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Sustainability Assessment of Nanosilica Sand as a Filler in Porous Asphalt with Experimental Approach

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ABSTRACT

The use of silica sand, particularly nanosilica in porous asphalt has gained interest for its potential to enhance mechanical performance and sustainability. Laboratory tests examined mixtures containing 0%-5% nanosilica, compacted using the Marshall and Gyratory methods, to assess stability, permeability, and durability. Stability increased significantly and peaked at 3% (1044.70 kg), representing an improvement of approximately 35% compared to the 2% content. The Cantabro Loss value at 3% was 21.45%, which still met durability requirements. In terms of drainage performance, the permeability coefficient remained stable at 1-3% (0.01781-0.01791 cm/s), but dropped sharply by 29% when nanosilica content increased from 3% to 4%. Total and connected voids remained within Australian Asphalt Pavement Association (AAPA) 2004 specifications (>18%). Overall, a filler content of 3% was identified as optimal because it achieved the highest stability and permeability while maintaining durability. Nanosilica demonstrates strong potential as a sustainable filler for porous asphalt, enhancing both mechanical and environmental performance. Careful optimization is essential to balance durability and permeability, guiding future research in sustainable pavement technologies.

1. INTRODUCTION

Porous asphalt mixtures gain increasing attention in modern pavement engineering due to their ability to enhance surface drainage, reduce hydroplaning risks, and improve road safety. However, their inherently open structure presents challenges in terms of mechanical strength, durability, and long-term performance. Recent advancements in nanotechnology introduce nanosilica sand as a promising additive to address these limitations. The integration of nanosilica sand into porous asphalt mixtures has demonstrated significant potential in improving mechanical properties, enhancing durability, and promoting sustainability in road construction. Porous asphalt was first developed in the United States in the 1930s and became widely used in the 1970s. Subsequent improvements in Europe helped popularize porous asphalt in many countries due to its benefits in enhancing safety under wet conditions and reducing noise. According to the National Cooperative Highway Research Program (NCHRP) Report 640, the adoption of porous asphalt is primarily driven by policy factors, followed by traffic volume considerations. Therefore, China should draw on international experience, strengthen policy support, and adapt porous asphalt materials and structures to its traffic conditions. Other factors such as safety, winter maintenance, and wet-weather accident history remain important, although they are not the primary determinants [1].

Nanosilica's unique physicochemical characteristics, particularly its large surface area and superior dispersion capability, contribute to improved binder-aggregate interaction, resulting in enhanced stiffness and reduced susceptibility to common distresses such as binder draindown and raveling. Masri et al. [2] reported that incorporating nanosilica into asphalt binders significantly increases the mixture's resistance to deformation and mechanical degradation, thereby extending pavement service life. These improvements are particularly critical in porous asphalt applications, where structural integrity is often compromised by environmental exposure and traffic loading. Beyond mechanical enhancement, nanosilica exhibited efficacy in improving moisture resistance and aging performance. Gupta et al. [3] highlighted that nanosilica-modified mixtures exhibit superior resistance to water infiltration, which is essential for maintaining the functional and structural performance of porous pavements. Samsudin et al. [4] further demonstrated that nanosilica contributes to the preservation of binder microstructure under long-term aging conditions, thereby mitigating oxidative hardening and maintaining flexibility over time. These findings underscore the role of nanosilica in enhancing the durability of asphalt mixtures under varying climatic and operational conditions.

Parallel to asphalt research, numerical modeling has emerged as a critical tool for analyzing embankment behavior on soft soils. Anggraini and Maizir [5] employed Plaxis 2D to assess the impact of geofoam thickness on embankments, comparing models without geofoam and with 30 cm and 40 cm layers. Their results indicated that increased geofoam thickness significantly reduces settlement, deformation, and soil stress, offering a practical solution for improving stability over weak subgrades. Similarly, Jusi and Maizir [6] explored foam mortar reinforcement in soft-soil embankments at varying subgrade heights (60, 120, and 180 cm). Their findings revealed that thicker soft-soil layers correspond to higher settlement and greater deformation, reinforcing the necessity of adequate reinforcement strategies to mitigate structural risks.

