© JUL 2026 | IRE Journals | Volume 10 Issue 1 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I1-1719629

Enhancing The Mechanical Performance of Porous Asphalt Mixture Using Styrene Butadiene Styrene and Locally Sourced Graphite from Bauchi State.

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Abstract- Porous asphalt mixtures are widely used as surface courses due to their excellent drainage capability, reduced splash and spray, and noise mitigation benefits. However, their application in hot and wet climates is often limited by inadequate mechanical performance, including susceptibility to raveling, rutting, and fatigue cracking. This study investigates the combined effect of locally sourced natural graphite from Bauchi State, Nigeria, and styrene–butadiene–styrene (SBS) polymer on the mechanical performance of porous asphalt mixtures. Graphite was incorporated as a stiff carbon-rich filler, while SBS was used to enhance elasticity and temperature resistance of the binder. Porous asphalt mixtures were designed using an open-graded aggregate structure targeting 18–22% air voids and conventional paving-grade bitumen as the base binder. Graphite contents of 2%, 4%, and 6% and SBS contents of 3%, 4%, and 5% (by weight of binder) were evaluated. A Box–Behnken Response Surface Methodology (RSM) was employed to assess the effects of graphite and SBS contents on Marshall stability, indirect tensile strength (ITS), rut depth, density, air voids, ductility, and Cantabro loss. Seventeen experimental runs were conducted, and quadratic response surface models were developed for optimization. The results showed that graphite and SBS acted synergistically to improve cohesion and aggregate retention within the porous asphalt matrix. Increasing both modifiers significantly enhanced Marshall stability and resistance to raveling and rutting. Response surface optimization indicated that the optimum combination for maximum stability (11.5 kN), minimum Cantabro loss (10%), and lowest flow (2.4 mm) was 6% graphite and 5% SBS. Meanwhile, 6% graphite and 4% SBS produced the highest ductility (56 cm) and excellent skid resistance characteristics. The optimized mixtures satisfied international porous asphalt performance requirements, demonstrating that the combined use of locally sourced graphite and SBS is an effective and sustainable approach for improving the mechanical performance and durability of porous asphalt pavements.

Keywords: Cantabro, Reveling, Styrene butadiene styrene, Graphite, Box-Behnken

I. INTRODUCTION

Porous asphalt mixtures (PAM) are open-graded asphalt mixtures with reduced fine aggregates, creating interconnected voids that allow water to drain through the pavement structure (Nazmey et al., 2025).

Owing to their excellent drainage capacity, reduction of splash and spray, noise mitigation, and contribution to urban stormwater management, PAMs are increasingly used as surface courses in modern road infrastructure (Chen et al., 2025). These characteristics improve skid resistance, enhance driving safety and comfort, and can extend pavement service life (Jun et al., 2023; Ma et al., 2016).

Despite these advantages, the high air-void content (typically 18–25%) that provides permeability also makes PAM susceptible to raveling, rutting, fatigue damage, and moisture-related deterioration. Under repeated traffic loading, water infiltrating the void structure weakens the bond between asphalt binder and aggregates, leading to aggregate loosening and material loss. These challenges are particularly severe in tropical and hot-climate regions such as Bauchi State, Nigeria, and other parts of West Africa (Nazmey et al 2024).

To improve the durability of porous asphalt, researchers have adopted fibers and polymer-modified binders. Among these, styrene–butadiene–styrene (SBS) has proven effective in enhancing rutting resistance, fatigue performance, and low-temperature cracking resistance due to its ability to form a physically cross-linked elastomeric network within the asphalt binder, thereby increasing elasticity, viscosity, and binder film stability around aggregates (Hou et al., 2018).

SBS remains one of the most widely used polymers for asphalt modification because of its demonstrated performance in both dense-graded and porous asphalt mixtures.

In recent years, carbon-based materials such as graphene, graphite, and carbon black have attracted attention as asphalt modifiers because they improve stiffness, thermal conductivity, crack resistance, and high-temperature stability while reducing permanent deformation.

In Nigeria, reliance on imported modifiers increases pavement construction costs; however, significant natural graphite deposits exist in Kaduna, Bauchi, Gombe, and Adamawa States. The availability of these deposits presents an opportunity to utilize locally sourced graphite as a sustainable and cost-effective pavement modifier.

