VOLUMETRIC PROPERTIES OF STONE MASTIC ASPHALT MIXTURE INCORPORATED WITH NANO SILICA AND GLASS FIBER

Abdullah Omar Abdullah Baqadeem, Khairil Azman Masri*, Mazlan Abu Seman, Muzamir Hasan, Othman Che Puan, and Ramadhansyah Putra Jaya

Received: April 03, 2024; Revised: January 30, 2025; Accepted: February 27, 2025

Abstract

Stone Mastic Asphalt (SMA) has become integral to contemporary road construction due to its exceptional durability and performance. The stability of SMA, a key determinant of its resistance to deformation under diverse traffic and environmental conditions, underscores its effectiveness. Moreover, the flow characteristics of SMA play a pivotal role in its workability and compaction during construction. This study aims to evaluate the impact of nano silica-modified bitumen on rheological properties, encompassing viscosity, penetration, and softening point. Additionally, the research investigates the influence of glass fiber reinforcement on the mechanical properties of the asphalt mixture, explicitly focusing on volumetric properties and the Marshall stability test. In pursuit of these objectives, pure bitumen underwent modification with (1-5%) nano silica using a high-shear mechanical mixer, and (0, 0.2, 0.4, 0.6, 0.8, and 1%) glass fiber was incorporated into the asphalt mixture. The findings reveal that the asphalt mixture exhibits enhanced Marshall stability, stiffness, and flow values compared to conventional asphalt mixtures. Notably, the modified bitumen containing 4% nano silica and the hybrid asphalt mixture with a 0.4% glass fiber concentration demonstrate the most significant improvements in Marshall stability. The study establishes a positive correlation between the addition of nano silica to bitumen and glass fiber to the asphalt mixture, indicating a beneficial impact on the overall mechanical characteristics of the pavement.

Keywords: **Asphalt; Glass fiber; Modified Bitumen; Nano silica; Stone Mastic Asphalt**

Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26300, Pahang, Malaysia. E-mail: abdullahbaqadeem@gmail.com; khairilazman@umpsa.edu.my; mazlanseman@umpsa.edu.my; muzamir@umpsa.edu.my; othmancp@umpsa.edu.my; ramadhansyah@ump.edu.my*

* *Corresponding author*

DOI: https://doi.org/10.55766/sujst4104

Introduction

The Asphalt pavements, widely utilized in the construction of highways and runways, often employ Stone Mastic Asphalt (SMA) due to its commendable resistance to deformation, superior skid resistance, and heightened durability (Hainin *et al*., 2012; Hainin *et al*., 2015). SMA performance can be optimized by incorporating diverse additives or modifiers, with glass fiber and nanosilica emerging as notable enhancers.

Nanosilica

Notably, nanosilica modification stands out for its capacity to elevate the stiffness and strength of the asphalt binder, facilitated by the high surface area-to-volume ratio of nanosilica particles (Aggarwal *et al*., 2015; Ţălu, 2015). This unique characteristic enables the formation of a network-like structure within the binder, fortifying intermolecular forces and resulting in a stiffer binder adept at withstanding deformation and cracking (Zhuang and Chen, 2019).

The advantageous impact of nanosilica on asphalt mixtures is corroborated by several studies demonstrating improvements in stiffness, rutting resistance, fatigue resistance, and adhesion between the asphalt binder and aggregate particles (Sadeghnejad and Shafabakhsh, 2017; Arshad *et al*., 2019; Shahnewaz *et al*., 2023). This enhancement contributes to a more stable and durable mix, underscoring the pivotal role of nanosilica in optimizing asphalt pavement performance. For example, studies have shown that adding nanosilica can significantly enhance the high-temperature performance of asphalt by increasing its stiffness modulus and reducing permanent deformation (Guo *et al*., 2018; Al-Sabaeei *et al*., 2022). Additionally, a study by Khattak *et al*. (2025) identified 6% Bakelite as optimal for single modification and 6% Bakelite with 4% Nano clay as the best combination, improving permanent deformation resistance by 39.2%, resilient modulus by 1.6 times and reducing moisture susceptibility by 22.56%.

Glass Fiber

On a parallel track, the historical evolution of incorporating fibers in asphalt mixtures traced back to the 1950s, has evolved into a well-established construction technique (Slebi-Acevedo *et al*., 2020). Glass fibers, woven into a fabric-like material, possess high tensile strength and resistance to weathering (Kim *et al*., 2018), making them a staple in high-performance asphalt mixtures (Tanzadeh and Shahrezagamasaei, 2017). The addition of glass fibers mitigates crack formation and propagation (Ziari and Moniri, 2019), bolstering pavement durability against environmental degradation (Sheng *et al*., 2017), thereby minimizing the frequency of repairs and maintenance (Kiran and Ravitheja, 2019; Enieb *et al*., 2021).