This study aims to comprehensively evaluate the sustainability of incorporating nanosilica sand as a filler in porous asphalt mixtures by examining its technical, environmental, and economic implications. Specifically, it seeks to analyze the particle size reduction and morphological transformation of nanosilica sand, assess its influence on the mechanical performance of porous asphalt using the Marshall compactor, and determine its impact on permeability characteristics. Furthermore, the research will critically compare the advantages and disadvantages of nanosilica sand as a filler while integrating environmental and economic indicators to establish its viability as a sustainable alternative in pavement engineering. Through this multi-dimensional approach, the study intends to provide a holistic understanding of nanosilica sand's role in enhancing asphalt performance and promoting eco-friendly infrastructure solutions.

2. METHOD

This research employed a laboratory-scale experimental approach to assess the impact of silica sand-based nanomaterial fillers on the performance of porous asphalt mixtures. The study was designed to investigate how varying filler contents affect the key volumetric and mechanical properties of asphalt mixtures compacted using two different methods: the Marshall and Gyratory methods. The experimental design was guided by previous findings that highlight the potential of nanomaterials to enhance asphalt performance by improving binder-filler interactions and reducing air voids [7].

The aggregates used in this study, both coarse and fine, were sourced from the Gunung Katunun quarry in South Kalimantan, Indonesia. These aggregates exhibited a hardness level of 20%, which is within the acceptable range for porous asphalt applications. The physical and mechanical properties of the aggregates were characterized in accordance with standard procedures to ensure consistency and reliability in the mixture design. The selection of local aggregates also aligns with sustainable construction practices by minimizing transportation-related environmental impacts.

Silica sand-based nanomaterials were employed as fillers due to their large surface area and chemical reactivity, which may enhance the performance of asphalt mixtures. The filler was incorporated at five different proportions: 0%, 1%, 2%, 3%, 4% and 5% by total aggregate weight. These dosage levels were selected based on prior studies that demonstrated the effectiveness of nano-silica in improving mixture stability, reducing moisture susceptibility, and enhancing durability [8]. The use of nano-silica is further supported by its ability to form chemical bonds with asphalt binders, thereby improving the rheological and mechanical properties of the mixture [9].

The porous asphalt mixtures were prepared using a fixed optimum asphalt content (OAC) of 5.0%, determined through preliminary trials. Two compaction methods were employed to simulate different field conditions: the Marshall compactor, following the 2004 Australian Asphalt Pavement Association (AAPA) specifications, and the Gyratory compactor, which provides a more realistic simulation of field compaction. The dual compaction approach enabled a comparative analysis of the effects of compaction techniques on the performance of nanomaterial-modified mixtures, as suggested by Raufi et al. [10].

The porous asphalt specimens were prepared using a Marshall compactor with nanomaterial filler contents of 0%, 1%, 2%, 3%, 4%, and 5%. In the Marshall test, three specimens were used for each filler content, resulting in a total of 15 samples to evaluate the mixture characteristics, including stability, flow, and volumetric properties. The material damage test also used three specimens for each filler content, with a total of 15 samples to assess the mixture's resistance to loading and environmental conditions. Meanwhile, the Cantabro Loss test used two specimens for each filler content, resulting in a total of 10 samples to evaluate aggregate particle loss due to ravelling. Overall, a total of 40 specimens were used in this study, all of which were prepared and compacted using a Marshall compactor to ensure uniform density in accordance with porous asphalt testing procedures.

In the Cantabro test, two specimens were used for each filler content, resulting in a total of 10 samples to evaluate the mixture's resistance to ravelling. Meanwhile, the permeability test used one specimen for each filler content, resulting in a total of 5 samples to assess the mixture's ability to allow water to pass through its void structure. Overall, a total of 15 specimens were used in this advanced testing stage, all of which were compacted using a gyratory compactor to ensure uniform density distribution and void structure in accordance with porous asphalt testing specifications.

Performance testing was conducted on the compacted samples to evaluate their mechanical and volumetric characteristics. Marshall-compacted specimens were tested for stability, durability, and void content, while Gyratory-compacted specimens were assessed for permeability using a falling head permeameter. These tests were selected based on their relevance to the functional performance of porous asphalt, particularly in terms of structural integrity and drainage capacity [11]. The testing procedures adhered to established standards to ensure the validity and reproducibility of the results.

Finally, the data obtained from the laboratory tests were analyzed to determine the relationship between nanomaterial filler content and the performance indicators of the asphalt mixtures. The independent variable in this study was the amount of nanomaterial filler, while the dependent variables included void content, asphalt content, and stability. Statistical analysis was employed to identify trends and correlations, enabling a comprehensive understanding of the influence of nanomaterial fillers on the volumetric and mechanical behavior of porous asphalt. These findings were interpreted in the context of existing literature, which consistently supports the beneficial role of nanomaterials in enhancing asphalt mixture performance [8].

