic fractions from waste PCBs has witnessed remarkable progress in recent times, with a greater stress on finding safer and more effective alternatives to the current hydrometallurgical methods. However, effective management of the escalating volume of remaining Non-Metallic Fractions (NMFs) derived from PCBs holds significant importance for achieving enhanced sustainability objectives. NMFs, which constitute approximately 70 percent of waste PCBs, comprise materials such as glass fiber, cured epoxy resin, and impurities. It is clearly noted that NMFs of PCB waste must be recycled in a sustainable process. Nonetheless, recycling techniques for the NMF component remain relatively underdeveloped, and research in this area is still in its early stages.

To date, most of the experience with the reuse of recovered NMF primarily revolves around incorporating it as fillers in applications such as partial substitute in construction materials [5]. In recent years, several researchers have directed their attention towards repurposing NMFs in the form of asphalt mix materials, aiming to tackle the mounting quantities of these fractions. In the field of road construction materials, a significant portion of past studies has centered around exploring the application of what is known as the ‘wet process’ in which the NMF is introduced as an asphalt binder modifier [6–19]. In the wet process, NMF is blended with neat asphalt binder at a precise temperature and duration, utilizing a mechanical mixing machine to induce a reaction, aiming to achieve a homogeneous asphalt binder as the desired outcome. While previous endeavors have shown some promising mechanical characteristics, the intricate mixing demands associated with this approach can pose considerable challenges and expenses, particularly in the short term. Additionally, these modified asphalt binders often face challenges with poor storage stability and phase separation. Conversely, the ‘dry process’, which involves adding the NMF to the aggregate before it comes in to contact with the asphalt binder, seems to offer a simpler and more viable solution. Therefore, there's a pressing need for further research in this domain and develop more mix designs that better align with current plant technologies. Much of the already scant existing research regarding the dry process of e-waste in asphalt mixes has been conducted utilizing the Marshall mix design method [20–22]. The

Marshall method of mix design, despite its global prevalence, suffers from some inherent limitations. The limitations of this method include impact-based laboratory compaction of specimens using a drop hammer, which might not accurately replicate mix densification as experienced under actual traffic conditions on pavements. Moreover, relying on the Marshall stability parameter in this method might not adequately reflect the mix's shear strength concerning specific performance factors, especially in terms of rutting which holds crucial significance in pavement design [23]. Over the past two decades, a more modern system of mix design known as Superpave has been extensively adopted across various regions of Canada, albeit without incorporating rutting and cracking performance tests. In recent times, there's been greater attention on the benefits of performance testing, following the historical absence of these tests in Superpave mix design [24].

The primary objective of this study is to explore the feasibility of integrating NMF materials into a typical Superpave mix via dry process, with a specific focus on comprehending the effects of this integration on mechanical properties and its applicability for durable pavement designs. Different performance tests were carried out to evaluate the characteristics of a Superpave mix suitable for urban road paving application in Canada. Furthermore, the design approaches for flexible pavements have undergone a significant transformation, shifting towards robust Mechanistic-Empirical (ME) methodologies. The ME approach involves utilizing mechanistic methods to identify critical stress, strain, or deflection within the pavement, followed by the application of empirical failure criteria to predict resulting distresses [25]. In this paper, American Association of State Highway and Transportation Officials AASHTOWare Pavement Mechanistic-Empirical Design (PMED) software, which builds upon the AASHTO mechanistic-empirical pavement design guide [26,27], was employed to predict the behaviour of a pavement surfaced with NMF-infused asphalt mix.