Delving into specific studies on glass fiber modification, Luo *et al*. (Luo *et al*., 2019) advocate for a recommended mix of 0.25% glass fiber based on the total mixed weight, showcasing notable improvements in iHot Mix Asphalt (HMA) properties. Another investigation by Taherkhani (2016) and Masri *et al*. (2022) contrasts the effectiveness of glass fibers and nanoclay in asphalt mixtures, revealing the superior impact of glass fibers on the indirect tensile strength. Additionally, Wu *et al*.'s study (Wu *et al*., 2007) sheds light on the dynamic properties of asphalt mixtures modified with fibers, indicating a higher dynamic modulus than control mixtures. These studies underscore the multifaceted advantages of incorporating glass fibers in asphalt mixtures for substantial performance enhancements.

Nanosilica and glass fiber are chosen for their complementary roles in enhancing SMA performance. Nanosilica strengthens the binder by increasing stiffness and deformation resistance, while glass fiber improves durability by reducing cracks and resisting environmental damage. They enhance binder performance and structural integrity, creating a more durable and resilient SMA mixture.

While the individual effects of nanosilica (NS) and glass fiber (GF) on Stone Mastic Asphalt (SMA) are well-documented, their synergistic impact on SMA mixtures has not been extensively studied. Most research focuses on either NS or GF in isolation, with limited exploration of how these two modifiers interact to enhance the overall performance of SMA. This study aims to assess the impact of NS and GF on the mechanical properties, particularly the volumetric characteristics and stability, of SMA mixtures.

This research centers on enhancing the mechanical properties of asphalt mixtures, particularly volumetric characteristics, by incorporating glass fiber and nanosilica-modified asphalt binder into Stone Matrix Asphalt (SMA) mixes. The investigation focuses on the synergistic impact of these two modifiers, an aspect not extensively explored in prior research. The outcomes of this study are anticipated to play a pivotal role in advancing the durability and longevity of asphalt pavements, thereby positively impacting transportation infrastructure and the economy.

Materials and Methods

Aggregate

To comply with the gradation requirement for Stone Mastic Asphalt 20 (SMA20), the coarse and fine aggregates retrieved from the quarry were mixed per the guidelines provided by the Malaysian Public Works Department (*Standard_Specification_For_Road_WorksFlexible _Pavement*, n.d.). The SMA20 gradation envelope restricts specifying the range of aggregate sizes selected, which can be observed in Table 1.

Table 1. Gradation limits of combined aggregate

Sieve Size (mm)	% Passing			% Retained	Weight (g)
	Min.	Max.	Mid.		
19	100	100	100	0.0	0.0
12.5	85	95	90	10.0	120
9.5	65	75	70	20.0	240
4.75	20	28	24	46.0	552
2.36	16	24	20	4.0	48
0.60	12	16	14	6.0	72
0.30	12	15	13.5	0.5	6
0.075	8	10	9	4.5	54
OPC				2.0	24
Pan				7.0	84
				100	1200

Asphalt Binder

Nanosilica modified bitumen was produced by mixing 60-70 penetration grade bitumen with five different percentages of the weight of bitumen (1, 2, 3, 4, and 5%). These values are typically used based on various related studies using NS for asphalt modification. First, the required weight of bitumen and the weight percentage of nano silica were determined. The bitumen was then preheated to a temperature of around 160°C, and the amount of needed nanosilica was weighed out and added to the preheated bitumen. The nanosilica was added gradually to bitumen and mixed thoroughly using a mixer machine for 60 minutes, and the speed was 2000 revolutions per minute until a homogenous mixture was obtained. The modified bitumen was then returned to the oven until the air bubbles disappeared before it was ready to test its properties.

This process was repeated for different weight percentages of nano silica ranging from 0-5% with an increment of 1%. The properties of each modified bitumen sample, including its viscosity, softening point, and penetration, were then tested. The data obtained from the tests was analyzed, and the properties of the modified bitumen samples, including the unmodified bitumen sample, were compared. The percentage of nano silica that provides the best enhancement in the properties of the modified bitumen was then selected based on the results of the tests. Table 2 shows the properties of NS used in this study.