3. RESULTS AND DISCUSSION

3.1 Particle size reduction and morphological transformation

Figure 1 shows the Initial Dimensions Before Mechanical Testing. Mechanical activation of silica sand through dry transverse ball milling for durations ranging from 3 to 6 hours resulted in a substantial reduction in particle size. Initially measuring approximately 1.00 mm, the particles were ground to the nanoscale, resulting in the formation of nanosilica. Scanning Electron Microscope (SEM) analysis revealed a distinct morphological transformation, with particles changing from large, rectangular shapes to significantly smaller and more irregular forms. This transformation occurred without thermal influence, indicating that mechanical energy alone was sufficient to induce fragmentation and refinement of the silica particles, as shown in Figure 2.

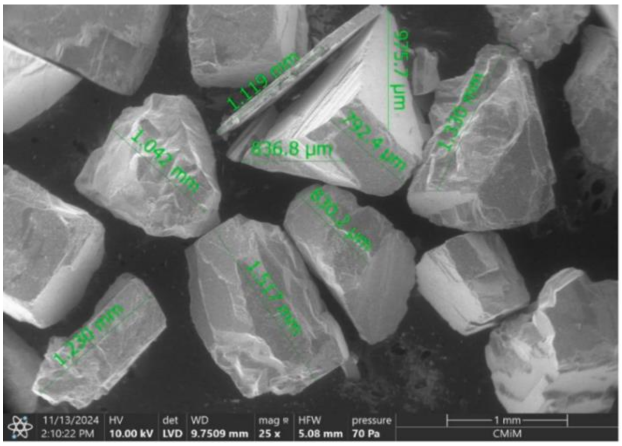

Figure 1. Initial size before mechanical testing
Source: Laboratory testing

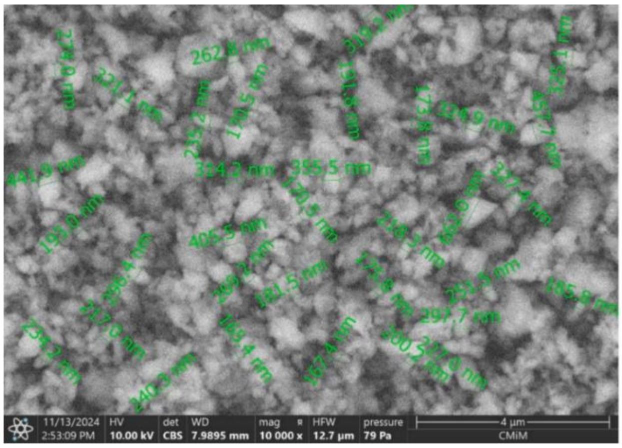

Figure 2. Dimensions after mechanical testing
Source: Laboratory testing

The observed morphological changes are consistent with findings by Rasheed et al. [12] who reported that mechanical processing of silica powder enhances its surface area and reactivity, thereby improving its integration into composite materials such as asphalt binders. Similarly, Mashaan [13] emphasized that the reduced particle size of nanosilica contributes to improved dispersion and bonding within bituminous matrices, thereby enhancing mechanical performance.

Table 1 shows the X-Ray Fluorescence (XRF) test results. XRF analysis was conducted to assess the elemental composition of the processed nanosilica. The results indicated a dominant presence of silica (SiO_2) at 91.83%, followed by alumina (Al_2O_3) at 6.66%, with trace amounts of other elements. This high silica content aligns with the requirements for advanced material applications, particularly in civil engineering and pavement technologies. The purity and composition of nanosilica are critical for its performance in modified asphalt mixtures. Taher and Ismael [14] demonstrated that nanosilica with a high SiO_2 content significantly enhances rutting resistance and durability in hot-mix asphalt, especially under aging conditions. Furthermore, Aodah et al. [15] highlighted the role of silica-rich aggregates in mitigating moisture damage in bituminous materials, reinforcing the importance of mineralogical integrity.