2. Methodology

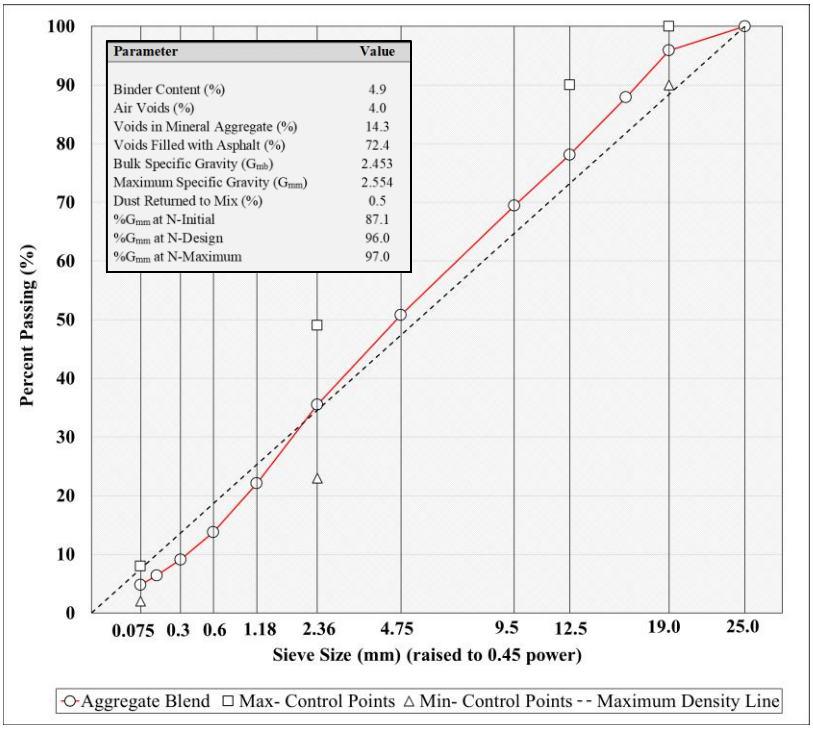
To undertake this study, it was aimed to design a 19-mm Nominal Maximum Aggregate Size (NMAS) Superpave mix (SP 19.0), suitable for an anticipated traffic level range of 3-10 million Equivalent Single Axle Load (ESAL), following AASHTO R35. An unmodified asphalt binder, classified as PG 64-22 according to AASHTO M 320, was selected for this experiment, with basic properties shown in Table 1.

Table 1. Key physical characteristics of the PG 64-22 asphalt binder

Property	**Test Method**	**Results**
Flash Point Temperature (°C)	ASTM D92	325
Rotational Viscosity at 135°C (Pa.s)	AASHTO T316	0.383
Unaged G*/Sinδ at 64°C (kPa)	AASHTO T315	1.25
RTFO*-aged G*/Sinδ at 64°C (kPa)	AASHTO T315	3.25
PAV**-aged G*×Sinδ at 25°C (kPa)	AASHTO T315	4566
BBR*** m-value at -12°C	AASHTO T313	0.340
BBR Creep Stiffness at -12°C (MPa)	AASHTO T313	176
Ash Content (%)	ASTM D8078	0.13
Degree of Solubility (%)	AASHTO M320	100
Penetration at 25°C	ASTM D5	69
Density (kg/L)	ASTM D70	1.032

* Rolling Thin-Film Oven
** Pressure Aging Vessel
*** Bending Beam Rheometer

The mix design incorporated coarse aggregates and manufactured fines sourced from dolomitic limestone quarries. The aggregate structure in the mix design was a blend of five different stockpiles including 24 percent of 14-20 mm stones, 18 percent of 4-14 mm stones, 10 percent of 2.5-7 mm stones, 26 percent of 0-5 mm manufactured sand and 22 percent of 0-7 mm screenings. Figure 1 shows the gradation curve of asphalt mix in this study. As part of the aggregate selection process, the suitability of coarse and fine proportions in terms of source and consensus properties was also ascertained for use in the mix design. With regards to the compaction level, number of gyrations for N-initial, N-design and N-maximum were equal to 8, 100 and 160, respectively. Also, the compaction temperature for producing specimens for all mixes was 145°C. To address the need for identifying the optimum NMF ratio, this study initially considered a parametric investigation. Three initial trials were executed with NMF at three dosage rates of 1, 2 and 3% (by weight of aggregates). In all trials, ground NMF particles were added directly to the aggregate before coming into contact with the asphalt binder, principally via dry process fabrication method, as illustrated in Figure 2. The mix was prepared in a manner that ensured uniform distribution of the NMF particles within the blend, preventing clustering at specific or discrete locations, allowing for effective integration and interaction with the other components. By avoiding clustering, the mix could maintain a consistent distribution of NMF, thereby enhancing its potential benefits and ensuring uniform performance across the asphalt mix. In seeking to find a ratio that balances volumetric properties according to the Superpave mix design system, the trials showed that using 2-3% of NMF as aggregate replacement had an adverse effect. Specifically, it increased air voids to around 8%, surpassing the optimal threshold of 4% for laboratory compaction [28], mainly due to significant differences in specific gravity values. This observation aligns with the literature, noting that as the percentage of e-waste increased, there was a corresponding increase in air voids within the mix, surpassing 4% [8]. Also, asphalt absorption increased at elevated dosages of NMF, which could contribute to the higher air voids in the trial mixes. Based on the findings of three initial trials, final design consisted of 1% of NMF and 4.9% of asphalt binder which was then taken as the basis for the study.