Table 2. Properties of Nanosilica

Properties	Value
Appearance	Slight Milky Transparent
SiO_2 (%)	30%
Na_2O (%)	0.5%
pH	8.5-10.5
Density	1.19-1.22 g/cm^3

Fourier Transform Infrared Spectrometer (FTIR)

FTIR analysis will be conducted to determine the presence of functional groups. The Nicolet iS5 Model FTIR (Spectrum100) was used to measure the sample, and the resulting spectra will be evaluated using OMNIC software in terms of transmittance (%) within the wave number range of 400 to 4000 cm^{-1} and 32 scans. A total of 6 specimens were prepared for this test with the ranges of NS content, where each specimen was scanned at least three times to obtain consistent values. Each scanned specimen is compared to spectra images from previous studies (Rajaeiyan and Bagheri-Mohagheghi, 2013; Yang *et al*., 2010).

Glass Fiber

A glass fiber-modified asphalt mixture sample was produced by adding five different percentages of glass fiber (0.2, 0.4, 0.6, 0.8 and 1%) of the weight of aggregate and in addition to the control sample with 0% of glass fiber. These values are also typically used based on various related study using NS for asphalt modification. The dry blending technique was used, whereby the glass fibers were mixed for a while with the hot aggregate and filler before the addition of the nanosilica modified bitumen. The properties of glass fiber used in this study are shown in Table 3.

Table 3. Properties of Glass Fiber

Features	Unit	Glass Fiber
Color	–	White
Specific gravity	g/cm^3	1.18
Length	mm	12
Diameter	mm	<0.13
Tensile strength	MPa	>1000
Melting point	°C	800-900
Water absorption	%	0

Marshall Stability Test

The Marshall stability test involves preparing cylindrical specimens (101.6 mm diameter, 63.5 mm height) using hot-mix asphalt. Aggregates and bitumen are heated to 160-170°C before mixing. The mix is compacted with 75 blows per side, as per

ASTM D6927. Specimens are cured for 24 hours at room temperature and conditioned at 60°C ± 1°C in a water bath for 30-40 minutes before testing. The test uses a stability machine applying a load at 50.8 mm/min and measures deformation using a flow meter.

Results and Discussion

Asphalt Binder Properties

Table 4 elucidates the physical properties extracted from an extensive examination of various nano silica concentrations, offering crucial insights into the dynamic behavior of the modified asphalt binders. Notably, a compelling trend emerges, revealing that an escalation in nano silica (NS) concentration leads to a systematic reduction in penetration values, a phenomenon impeccably depicted in Figure 1. These results harmonize seamlessly with the conclusions drawn in prior research endeavors by (Enieb and Diab, 2017) and (Samsudin *et al*., 2016), fortifying the robustness of the observed pattern.

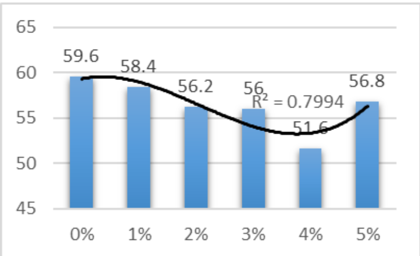

Figure 1. Penetration Test Results

The underlying mechanism driving this trend is rooted in the substantial influence of NS content on diminishing penetration, achieved through the augmentation of stiffness in the NS-modified bitumen binder. As illustrated in Figure 2, an explicit elevation in softening points is discerned as the concentration of nanosilica in the bituminous specimens is heightened. This augmentation is attributed to a concurrent increase in asphaltenes, fortifying the stiffness property and rendering the modified binder less susceptible to temperature fluctuations.

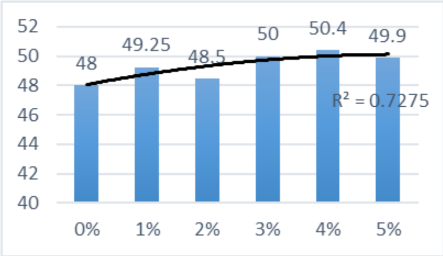

Figure 2. Softening Point Results vs. various NSMB contents

Figure 3 delves into Brookfield viscosity, spotlighting a conspicuous rise as NS content escalates. The outcomes illuminate a nuanced relationship between temperature and viscosity, demonstrating a consistent decrease in viscosity with the ascent temperature, specifically at 135°C and 165°C. The viscosities of nanosilica-modified asphalt binders surpass those of their unmodified counterparts, underscoring the direct impact of temperature on the viscosity of the modified samples. This temperature-dependent viscosity shift, depicted graphically, aligns seamlessly with the findings of (Masri *et al*., 2020), thereby reinforcing the credibility of these research revelations. In essence, these results not only deepen our understanding of NS-modified asphalt binders but also amplify the persuasiveness of the argument for their utilization in optimizing asphalt properties.