Table 1. XRF test results

Composition	Mineral Content
Al_2O_3	6.66%
SiO_2	91.83%
P_2O_5	0.17%
SO_3	0.88%
CI	0.01%
TiO_2	0.07%
Cr_2O_3	0.01%
MnO	0.01%
Fe_2O_3	0.08%
BaO	0.13%
CaO	0.16%

Source: Laboratory testing

3.2 Influence of nanosilica filler on porous asphalt performance using Marshall compactor

Table 2 presents the material requirements for each variation in nanosilica content. The incorporation of fillers in porous asphalt mixtures plays a pivotal role in enhancing mechanical performance by forming a cohesive matrix between the asphalt binder and aggregates. This matrix contributes to the stability of the mixture despite its inherently high void content. Fillers also serve to absorb excess binder, thereby regulating adhesion and viscosity characteristics [3]. Table 3 shows the Test Results of Porous Asphalt Mixtures Using a Marshall Compactor with Variations in Nanosilica Content. The experimental results in Table 3 indicate that the addition of nanosilica filler has a significant influence on the stability of porous asphalt mixtures compacted using the Marshall method. Stability values increased with nanosilica content, reaching a peak at 3% filler concentration. This enhancement is consistent with previous findings that nanosilica improves the viscoelastic and mechanical properties of asphalt mixtures due to its large surface area and interaction with the binder [16]. However, beyond the 3% threshold, stability values declined, suggesting a saturation point beyond which additional filler may disrupt the internal structure or lead to binder deficiency.

The mean Marshall stability of 838.91 kg significantly exceeds the minimum requirement (>500 kg), indicating that nanosilica-modified porous asphalt mixtures generally exhibit adequate structural resistance. However, the relatively large SD (±113.15 kg) reflects substantial variability with filler dosage, confirming that stability is highly sensitive to nanosilica content. This statistically supports the observation that stability peaks at 3% nanosilica, while higher dosages do not consistently improve load-bearing capacity.

The average Cantabro Loss of 23.15% is close to the allowable threshold (≤25%), whereas the high SD (±8.72%) indicates pronounced dispersion between filler levels. This statistical spread is driven by the 4% and 5% nanosilica mixtures, where Cantabro Loss values exceed the specification. The large standard deviation quantitatively confirms a loss of durability and higher raveling susceptibility at excessive nanosilica contents, consistent with binder stiffening and brittleness mechanisms reported by Rohani et al. [17].

Both Voids in the Mixture (VIM) (21.05 ± 1.77%) and connected voids (19.05 ± 1.77%) exhibit identical standard deviations, suggesting a stable and proportional relationship between total and interconnected porosity. Statistically, the moderate SD indicates that void content remains within an acceptable range for porous asphalt, although the upward trend with higher nanosilica contents confirms that nanosilica does not act as an effective void-filling agent. This reinforces the conclusion that increased stability is not directly correlated with reduced porosity.

Table 2. Material requirements for each nanosilica content variation

Filter Size		OGA 14 Gradation AAPA 2004 Weight (%)		Material Requirements Per Nanosilica Filler Content (Kg)					
ASTM	mm	Passed	Stuck	0%	1%	2%	3%	4%	5%
¾”	19.00	100.00	-	-	-	-	-	-	-
½”	12.70	92.50	7.50	85.23	84.38	83.53	82.67	81.82	80.97
3/8”	9.50	57.50	35.00	397.74	393.76	389.79	385.81	381.83	377.85
2/7”	6.70	35.00	23.00	255.69	253.13	250.58	248.02	245.46	242.91
No. 4	4.75	17.50	17.00	198.87	196.88	194.89	192.90	190.92	188.93
No. 8	2.36	11.00	6.50	73.87	73.13	72.39	71.65	70.91	70.17
No. 16	1.18	9.00	2.00	22.73	22.50	22.27	22.05	21.82	21.59
No. 30	0.60	7.50	1.50	17.05	16.88	16.71	16.53	16.36	16.19
No. 50	0.30	6.00	1.50	17.05	16.88	16.71	16.53	16.36	16.19
No. 100	0.15	5.00	1.00	11.36	11.25	11.14	11.02	10.91	10.80
No. 200	0.08	3.50	1.50	17.05	16.88	16.71	16.53	16.36	16.19
Pan			3.50	39.77	39.38	38.98	38.58	38.18	37.79
Filler		1% - 5%		0	11.36	22.73	34.09	45.46	56.82
Asphalt Content		5%		60.00	60.00	60.00	60.00	60.00	60.00
Cellulose Fiber		0.30%		3.60	3.60	3.60	3.60	3.60	3.60
Total				1200	1200	1200	1200	1200	1200

Table 3. Test results of porous asphalt mixtures using a Marshall compactor with variations in nanosilica content