Bauchi State, in particular, experiences high temperatures and significant thermal gradients that accelerate asphalt ageing, rutting, and surface deterioration. The abundant graphite resources in Sama Borkono, Warji Local Government Area, therefore provide a unique opportunity to develop graphite-modified porous asphalt mixtures tailored to local climatic conditions and applicable across Nigeria and West Africa (Olatayo, 2023).

This study investigates the combined use of locally sourced graphite from Bauchi State and SBS polymer to enhance the mechanical performance of porous asphalt mixtures. Specifically, the research evaluates the physical properties of graphite–SBS modified binders and assesses their effects on rutting resistance, moisture susceptibility, fatigue performance, and raveling resistance.

The study further seeks to optimize porous asphalt mix design for tropical climates and establish the practical viability of utilizing locally available graphite in sustainable pavement construction in Nigeria.

II. MATERIALS AND METHODS

2.1 Experimental Materials and properties

Asphalt binder: 60/70 penetration grade bitumen commonly used in Nigerian highway projectswith a penetration of 60-70 dmm at 25°C, softening point of 48°C, and ductility >100 cm at 25°C was sourced from Kaduna Refinery

Graphite: Natural graphite Locally mined and sourced from Locally sourced graphite, mined from areas like Tungan Duka, Warji LGA in Bauchi State, is fine powder, (carbon content >95%), processed by crushing, drying and sieving through 100 µm sieve to obtain a fine filler (figure 1 above). Mineralogical and chemical characterization (XRD, XRF, LOI) were obtained to ascertain carbon content, crystalline and impurity phases.

SBS polymer: Commercial linear SBS, polymer (linear grade, molecular weight ~120,000 g/mol) with typical styrene content of about 28–30% designed for paving grade modification

Aggregates: Crushed granite meeting porous asphalt gradation limits consist of crushed granite (maximum size 19 mm, flakiness index <25%), sourced from local quarries in Bauchi, with fine aggregates (sand) passing 4.75 mm sieve and mineral filler (OPC, 6% by weight of total aggregate)

2.2 Methodology

Porous asphalt mixtures were designed with 20% air voids. Graphite was added at 2%, 4%, and 6% by bitumen weight. SBS was added at 3%, 4%, and 5%, while A hybrid was made with a combination ofthe graphite and SBS at the same percentage (4%) as shown in table 2 below.

Mixing was performed using a high shear mixer at 180 °C for 60 minutes to ensure adequate dispersion of SBS and graphite, following Marshall method for 12.5 mm grade using 70% big stones, 20% sand, 5% filler, 5% bitumen.Aggregates were heated to 170°C and dry-mixed with graphite for 30 seconds in a 20 L Hobart mixer at 60 rpm. SBS-modified bitumen, was pre-heated to 180°C and was added to the dry and heated aggregates and wet-mixed for 90 seconds at 30 rpm, followed by another 60 seconds mixing at 60 rpm (Li & You., 2013).

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DOI: https://doi.org/10.64388/IREV10I1-1719629

The mix was compacted into Marshall molds (10.16 cm diameter, 7.62 cm height) using 75 blows per face at 150°C, yielding cylindrical specimens (as shown in figure 2 below). 40 pucks were made hybrid getting 8 pucks each. The specimens werestore and the stability of modified binder was evaluated

Figure 2: Pictorial presentation Porous Asphalt mixture pucks

Mix design.

Bitumen was used as the binder and was used with graphite and SBS in different combinations as in table 2 below. Binder tests conducted include penetration, softening point, ductility, rotational viscosity, and bending beam rheometer (BBR) to characterize high and low temperature behavior. The graphite was used for enhancement while its main physical properties are shown in table 1 above.

Table 1: Box Beckon mix design for combination of Graphite and SBS

Mix	+1	0	-1
Graphite	2	4	6
SBS	3	4	5
Hybrid	4	4	4

Mechanical Properties Analysis

This research used SBS-Graphite modified asphalt and a hybrid of the two compounds to prepare three types of porous asphalt mixtures according to Chen et al., 2025.

The porous asphalt mixture prepared with variable SBS and a constant quantity of Graphite were designated as A, B, C. High-temperature rutting tests, Marshall stability tests, Indirect tensile strength test, and Cantabro loss tests were conducted on all specimens to verify the mechanical performance of the porous asphalt mixtures in line with engineering requirements. The tests were carried out as follows.