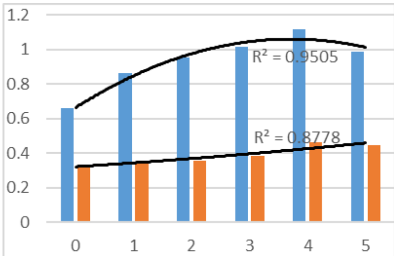

Figure 3. Brookfield Viscosity Results at 135°C and 165°Cvs. Various NSMB content

Table 4. Physical Properties of Nanosilica Modified Bitumen

NSMB content %	0%	1%	2%	3%	4%	5%
The penetration test is 100 g, 5 s, 25 C, 0.1 mm.	64.4	58.4	56.2	56	51.6	56.8
Softening Point Test	48	49.25	48.5	50	50.4	49.9
Viscosity @135°C (Pa.s)	0.663	0.866	0.957	1.014	1.12	0.989
Viscosity @135°C (Pa.s)	0.323	0.351	0.356	0.382	0.461	0.444

Fourier Transform Infrared Spectroscopy (FTIR) Analysis

The FTIR test results of pure and bitumen were modified, with concentrations ranging from 1% to 5% of nanosilica. These have provided valuable insights into the chemical changes induced by adding nanosilica. The analysis of the transmittance peaks within the wavenumber range of 477.66 cm^{-1} to 2921.70 cm^{-1} as shown in Figure 4 revealed distinct variations in the functional groups present in the modified bitumen compared to the pure bitumen.

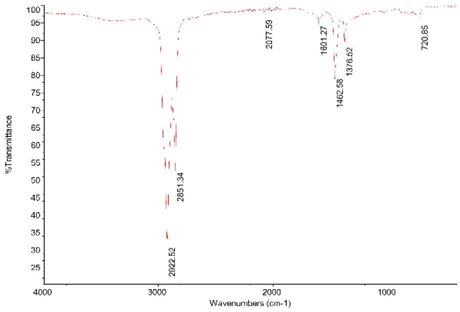

Figure 4. Transmittance Peaks 0%NSMB

For pure bitumen, characteristic peaks corresponding to aliphatic hydrocarbons were observed within the range of 477.66 cm^{-1} to 2921.70 cm^{-1}, confirming the presence of hydrocarbon chains in the material. However, upon introducing nanosilica at various concentrations, notable changes were observed in the FTIR spectra within the same wavenumber range.

At the 1% nanosilica concentration shown in Figure 5, an additional peak attributed to aliphatic ethers appeared at approximately 1121.12 cm^{-1}, facilitated by nanosilica, creating a stronger network, improving deformation resistance and preventing rutting.

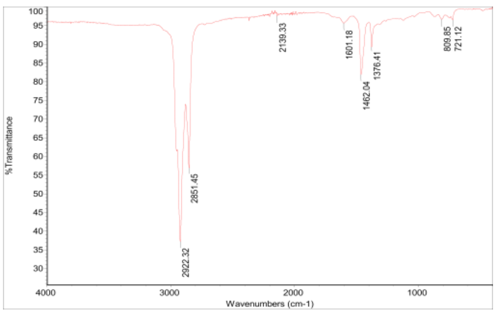

Figure 5. Transmittance Peaks 1%NSMB

As the nanosilica concentrations increased to 2% and 3%, further changes were observed in the FTIR spectra within the 477.66 cm^{-1} to 2921.70 cm^{-1} range as shown in Figure 6 and Figure 7. The new peaks corresponding to aliphatic primary amines emerged at approximately 720.39 cm^{-1} and 1601.48 cm^{-1}. These amine groups are likely a result of interactions between the nanosilica and the binder matrix, which could enhance chemical bonding and improve the structural stability of the modified asphalt. Forming these functional groups may also contribute to increased adhesion with aggregates, thereby improving the asphalt mixture's moisture resistance and overall performance.