No	Mixed Properties	unit	Filler Nanosilica (%)						Specification	Mean ± SD
			0%	1%	2%	3%	4%	5%		
1	Stability	kg	728.16	773.56	772.25	1044.7	857.81	856.97	> 500	838.91 ± 113.15
2	*Cantabro*	%	10.85	24.45	17.37	21.45	35.56	29.19	< 25	23.15 ± 8.72
3	VIM	%	19.63	18.95	21.09	21.17	21.36	24.07	18 - 23	21.05 ± 1.77
4	R Connected	%	17.63	16.95	19.09	19.17	19.36	22.07	-	19.05 ± 1.77

Despite the observed increase in stability, the Cantabro Loss values at 4% and 5% filler concentrations exceeded the acceptable limit of 25%, registering at 35.56% and 29.19%, respectively. These results indicate a reduction in durability and resistance to raveling at higher filler contents. Rohani et al. [17] reported similar degradation in performance at elevated nanosilica levels, who attributed the phenomenon to reduced binder coating and increased brittleness.

Interestingly, the void content and connected voids continued to increase with higher filler concentrations. This trend suggests that nanosilica, while enhancing stability up to a certain point, does not effectively reduce voids in the mixture. The lack of correlation between stability, void content, and Cantabro Loss underscores the complex interplay between filler dosage and mixture performance. Arabani et al. [18] emphasized that the type and dosage of filler must be carefully optimized to balance cohesion, adhesion, and durability in porous asphalt systems.

The findings align with those of Bala [19] who demonstrated that nanomaterial optimization in asphalt mixtures requires a multi-parameter approach, considering not only mechanical strength but also durability and permeability. Moreover, Eisa et al. [20] highlighted that nanomaterials, such as graphene and nanosilica, can enhance mechanical properties; however, their effectiveness is highly dependent on the quality of dispersion and interaction with the binder.

The optimal nanosilica filler content for porous asphalt mixtures, as determined using the Marshall compactor, is 3%, which yields the highest stability without compromising durability. Concentrations above this threshold are not recommended due to excessive Cantabro Loss and increased void content. These results underscore the importance of precise filler optimization in porous asphalt design, aiming to strike a balance between structural integrity and functional performance.

3.3 Permeability performance of porous asphalt mixtures

Table 4 shows the permeability coefficient of Porous Asphalt Mixture. The compaction of porous asphalt mixtures using the gyratory compactor was conducted with 80 gyrations, in accordance with AAPA 2004 specification, which stipulates a minimum permeability coefficient of 0.01 cm/s. The results demonstrated that all filler content variations met the required permeability threshold. Notably, the highest permeability was observed at a nanosilica filler content of 3%, indicating that filler type and dosage significantly influence the volumetric properties of the mixture. This finding aligns with the observations of Chen and Li [21] who emphasized the sensitivity of asphalt mixture compaction characteristics to material composition, particularly under gyratory compaction. The gyratory method facilitates a more uniform aggregate orientation and interlock, which is critical in porous asphalt systems where interconnected voids govern permeability.

The mean permeability coefficient of 0.01627 cm/s comfortably exceeds the minimum requirement (> 0.01 cm/s), confirming that all mixtures retain adequate drainage capability. The relatively small SD (± 0.00281 cm/s) indicates consistent permeability performance across filler levels, although a measurable reduction occurs at 4-5% nanosilica. This statistical behaviour supports the finding that 3% nanosilica offers the most balanced permeability stability performance, in agreement with Chen and Li [21].

Table 4. Permeability coefficient of porous asphalt mixture (gyratory compactor)

Filler (%)	Permeability Coefficient
0	0.01872
1	0.01781
2	0.01783
3	0.01791
4	0.01270
5	0.01265
Specification	> 0.01 cm/s
Mean ± SD	0.01627 ± 0.00281

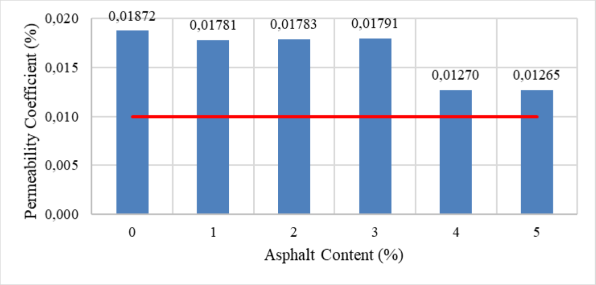

Figure 3. Permeability coefficient of porous asphalt mixture

Figure 3 shows the permeability coefficient of the porous asphalt mixture. While the addition of filler enhances the structural integrity of the mixture, excessive filler content may lead to an increase in interconnected voids, thereby elevating permeability but potentially compromising mechanical stability. This trade-off is consistent with the findings of Tapkın and Keskin [22] who reported that modified asphalt specimens compacted with gyratory equipment exhibited varying rutting resistance depending on the types of filler and additive. Moreover, the mechanical behavior of the mixture under compaction and traffic loads is influenced by aggregate crushing and migration, as highlighted by Jiang et al. [23]. These studies emphasize the importance of aggregate behavior during compaction, which has a direct influence on the formation and stability of void structures in porous asphalt.