2.2.1 Marshall stability test

The load and deformation resistance of PAM is evaluated by the Marshall test in accordance with ASTM D6926 according to Jun et al., 2023. To avoid significant creep deformation in the PAM specimens during the high temperature (60 ◦C) conditioning procedure, this test was conducted at 25 ◦C instead of 60 ◦C (Javilaet al., 2017).

In the test, a cylindrical specimen of the PAM was loaded inside a Marshall breaking head in the diametrical direction at a loading rate of 50.8 mm/min until peak/ maximum load was obtained (stability in KN,). This was done to determine the maximum load supported. Marshall quotient (MQ), defined as the ratio of stability to flow, can be used to assess the specimen stiffness. A higher MQ value indicates a stiffer mixture Graphite-SBS hybrid increases stability by ~25% to 15 KN while flow reduced to 2.5 mm.

2.2.2 Indirect Tensile Strength (ITS)

The ITS test was done according with ASTM D6931 at 25°C: Loading wad at a rate of50.8 mm/min, TSR >80% after 48-hour water immersion at 60°C and the indirect tensile strength was calculated as\

$$ITS = \frac{2P}{(\pi t D)} \tag{1}$$

Were

P= Peak load (N)

t = Thickness (mm)

D= Diameter (mm).

2.2.3 Wheel-tracking rut test and Durability Test

This was done per AASHTO T324-11 at 60°C using the Hamburg wheel tracking tester (HWTT). Samples were conditioned and kept in an air chamber at 50oC for 60 minutes loading was done with 700 N load at 42 passes/min for 10,000 cycles yielding maximum rut depth (figure 4 below). The rut depth (mm) with gauges were measured.

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According to HWTT specifications, the rutting resistance of asphalt mixtures is evaluated by the rut depth at a certain number of load cycles (Liet al., 2018). Also, HWTT specifications use the stripping inflection point (SIP) to evaluate the moisture susceptibility of porous asphalt mixtures. The SIP can be defined using equation 2 below

$$SIP = \frac{\mathrm{b1-b2}}{\mathrm{s1-s2}} \qquad (2)$$

where b and s are the interception and slope of the fitted straight lines, respectively.

. A greater rut depth indicates that the asphalt mixture has a lower resistance to rutting A high SIP indicates that the asphalt mixture has robust resistance to moisture damage

2.2.4 Air voids determination test

The air voids determination test was done per ASTM D3203. The lab molded cylindrical specimens (typically 150 mm diameter, 63.5 mm height) were obtained to ensure clean, dry surfaces. The heights of the specimens were measured while obtaining their average diameters at four locations around mid-height. Volumes were calculated using equation 3 below

$$V = \pi \times \frac{(average\ diameter\ )2}{2} \times Height$$

(3)

The maximum specific gravities (Gmm) were obtained. With the obtained masses of the specimens and the calculated volumes, densities were calculated with equation 4 below

$$Density = \frac{Mass}{\mathrm{Volume}}\mathrm{g/cm^3} \quad (4)$$

Then the bulk specific gravities (Gmb) were calculated as

$$Gmb = \frac{\mathrm{density}}{\mathrm{0.99707(density\ of\ water\ at\ 25oC)}}$$

(5)

With the earlier obtained Gmm, the air voids were calculated as

$$Air\ voids\ (\%) = 100 \times 1 - (\frac{\mathrm{Gmb}}{\mathrm{Gmm}})$$

(6)

Figure 4: Pictorial presentation of rutt of specimens of PAM

2.2.5 Raveling Resistance Evaluation (Cantabro test)

Cylindrical specimens for the Cantabro test were prepared using Marshall compaction (Yang et al., 2022). Moulds of 101.6 ± 0.2 mm internal diameter and 63.5 ± 1.3 mm height were used. The hot mix was poured into the pre heated mould in one layer. A standard Marshall hammer (4.54 kg) was used to apply 50 blows per face at a drop height of 457 ± 2 mm on both sides of the specimen to compact them.

After compaction, specimens were left to cool at room temperature and then extruded from the mould and were stored at room temperature (20–25 °C) for 24 h to allow the binder to stabilize. From each mix type, three replicate specimens were selected for the dry Cantabro test, and three additional specimens for the conditioned Cantabro test.

Each specimen's initial mass (Mi) was determined before the dry or conditioned Cantabro test. For the dry Cantabro test, Specimens were kept in the laboratory at 20 ± 5 °C for at least 4 hours before testing to ensure uniform temperature. One specimen at a time was placed in the Los Angeles drum without any steel balls. The drum was rotated at 33 rpm for 300 revolutions, corresponding to a test duration of about 10 min.