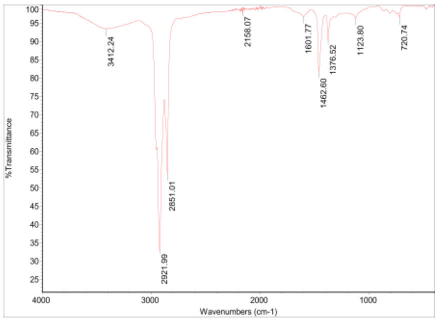

Figure 6. Transmittance Peaks 2%NSMB

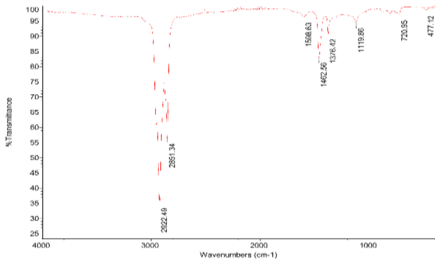

Figure 7. Transmittance Peaks 3%NSMB

Additionally, the intensity of the aliphatic ether peaks at approximately 1121.12 cm^{-1} increased with higher nanosilica concentrations, suggesting a higher degree of interaction between the nanosilica and bitumen, as shown in Figure 8.

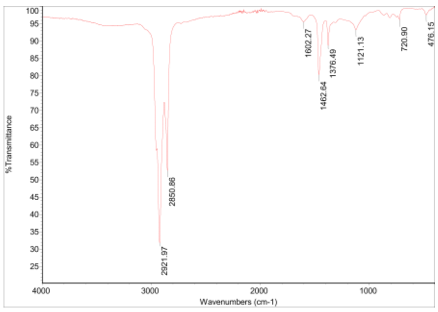

Figure 8. Transmittance Peaks 4%NSMB

In Figure 9, at the highest concentration of 5% nanosilica, the FTIR spectrum within the range of 477.66 cm^{-1} to 2921.70 cm^{-1} revealed a more pronounced presence of aliphatic primary amines and aliphatic ethers, indicating a substantial modification of the bitumen's chemical structure due to the higher nanosilica loading.

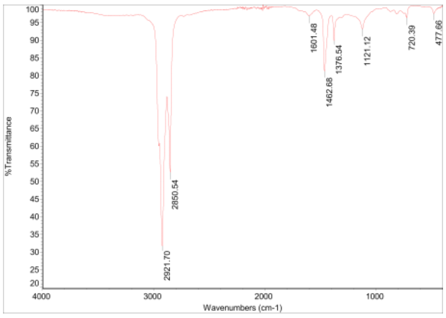

Figure 9. Transmittance Peaks 5%NSMB

In conclusion, the FTIR test results within the specific wavenumber range of 477.66 cm^{-1} to 2921.70 cm^{-1} demonstrate that adding nanosilica to bitumen induces significant chemical changes in the material. The appearance of new peaks corresponding to aliphatic ethers and aliphatic primary amines indicates the successful incorporation of these functional groups through the nanosilica modification. The increasing intensity of these peaks with higher nanosilica concentrations confirms the enhanced interaction between nanosilica and bitumen.

Overall, these findings within the specified wavenumber range highlight the potential of nanosilica as an effective modifier for bitumen, offering opportunities to tailor the material's properties and performance for various applications. The knowledge gained from this study can aid in developing advanced bitumen-based materials with improved mechanical properties, durability, and resistance to environmental factors, thereby contributing to the advancement of construction and infrastructure industries.

Marshall Stability Characteristic

Table 5 meticulously unveils the outcomes of the Marshall stability test applied to asphalt mixtures fortified with glass fiber, offering a comprehensive assessment of key parameters. The parameters scrutinized encompass stability (N), flow (mm), bulk density (g/cm^3), VTM (%), VFA (%), and stiffness (N/mm). The asphalt mixtures exhibit a range of values from 5690.21 N to 7852.3 N, underscoring the diverse performance of the various asphalt mixtures. A noteworthy pinnacle in stability is discerned in the mixture enriched with 0.6% glass fiber, showcasing the substantial impact of this additive on the structural integrity of the asphalt. Beyond 0.6%, perhaps the fibers start to agglomerate because the matrix has too much fiber content to handle. The mixing process might not distribute them evenly anymore, leading to clusters. These clusters also can't transfer stress and might even act like defects. Examining flow properties, values oscillate between 2.4 mm and 4.1 mm, signifying a consistent and reliable flow characteristic across different proportions of glass fiber-infused asphalt mixtures.

For a visual representation of these findings, Figures 10 until Figure 15 vividly illustrate the interplay between Marshall parameters, providing a graphical insight into the nuanced relationship between glass fiber content and asphalt mixture performance. This comprehensive analysis not only enhances our understanding of the influence of glass fiber but also strengthens the argument for its efficacy in optimizing asphalt mixture properties.