The permeability values obtained in this study were generally close to the minimum specification limit. This finding may be attributed to limitations inherent in the measurement techniques employed, e.g., the Falling Head and Constant Head methods, which primarily assess vertical flow. However, as porous asphalt exhibits both vertical and lateral flow characteristics, these methods may not fully capture the actual permeability behavior of the mixture. Oktaviani et al. [24] similarly noted that functional performance assessments of modified porous asphalt require comprehensive evaluation methods that account for multi-directional flow. The need for more accurate and representative testing protocols is further supported by Mu et al. [25] who demonstrated that intelligent gyratory compaction can reveal nuanced mechanical responses in reclaimed asphalt pavement materials, suggesting potential for more advanced permeability assessment techniques.

The results suggest that an optimal filler content must strike a balance between permeability and mechanical stability. While nanosilica at 3% yielded the highest permeability, further investigation is needed to assess its long-term durability under traffic loading. Additionally, the development of improved permeability testing methods that incorporate both vertical and lateral flow dynamics is essential for more accurate characterization of porous asphalt mixtures. Future research should also explore the integration of warm mix asphalt (WMA) and reclaimed asphalt pavement (RAP) technologies, as proposed by Yu et al. [26] to enhance sustainability without compromising functional performance. The influence of compaction temperature and method, as discussed by Li et al. [27] may also offer insights into optimizing mix design for varying environmental and operational conditions.

3.4 Advantages and disadvantages of nanosilica sand for porous asphalt

Table 5 presents the advantages and disadvantages of silica sand in porous asphalt. Silica sand enhances mechanical strength, durability, and water drainage, thereby improving road performance and sustainability. Its contribution to mixture porosity enables better water management, reducing surface water, minimizing hydroplaning, and improving skid resistance, especially under wet conditions [28, 29]. Furthermore, silica sand can increase the stability and durability of asphalt mixtures. Research suggests that adding silica can enhance the overall composition and performance of porous asphalt mixtures, resulting in improved stability test results [24]. The flame retardancy and thermal stability of silica may also contribute to the longevity of asphalt mixtures by enabling them to withstand extreme temperature conditions typically encountered during the mixing process [30].

Moreover, silica can help form a strong matrix within the asphalt, promoting better aggregate binding and enhancing the pavement's mechanical strength. This improvement in workability is essential during application for achieving optimal compaction and uniformity [31]. The use of silica sand not only addresses various performance issues but also aligns with sustainable practices. Research indicates that incorporating natural aggregates, such as silica sand, can reduce the environmental impact associated with asphalt production by minimizing the need for synthetic additives, thereby contributing to a more eco-friendly construction process [31].

Incorporating silica sand into porous asphalt mixtures has generated considerable interest in recent years, particularly due to the material's potential advantages. However, there are specific disadvantages associated with using silica sand for porous asphalt. These concerns revolve around issues related to performance, environmental impacts, and mechanical properties. One of the primary drawbacks of using silica sand in porous asphalt mixtures is its impact on the mechanical performance of the asphalt. Some research suggests that aggregates in porous asphalt may not cohesively bind, which can result in compromised structural integrity under load [32]. This point is critical because the applications of porous asphalt often occur in settings such as low-traffic roads and parking lots, where structural failure can lead to significant maintenance costs and safety concerns [32].

Additionally, while silica sand is prized for its numerous beneficial traits, its excessive use has raised environmental concerns. The extraction and transportation of silica sand can lead to ecological degradation, including habitat damage and increased biodiversity loss. Furthermore, the thermal sensitivity of asphalt mixtures that include silica can lead to thermal cracking under varying temperature conditions, particularly in regions with high temperature fluctuations. Research indicates that silica sand aggregates do not consistently enhance the thermal resilience of porous asphalt, creating risks of cracking and durability issues over time [31]. Another significant disadvantage is related to the porosity and permeability of the asphalt mixtures. While a certain level of porosity is desirable to allow for water drainage, excessive porosity resulting from improper gradation or excessive silica sand usage can lead to decreased load-bearing capacity and ineffective noise absorption [33]. Moreover, porous asphalt with high porosity can be significantly less durable, especially in climates where freeze-thaw cycles are prevalent. This assertion is exacerbated by moisture infiltration, which leads to the degradation of the asphalt matrix and thereby increases the likelihood of material failure [28].