Parameter	Value
Binder Content (%)	4.9
Air Voids (%)	4.0
Voids in Mineral Aggregate (%)	14.3
Voids Filled with Asphalt (%)	72.4
Bulk Specific Gravity (G_{mb})	2.453
Maximum Specific Gravity (G_{mm})	2.554
Dust Returned to Mix (%)	0.5
%G_{mm} at N-Initial	87.1
%G_{mm} at N-Design	96.0
%G_{mm} at N-Maximum	97.0

Fig 1. Gradation curve and key physical properties of asphalt mix

Fig 2. Using NMF Particles in Dry Mixing Process

With respect to the AASHTOWare PMED process, major controlling variables, as depicted in Table 2, were compiled and selected from the Manual of Practice document [29] and a number of Canadian guides [30]. In instances where information was lacking, level 3-calculated input values, serving as the software's default best estimates, were utilized. The analysis involved the selection of a climate file specifically for Vancouver which represents the characteristics of southwestern-coastal region of British Columbia. Four typical pavement scenarios underwent analysis covering two levels of traffic volume and subgrade strength, as detailed in Table 3. The evaluation aimed to gauge the pavement's performance against criteria related to major distresses, including permanent deformation and bottom-up fatigue cracking. The thickness of granular and bound surface layers served as the primary design parameter. An initial design, based on typical municipal cross-sections, underwent evaluation within the software. For each trial section, PMED analysis was conducted, and results were scrutinized to predict potential pavement failure. These outcomes guided modifications to address premature failure or prevent over-design. The iterative process ensured obtaining suitable pavement cross-sections for all traffic and subgrade combinations.

Table 2. Summary of Key Input Parameters

Category	Parameter	Value
Design Criteria	Reliability Level	90 %
	Fatigue Cracking Threshold	35%
	Permanent Rutting Threshold	
Thermal and Mechanical Properties	Asphalt Heat Capacity	963 J/kg-K
	Asphalt Thermal Conductivity	1.16 W/m-K
	Asphalt Unit Weight	2520 kg/m^3
	Air Voids	7 %
	Resilient Modulus of Granular Base	250 MPa
	Resilient Modulus of Granular Subbase	200 MPa
	Resilient Modulus of Coarse-Grained Subgrade	50 MPa
	Resilient Modulus of Fine-Grained Subgrade	30 MPa
Climate Information	MERRA-2** Station ID	154461
	Mean annual air temperature	9.73 ºC
	Mean annual precipitation	1557.27 mm
	Average annual number of freeze/thaw cycles	46

** Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2)

Table 3. Various Pavement Scenarios Simulated Using AASHTOWare PMED

Scenario ID	Subgrade Type	AADTT*	Layer Thickness (mm)		
			NMF-Modified Asphalt Mix	Granular Base	Granular Subbase
C-L	Coarse-Grained Soil	2,500 (Low)	170	200	300
C-H		6,500 (High)	240	250	400
F-L	Fine-Grained Soil	2,500 (Low)	200	350	450
F-H		6,500 (High)	260	350	550

* Annual Average Daily Truck Traffic (AADTT)

3. Test results and discussion

Performance testing helps in achieving a well-balanced asphalt mix that delivers the desired levels of durability, strength, flexibility, and resistance to distresses, thereby ensuring long-lasting and cost-effective pavements. Ultimately, performance testing provides essential insights and data that contribute to the development of sustainable and reliable asphalt mix designs.