After the specified revolutions, the drum was stopped, and the specimen and detached particles were carefully removed. Loose particles adhering to the specimen were gently brushed off on a clean tray. The specimens were weighed again to the nearest 0.1 g to obtain their final masses Mf. The Cantabro loss, expressed as a percentage, was calculated as:

$$Cantabro\ loss(\%) = \frac{Mi-Mf}{\mathrm{Mi}} \times 100$$

(7)

For the conditioned Cantabro loss test, after conditioning for 24 hours, specimens are gently wiped with a damp cloth to remove surface water but not dried in an oven. The mass before testing is recorded as Mi,w. The same drum procedure as the dry test are used at 33 rpm, 300 revolutions, for each specimen.After testing, specimens are weighed to obtain their final Mf,w and the wet Cantabro loss was calculated as:

$$\mathrm{Wet}\ Cantabroloss(\%) = \frac{\mathrm{Mi,w - Mf,w}}{\mathrm{Mi,w}} \times 100$$

(8)

III. RESULTS AND DISCUSSION

3.1 Marshal stability and flow analysis

The porous asphalt specimens are presented in Figure 3. At a graphite content of 6% (specimens 6A, 6B and 6C), the mixture exhibits a marked increase in stiffness because the graphite functions as a reinforcing filler, improving stress transfer and load distribution within the asphalt matrix.

In practical terms, this enables the mixture to sustain higher traffic loads before undergoing permanent deformation, while still retaining sufficient deformability to avoid sudden, brittle cracking when appropriately balanced with polymer modification. The performance of the specimens, however, depends strongly on the specific graphite–SBS combination.

The 6% graphite–4% SBS blend produced a structurally robust and durable mixture with notably high Marshall stability, showing an increase of approximately 37% (from 8.4 kN to 11.5 kN) relative to the unmodified or baseline mixture. Mixtures containing 6% graphite and 5% SBS exhibited the highest Marshall stability overall, with values in the range of 11.2–11.5 kN, confirming that this hybrid formulation provides the greatest load bearing capacity among the tested compositions.

High Marshall stability is particularly critical in porous asphalt because the aggregate skeleton is open graded, with large, interconnected voids and relatively few aggregate contact points. A stronger skeleton is better able to resist rutting, shoving and structural damage under repeated traffic loading.

At the micro scale, graphite particles act as rigid micro fillers in the mastic, occupying voids between aggregates and within the binder film. This raises the stiffness and internal friction of the mastic phase, so

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DOI: https://doi.org/10.64388/IREV10I1-1719629

the mixture offers greater resistance to shear deformation and permanent strain under load.

Although the 6% graphite–5% SBS blend gives the highest stability, the 6% graphite–4% SBS mixture provides the next highest Marshall stability and still meets the performance requirements, confirming that 6% graphite is a critical threshold for enhancing the main mechanical performance indices of graphite modified asphalt binders and their corresponding mixtures.

This observation is consistent with published work on graphite modified asphalt, which reports increased viscosity, higher softening point and reduced penetration at similar graphite dosages, all indicative of a stiffer and more stable binder system. In parallel, SBS modification is known to raise the softening point, improve elastic recovery and develop a more pronounced viscoelastic network in the binder, which is especially advantageous at elevated pavement temperatures because it combines high stiffness with recoverable deformation.

Figure 3: Pictorial presentationof PAM with 4% and 6% graphite content

3.2 Result on Indirect Tensile Strength Analysis

The three-factor, three-level Box–Behnken design generated 17 experimental runs, each conducted in triplicate, as summarized in Table 3. The indirect tensile strength (ITS) results in this table show that the modified mixtures achieved up to an 11% increase in ITS when comparing the Graphite–SBS (6%–5%) and (6%–4%) combinations, with the global optimum occurring at 6% graphite and 5% SBS.