In summary, the research underscores the considerable impact of fiber asphalt mastic properties on the durability of asphalt. Specifically, incorporating glass fiber significantly enhances asphalt characteristics and longevity. Various researchers have reported similar findings and

Table 5. Summary of Marshall stability

Parameter	Results of Asphalt Mixture							JKR Specification (JKR 2008)
	Control mix	0%	0.2%	0.4%	0.6%	0.8%	1%	
Stability, N	5978.04	5690.21	7236.8	7792.05	7852.3	7568.65	6430.02	> 6200 N
Flow, mm	2.4	2.5	2.7	2.9	3.5	4.0	4.1	2.0 - 4.0 mm
Stiffness, KN/mm	2443.3	2246.1	2663.85	2690	2260.74	1916.11	1585.05	> 2000 N/mm
Void in Total Mix (VTM), %	4.5	4.7	4.7	4.2	4.5	5.5	7.2	3.0 - 5.0%
Void filled with Asphalt (VFA), %	76.1	75.2	75.0	77.1	76.1	71.9	65.9	70 - 80%

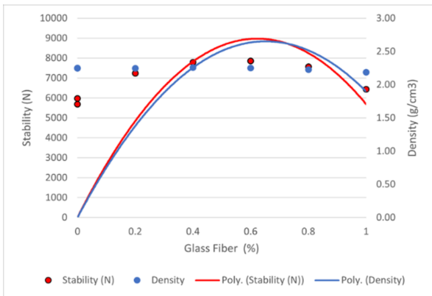

Figure 10. Stability and Density

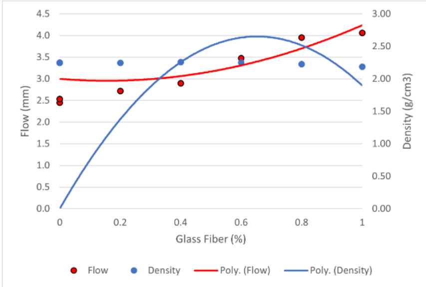

Figure 11. Flow and Density

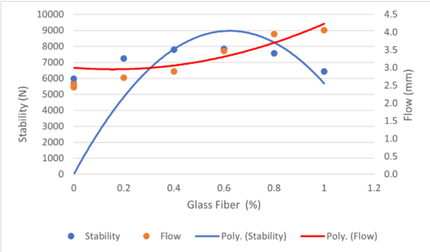

Figure 12. Stability and Flow

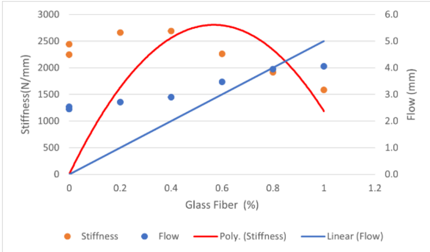

Figure 13. Stiffness and Flow

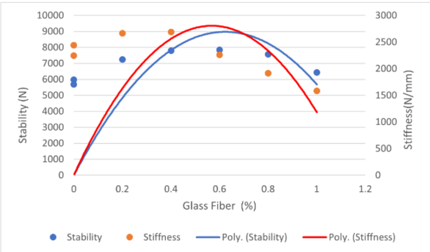

Figure 14. Stability and Stiffness

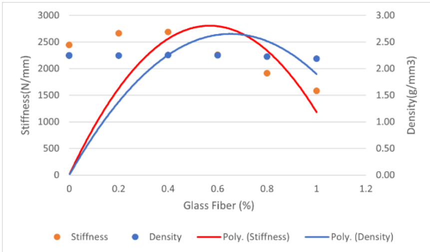

Figure 15. Stiffness and Density

employed different fiber types to reinforce constructions(Aliha *et al*., 2017; Kim *et al*., 2018; Jia *et al*., 2021). Their studies revealed that the judicious addition of fibers can enhance the mechanical strength of constructions. This study emphasizes the use of glass fibers, highlighting their role in improving asphalt pavement durability, reducing project costs, and fostering sustainable transportation development. In contrast to asphalt specimens without fibers, the fiber asphalt mixture demonstrates a higher value and a slower rate of decrease, indicating that adding fibers substantially contributes to improving the durability of the asphalt mixture.

Conclusion

In summary, this investigation delves into the influence of nano silica (NS) modification on key physical attributes of bitumen, precisely viscosity, penetration, and softening points. Notably, heightened concentrations of NS correlate with diminished penetration values, elucidating the heightened rigidity introduced by NS in the modified bitumen binder. Moreover, an escalation in nanosilica content directly corresponds to an elevated softening point, attributed to increased asphaltenes that fortify binder stiffness and enhance temperature resilience.