Finally, there are implications regarding the cost and sustainability of sourcing silica sand. With increasing regulatory scrutiny and competition for sand for various construction purposes, the market dynamics for silica sand have shifted, potentially leading to inflated prices. This change can impact the overall economic feasibility of using silica sand in porous asphalt construction, prompting civil engineers and consultants to seek alternative materials that offer similar benefits with a lower environmental impact or cost burden [34].

Table 5. Advantages and disadvantages of silica sand for porous asphalt

Author/Year	Advantages	Disadvantages	Finding
Siala et al. [28]	Enhances porosity and drainage, improves skid resistance	Excessive porosity can reduce durability in freeze-thaw climates	Silica sand improves water management but may compromise longevity in cold regions.
Putra [29]	Improves skid resistance and mechanical performance	NA	Silica sand enhances surface safety during wet conditions.
Oktaviani et al. [24]	Increases stability and durability	NA	Silica improves asphalt composition and performance in stability tests.
Wang et al. [30]	Flame retardancy and thermal stability	NA	Silica contributes to heat resistance during mixing and application.
Wang et al. [31]	Enhances matrix strength and workability	Thermal sensitivity may lead to cracking in fluctuating climates	Silica improves compaction but may reduce thermal resilience.
Sabitri et al. [35]	Reduces need for synthetic additives, supports sustainability	NA	Silica sand promotes eco-friendly construction practices.
Marelo and Nataadmadja [32]	NA	Poor cohesion under load, structural failure risk	Silica may compromise structural integrity in low-traffic applications.
Lv et al. [33]	NA	Excess porosity reduces load-bearing and acoustic performance	High porosity affects durability and noise absorption.
Tay et al. [34]	NA	Environmental degradation from extraction and rising costs	Silica sand sourcing may become economically and ecologically unsustainable.

3.5 Environmental and economic indicators

From an environmental perspective, the sustainability of using nanosilica derives from its potential to reduce energy consumption and minimize waste in asphalt production. The significant improvement in performance metrics suggests that less material may be required overall in pavement applications, which can contribute to lower impacts on aggregate extraction and fabrication. For instance, the efficacy of nanosilica as a reinforcing agent may reduce reliance on traditional, more environmentally damaging materials in asphalt mixtures Kong et al. [36].

Life Cycle Assessment (LCA) studies have shown that incorporating nanomaterials can enhance overall sustainability by reducing the carbon footprint associated with asphalt paving operations [37]. By evaluating energy use and emissions throughout the life cycle of pavement materials that use nanosilica, researchers can gauge the potential reductions in greenhouse gas emissions compared to conventional asphalt formulations. The comprehensive assessment of environmental impacts extends to the utilization of industrial byproducts, such as the improved durability observed with recycled materials augmented with nanosilica, further promoting circular economy principles [38].

From an economic standpoint, the initial investment in incorporating nanomaterials such as nanosilica into asphalt mixtures may be offset by the long-term savings realized through enhanced durability and reduced maintenance costs [39]. As demonstrated, the enhanced properties of asphalt mixtures with nanosilica can lead to longer intervals between repairs and enhanced performance, which translates into lower life-cycle costs for municipalities and agencies responsible for infrastructure management [37]. Evaluating the sustainability of using nanosilica sand in porous asphalt should consider multiple indicators across environmental sustainability and economic efficiency. The potential gains in durability and reduction in maintenance costs, coupled with favorable environmental impacts, position nanosilica as a promising alternative filler in paving applications.

From a sustainability perspective, the integration of nanosilica in asphalt mixtures can be more rigorously justified when assessed using quantitative life-cycle indicators. LCA results for nano-silica-modified asphalt mixtures indicate that, at the material production stage, the global warming potential (GWP) is comparable to that of conventional asphalt, with values of approximately 7.45×10^3 kg CO_2-eq per functional unit, compared to 7.42×10^3 kg CO_2-eq for unmodified mixtures. This finding demonstrates that the environmental burden introduced by nanosilica during production remains marginal [37]. Importantly, this near-equivalent embodied carbon at the production stage can be offset over the pavement life cycle due to performance-related benefits. Studies linking nanosilica to enhanced mechanical properties such as improved stiffness, rutting resistance, and durability suggest reduced material demand and extended service life, which, in LCA terms, lowers impacts associated with aggregate extraction, binder production, and repeated maintenance interventions [36, 38].