At the outset, to understand the rutting potential and stripping susceptibility of asphalt mixes in high temperature, submerged specimens were tested via Hamburg Wheel Tracking (HWT) in accordance to AASHTO T 331. Fundamentally, this test is about measuring the depth of the rut formed in the asphalt specimen to track its progress over the number of wheel passes. As a 705 N-loaded wheel rolled across the surface of specimens, series of Linear Variable Differential Transducers (LVDTs) measured the rutting depths as presented in Figure 3. The average rut depths after 1000, 5000, 10000, 15000 and 20000 passes were found to be 2.10, 3.46, 4.45, 6.24, and 8.18 mm, respectively. One notable finding is the acceptable final rut depths, measuring below 12.5 mm after 20,000 passes at 50°C, which is generally deemed satisfactory. Next, the creep and stripping slopes were analyzed for each test to determine the Stripping Inflection Point (SIP), defined as where the creep slope and stripping slope intercept. Commonly, if the SIP occurs at a low number of load cycles, the mix may be susceptible to moisture damage which was not the case in the present work. Overall, the specimens exhibited satisfactory resistance against rutting and moisture damage, consistent with findings from several previous studies, despite their primary use of wet mixing methods for the purpose of modifying the asphalt binder. For instance, Movilla-Quesada et al. (2019) reported adequate rutting and moisture damage resistance when 10% of the binder was replaced with plastic scrap

[31]. Similarly, Shahane et al. (2021) demonstrated a notable 28% enhancement in rutting resistance at 40°C attributed to the addition of 5% e-waste plastic powder by weight of bitumen [16].

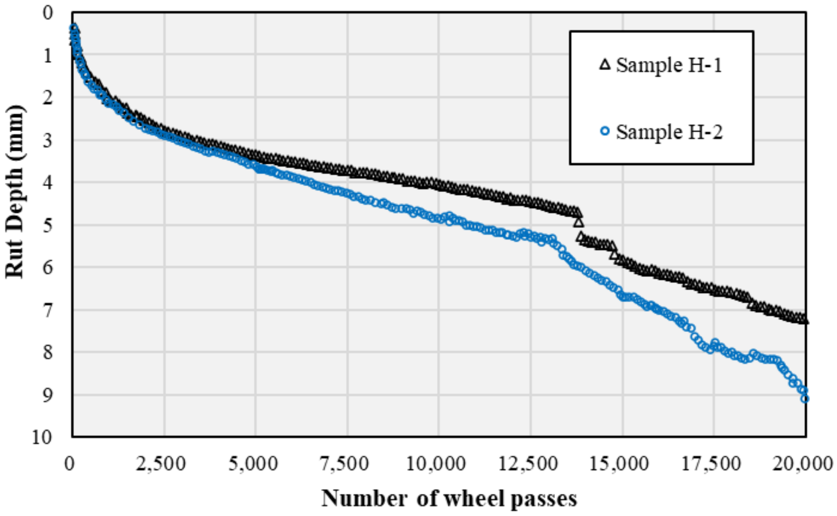


Fig 3. Rutting Performance Curves from HWT Test

Secondly, in order to evaluate the cracking behaviour of the mixes, notched semi-circular samples were subjected to the Illinois Flexibility Index Test (I-FIT) per AASHTO T 393. It is worth to mention that during the preparation of the I-FIT specimens, the loose mixtures were short-term aged for 4 hours at 135℃ and all the compacted specimens had air void content of 7 ± 0.5 %. Two 50mm-thick discs were sliced and extracted from the middle of Superpave gyratory briquettes. Subsequently, they were halved to yield two replicates of semi-circular specimens. Next, a notch with dimensions of 15±0.5 mm in length and 1.5±0.5 mm in width was sawn at the center of the flat side of each specimen. Utilizing the semicircular bend configuration, specimens conditioned and maintained through the test underwent testing with the load applied parallel to the notch direction. Figure 4 shows the testing results of four specimens loaded at a rate of 50 mm/min using a 10kN force. The results from the tests in terms of, Flexibility Index (FI), strength and Fracture Energy (FE) parameters were found to be 14.67, 0.40 *MPa* and 2724.5 J/m^2, respectively.