Furthermore, Fourier-transform infrared (FTIR) analysis underscores discernible chemical shifts in bitumen with added nanosilica, affirming the successful integration of functional groups and intensified interactions at higher concentrations. Additionally, introducing glass fibers into the asphalt mixture distinctly enhances Marshall's stability, with the 4% nano silica and hybrid asphalt mixture featuring a 0.4% glass fiber concentration exhibiting the most substantial improvement. This study thus provides comprehensive insights into the intricate interplay of nanomaterials and glass fibers on the physical and mechanical properties of asphalt, offering valuable implications for optimizing asphalt mixtures in construction applications.

List of Abbreviations

SMA = Stone Mastic Asphalt
GF = Glass Fiber
NS = Nano Silica
NSMB = Nano Silica Modified Bitumen
FTIR = Fourier Transform Infrared Spectrometer
VFA = Void Filled with Asphalt
VTM = Void in Total Mix

Acknowledgment

The authors would like to acknowledge Universiti Malaysia Pahang Al-Sultan Abdullah for funding this study under internal grant number RDU233302.

References

Aggarwal, P., Singh, R.P., and Aggarwal, Y. (2015). Use of nano-silica in cement-based materials-A review. Cogent Engineering, 2(1):1078018. https://doi.org/10.1080/23311916.2015.1078018

Aliha, M.R.M., Razmi, A., and Mansourian, A. (2017). The influence of natural and synthetic fibers on low-temperature mixed mode I + II fracture behavior of warm mix asphalt (WMA) materials. Engineering Fracture Mechanics, 182:322-336. https://doi.org/10.1016/j.engfracmech.2017.06.003

Al-Sabaeei, A.M., Napiah, M.B., Sutanto, M.H., Alaloul, W.S., Zoorob, S.E., and Usman, A. (2022). Influence of nanosilica particles on the high-temperature performance of waste denim fibre-modified bitumen. International Journal of Pavement Engineering, 23(2):207-220. https://doi.org/10.1080/10298436.2020.1737060

Arshad, A.K., Samsudin, M.S., Alam, S., Khairil, M., Masri, A., and Masri, K.A. (2019). Engineering properties of nanosilica modified asphalt binder. Journal of Mechanical Engineering, 16(3):29-40. https://doi.org/10.24191/jmeche.v16i3.15341

Enieb, M., and Diab, A. (2017). Characteristics of asphalt binder and mixture containing nanosilica. International Journal of Pavement Research and Technology, 10(2):148-157. https://doi.org/10.1016/j.ijprt.2016.11.009

Enieb, M., Diab, A., and Yang, X. (2021). Short- and long-term properties of glass fiber reinforced asphalt mixtures. International Journal of Pavement Engineering, 22(1):64-76. https://doi.org/10.1080/10298436.2019.1577421

Guo, W., Guo, X., Chang, M., and Dai, W. (2018). Evaluating the effect of hydrophobic nanosilica on the viscoelasticity property of asphalt and asphalt mixture. Materials, 11(11):2328. https://doi.org/10.3390/ma11112328

Hainin, M.R., Hainin, R., Reshi, W.F., and Niroumand, H. (2012). The importance of stone mastic asphalt in construction. Electronic Journal of Geotechnical Engineering, p. 18.

Jia, H., Sheng, Y., Lv, H., Kim, Y.R., Zhao, X., Meng, J., and Xiong, R. (2021). Effects of bamboo fiber on the mechanical properties of asphalt mixtures. Construction and Building Materials, 289:123196. https://doi.org/10.1016/j.conbuildmat.2021.123196

Khattak, N.U., Irfan, M., Hoy, M., and Khan, A. (2025). Effects of synergistic combined Bakelite and Nano clay modification on asphalt mixture performance properties. Road Materials and Pavement Design, p. 1-17. https://doi.org/10.1080/14680629.2024.2446427

Kim, M.J., Kim, S., Yoo, D.Y., and Shin, H. O. (2018). Enhancing mechanical properties of asphalt concrete using synthetic fibers. Construction and Building Materials, 178:233-243. https://doi.org/10.1016/j.conbuildmat.2018.05.070

Kiran K.N.L.N., and Ravitheja, A. (2019). Characteristics of stone matrix asphalt by using natural fibers as additives. Materials Today: Proceedings, 19(Part 2):397-402. https://doi.org/10.1016/j.matpr.2019.07.624

Luo, D., Khater, A., Yue, Y., Abdelsalam, M., Zhang, Z., Li, Y., Li, J., and Iseley, D.T. (2019). The performance of asphalt mixtures modified with lignin fiber and glass fiber: A review. Construction and Building Materials, 209:377-387. https://doi.org/10.1016/j.conbuildmat.2019.03.126