Furthermore, when nanosilica is combined with recycled or industrial by-product materials, such as incineration bottom ash or mining waste fillers, LCA evidence shows substantial reductions in heavy metal leaching (e.g., Cu reduced from 250.05 to 89.97 mg L^{-1}), alongside improved material stability, thereby reinforcing both environmental safety and circular-economy outcomes [36, 38]. From an economic standpoint, Life Cycle Cost Analysis (LCCA) demonstrates that pavements incorporating nanosilica can achieve life-cycle cost reductions of approximately 5-8 % compared with conventional asphalt, despite slightly higher initial material costs. These savings arise from extended maintenance intervals and reduced rehabilitation frequency over a 20-year analysis period [37, 39]. Collectively, these quantitative LCA and LCC results indicate that nanosilica-modified porous asphalt offers a balanced sustainability profile, maintaining comparable embodied emissions while delivering measurable long-term economic savings and environmental benefits through durability-driven life-cycle optimisation.

The LCA of nanosilica-modified asphalt mixtures (NSMA) can be defined using a cradle-to-grave system boundary that includes raw material extraction and production, nanosilica production, asphalt binder production, aggregate processing, NSMA modification and mixing, transportation, construction, use and maintenance, and end-of-life management. The functional unit is defined as [40, 41]:

$$FU = A \times t \times SLF \tag{1}$$

where, FU is the functional unit of pavement service ($\text{m}^2 \cdot \text{year}$), A is the pavement area (m^2), t is the pavement service life (year), and SLF is the service life factor (-), which can be set to 1.0 for the reference design life. In this study A=1 m^2, t=30 years, and SLF=1.0, giving:

$$FU = 1 \times 30 \times 1.0 = 30\ \text{m}^2.\text{year} \tag{2}$$

The life cycle inventory of NSMA is calculated as the sum of material inputs, energy inputs, transport activities, construction activities, maintenance activities, and end-of-life flows [42, 43]:

$$LCI_{NSMA} = \sum_{i=1}^{n} M_i + \sum_{k=1}^{m} E_k \tag{3}$$

$$+ \sum_{r=1}^{q} T_r + \sum_{c=1}^{s} C_c + \sum_{u=1}^{u} U_u + \sum_{e=1}^{w} EOL_e$$

where, LCI_{NSMA} represents the life cycle inventory of NSMA per functional unit. *Mi* is the mass of material input *i* (kg/FU), Ek is the energy consumed in process *k* (MJ/FU), *Tr* is the transport activity for route *r* (tonne.km/FU), *Cc* is the construction-related flow *c, Uu* is the use or maintenance phase flow *u,* and *EOLe* is the end of life flow *e,* this equation follows the inventory logic of LCA, in which inputs and outputs are quantified across foreground and background processes.

4. CONCLUSIONS

This study examines the sustainability and performance of silica sand, particularly in the form of nanosilica, as a filler in porous asphalt mixtures. Experimental testing demonstrated that nanosilica significantly enhances the mechanical stability, durability, and permeability of porous asphalt. The optimal filler content was found to be 3%, which provided the highest stability and permeability without compromising durability, confirming the importance of precise filler optimization. Experimental results showed that mechanical activation of silica sand effectively reduced particle size and transformed its morphology, improving binder interaction and mixture cohesion. The XRF analysis confirmed a high purity of SiO_2, supporting its suitability for advanced pavement applications. Additionally, the study highlighted the influence of compaction methods Marshall and Gyratory on mixture performance, with gyratory compaction yielding more consistent permeability results. These findings align with previous research emphasizing the role of nanomaterials in enhancing asphalt binder properties and structural integrity.

The study also explored the asphalt aggregate interface, showing that nanosilica improves bonding strength and reduces moisture susceptibility, which are critical for long-term pavement performance. In conclusion, this research contributes significantly to the body of knowledge on sustainable pavement materials by validating the use of silica sand especially nanosilica as a high-performance filler in porous asphalt. It offers practical guidelines for optimizing filler content and compaction methods to achieve balanced mechanical and functional properties. Future research should focus on long-term field performance, advanced permeability testing methods, and integration with reclaimed and warm mix asphalt technologies to further enhance sustainability and resilience in road infrastructure.

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