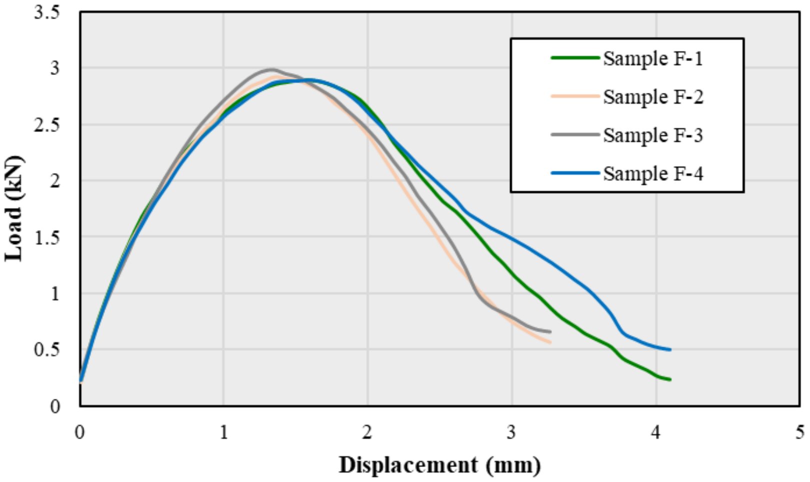


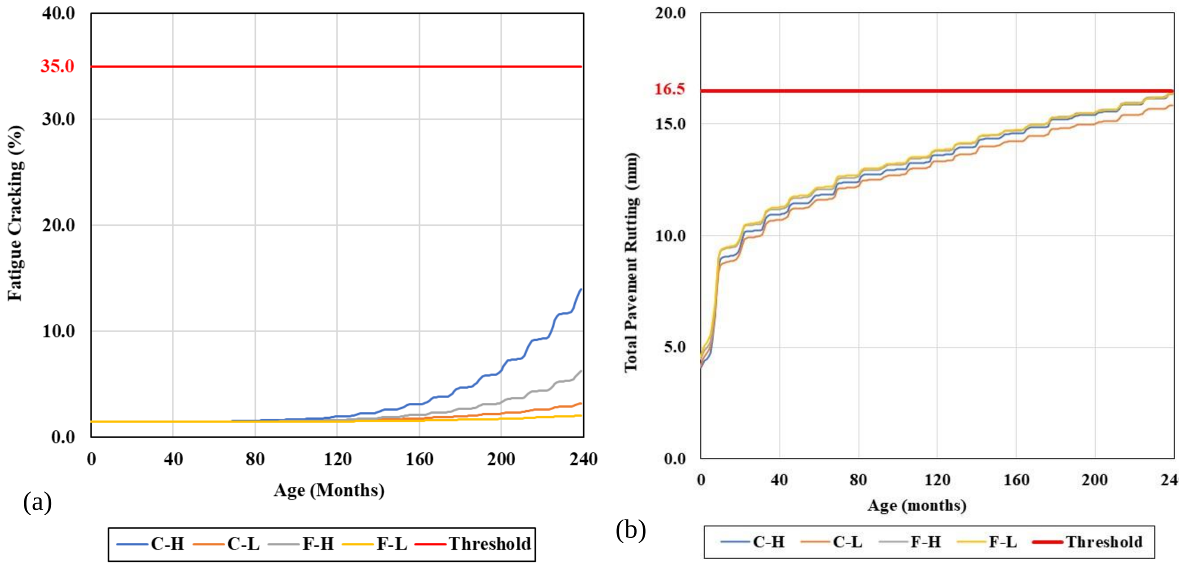
Fig 4. Load-Displacement Curves from I-FIT cracking test

Ultimately, analyzing the mix's resistance to moisture-induced damage plays a pivotal role in ensuring the longevity and reliability of asphalt pavements in various climate conditions, particularly in the cold regions of Canada [32,33]. According to the test for determining moisture susceptibility, outlined in "AASHTO T 283: Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage," six test specimens compacted to the target air voids of 7.0 percent were divided into two subsets—a conditioned subset and an unconditioned subset.