Masri, K.A., Jaya, R.P., Arshad, A.K., and Mahmud, M.Z.H. (2020). Morphological and physical characteristics of stone mastic asphalt mixture incorporating nano silica. The Open Civil Engineering Journal, 14(1):113-125. https://doi.org/10.2174/1874149502014010113

Masri, K.A., Nur Syafiqah, S.M.Z., Ramadhansyah, P.J., Abu Seman, M., and Mohd Hasan, M.R. (2022). The influence of nano titanium as bitumen modifier in stone mastic asphalt. Advances in Materials Science and Engineering, 2022:4021618. https://doi.org/10.1155/2022/4021618

Rajaeiyan, A., and Bagheri-Mohagheghi, M.M. (2013). Comparison of sol-gel and co-precipitation methods on the structural properties and phase transformation of γ- and α-Al2O3 nanoparticles. Advances in Manufacturing, 1(2):176-182. https://doi.org/10.1007/s40436-013-0018-1

Hainin, M.R., Aziz, M.A.M., Adnan, A.M., Hassan, N.A., Jaya, R.P., Liu, H.Y., and Bahru, J. (2015).Performance of modified asphalt binder with tire rubber powder. Jurnal Teknologi, 73(4). https://doi.org/10.11113/jt.v73.4288

Sadeghnejad, M., and Shafabakhsh, G. (2017). Use of Nano SiO2 and Nano TiO2 to improve the mechanical behaviour of stone mastic asphalt mixtures. Construction and Building Materials, 157:965-974. https://doi.org/10.1016/j.conbuildmat.2017.09.163

Samsudin, M.S., Masri, K.A., Arshad, A.K., and Ahmad, J. (2016). Physical properties of nanomodified asphalt binder. InCIEC 2015:935-946. https://doi.org/10.1007/978-981-10-0155-0_78

Sheng, Y., Li, H., Guo, P., Zhao, G., Chen, H., and Xiong, R. (2017). Effect of fibers on mixture design of stone matrix asphalt. Applied Sciences, 7(3). https://doi.org/10.3390/app7030297

Tanzadeh, J., and Shahrezagamasaei, R. (2017). Laboratory assessment of hybrid fiber and nano-silica on reinforced porous asphalt mixtures. Construction and Building Materials, 144:260-270. https://doi.org/10.1016/j.conbuildmat.2017.03.184

Wu, S., Ye, Q., Li, N., and Yue, H. (2007). Effects of fibers on the dynamic properties of asphalt mixtures. Journal Wuhan University of Technology, Materials Science Edition, 22(4):733-736. https://doi.org/10.1007/s11595-006-4733-3

Yang, H., Liu, M., and Ouyang, J. (2010). Novel synthesis and characterization of nanosized γ-Al2O3 from kaolin. Applied Clay Science, 47(3-4):438-443. https://doi.org/10.1016/j.clay.2009.12.021

Zhuang, C., and Chen, Y. (2019). The effect of nano-SiO2 on concrete properties: A review. Nanotechnology Reviews, 8(1):562-572. https://doi.org/10.1515/ntrev-2019-0050

Ziari, H., and Moniri, A. (2019). Laboratory evaluation of the effect of synthetic polyolefin-glass fibers on performance properties of hot mix asphalt. Construction and Building Materials, 213:459-468. https://doi.org/10.1016/j.conbuildmat.2019.04.084

Ţălu, Ş. (2015). Micro and Nanoscale Characterization of Three Dimensional Surfaces. Basics and Applications.

Taherkhani, H. (2016). Investigating the Properties of Asphalt Concrete Containing Glass Fibers and Nanoclay. Civil Engineering Infrastructures Journal, 49(1):45-58. https://doi.org/10.7508/ceij.2016.01.004

Slebi-Acevedo, C.J., Lastra-González, P., Indacoechea-Vega, I., and Castro-Fresno, D. (2020). Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibers. Construction and Building Materials, 234:117224. https://doi.org/10.1016/J.CONBUILDMAT.2019.117224

Shahnewaz, S.M., Masri, K.A., Ghani, N.A.A.A., Ramadhansyah, P.J., Chin, S.C., Giannakopoulou, P.P., Rogkala, A., Lampropoulou P., and Petrounias, P. (2023). Porous asphalt mixtures enriched with bamboo fibers as a new approach for future sustainable construction, Construction and Building Materials, 4071:133456. https://doi.org/10.1016/j.conbuildmat.2023.133456