The moisture susceptibility results comprised the average Indirect Tensile Strength (ITS) and the average Tensile Strength Ratio (TSR) for the tested mixes. It was noted that the average ITS for the conditioned subset was 802 kPa, while for the unconditioned subset, it measured 841 kPa. Consequently, the calculated TSR value of 95.3 percent substantially surpassed the standard threshold of 80.0 percent.

4. Pavement performance model

As illustrated in Figure 5 (a), the obtained values for fatigue cracking for all scenarios remain considerably lower than the threshold of 35%. Besides, the predicted values for permanent deformation in the total pavement remain below the threshold of 16.50 mm, as shown in Figure 5 (b). These findings indicate that the designed pavement structures exhibit reliable performance across various combinations of traffic volume, subgrade strength, and climate variation. Nevertheless, it is essential to recognize that conditions may vary regionally, and adjustments might be needed to ensure their suitability for local contexts. The successful mitigation of pavement distresses demonstrated by these innovative NMF-modified asphalt pavements showcases a promising avenue for sustainable and resilient roads.



(a)

(b)

Fig 5. Variation of Predicted (a) Fatigue Cracking and (b) Total Rutting

As the exploration of environmentally responsible paving solutions continues, the integration of e-waste by products in asphalt mixes presents an impactful step forward. Based on the findings of this study, there are several avenues for further exploration in the utilization of NMF in asphalt mixes. Firstly, additional pilot road trials could provide beneficial data regarding ride quality, using metrics such as the International Roughness Index (IRI) and surface friction characteristics, particularly in unique climates such as the cold regions of Canada. Employing non-destructive testing techniques such as Falling Weight Deflectometer (FWD) tests could also provide practical insights into the structural performance of these mixes under real-world conditions. Lastly, conducting comprehensive Life-cycle Cost Analysis (LCCA) and detailed assessments of the environmental impact associated with NMF utilization using Life Cycle Assessment (LCA) would offer valuable information into the long-term economic benefits and sustainability advantages of incorporating NMF in pavement construction.

5. Conclusions

This study demonstrated the promising potential of incorporating NMFs of PCB waste into asphalt mix following the Superpave design approach. Considering the advantages offered by the dry process, such as simplicity, cost-effectiveness in terms of equipment and energy, and direct control over NMF dosage, this method was opted for current study. Then, through a series of performance tests, it was found that mix damage caused by traffic and climate factors is within acceptable limits, affirming the viability of the chosen dry process method for incorporating NMFs into the asphalt mix. Notably, the average rut depth was limited to 8.18mm after 20,000 passes, indicating acceptable rutting resistance. Additionally, with a Flexibility Index (FI) of 14.67 and a strength of 0.40 MPa, the mix demonstrated the ability to resist fatigue cracking. Moreover, the mix exhibited a Tensile

Strength Ratio (TSR) of 95.3 percent, surpassing the standard threshold and confirming its resilience against moisture-induced damage.

Furthermore, M-E analysis of four pavement models revealed that predicted distresses consistently remained below the failure threshold even in the presence of varying subgrade conditions, traffic volumes and climate factors. Finally, in response to the urgency for sustainable practices, it can be inferred that the integration of NMFs into asphalt mix may represent a valuable avenue to promote circular economy principles and reduce the need for incineration or landfill disposal.

6. Acknowledgments

The National Research Council Industrial Research Assistance Program (NRC-IRAP) supported this work. We extend our appreciation to Zlatko Brcic for testing assistance and valuable insights, significantly enhancing this study. Gratitude is also extended to Dr. Omran Maadani for his review and feedback.

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