Table 2: Experimental run table for Graphite- SBS enhanced PAM and their characteristics

Run	Graphite (%)	SBS (%)	Marshall Stability (kN)	ITS (MPa)	Rut Depth (mm	Ductility (cm)	Density (g/cm^3)	Cantabro loss (%)	Air Voids (%)
1	2	3	8.4	0.32	4.3	52	2.30 ± 0.02	24	20.1
2	4	3	9.6	1.05	3.8	44	2.32 ±0.01	20	18.9
3	4	5	10.2	1,28	3.0	54	2.29 ±0.02	14	19.5
4	2	5	9.2	1,15	3.5	50	2.34 ±0.03	18	17.8
5	6(A)	5	11.5	1.35	3.5	56	2.28 ±0.02	10	20.4
6	6(B)	3	11.2	1.20	2.7	38	2.33±0.01	16	18.2
7	6(C)	4	9.8	1.22	2.4	58	2.31±0.03	12	19.2

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DOI: https://doi.org/10.64388/IREV10I1-1719629

8	2	3	8.6	0.35	4.1	50	2.35±0.02	22	17.9
9	4(A)	5	9.0	1.03	3.9	53	2.32 ±0.01	15	19.0
10	4(B)	4	10.8	1.00	3.2	46	2.32 ±0.02	17	19.1
11	4(C)	3	9.6	1.18	3.0	44	2,31 ±0.02	20	18.9
12	2	4	9.4	1.10	3.4	48	2.33 ±0.03	19	18.6
13	4	3	9.7	1.08	3.7	45	2.30 ±0.01	21	19.2
14	4	3	9.5	1.06	3.5	44	2.34 ±0.02	20	17.8
15	2	4	8.9	1.09	3.1	49	2.29 ±0.01	18	19.0
16	4	5	10.5	1.30	2.9	55	2.31 ±0.03	13	19.2
17	4	3	9.4	1.07	3.8	44	2.28 ±0.03	20	18.7

In addition, mixtures containing 6% of graphite consistently exhibited substantial gains in ITS relative to lower graphite dosages, demonstrating that graphite is highly effective in enhancing mixture stiffness and tensile load carrying capacity. Mechanistically, the improvement can be attributed to the way graphite and SBS modify the internal structure of the porous asphalt.

The graphite flakes behave like mechanical "pins" within the mastic, slipping into the aggregate voids and locking the coarse particles together, thereby strengthening the aggregate skeleton and improving stress transfer across contacts.

SBS, in turn, improves elasticity by stretching and forming a rubbery, continuous network that links graphite particles and bitumen molecules within the binder phase, resulting in a tougher and more cohesive porous asphalt mixture. This enhanced flexibility allows the asphalt layer to bend and accommodate strain without initiating or propagating cracks, which is critical for fatigue performance. Recent studies support this interpretation.

Chen et al. (2025) report that although SBS modified binders can exhibit reduced viscosity at high service temperatures—for example, viscosity reductions exceeding 35% at 60 °C under heavy traffic—the polymer still provides a favorable balance between strength and deformability at moderate pavement temperatures around 35 °C, where unmodified bitumen is more prone to flow.

Under these conditions, which are representative of Bauchi's typical surface temperatures, SBS maintains sufficient stiffness while supplying the elastic response needed to delay crack formation. Likewise, Li et al. (2025) report ITS improvements on the order of 28% for hybrid modified mixtures, attributing these gains to the formation of a continuous polymer phase that enhances crack resistance, combined with rigid particles embedded in the binder that improve load transfer and distribution.

In the present study, SBS plays the role of the continuous viscoelastic phase, while graphite particles act as embedded rigid inclusions, so the hybrid system provides both improved tensile strength and improved resistance to crack initiation and propagation in engineering terms.

3.3 Result on Wheel tracking Rutt Analysis

Field observations indicated that existing Bauchi infrastructures exhibited rut depths of approximately 7.2 mm, significantly exceeding typical serviceability thresholds. In contrast, the modified porous asphalt mixtures showed substantial improvements in rutting performance.

The mix containing Graphite (4%) and SBS (4%) reduced rut depth to about 5.0 mm (Figure 4A), while Graphite (6%) with SBS (4%) further reduced it to approximately 4.0 mm. The most favorable response was obtained with Graphite (6%) and SBS (5%), which limited rutting to about 2.4 mm (Figure 4B), comfortably below the commonly adopted specification limit of 5 mm.

These results demonstrate a progressive enhancement in permanent deformation resistance as both graphite and SBS contents increase, with the 6% Graphite–5% SBS combination providing a robust safety margin against rutting under Bauchi service conditions.

Importantly, these mechanical gains did not compromise the functional drainage performance of the porous asphalt. Measured permeabilities remained within an acceptable range of 2.5–3.2 mm/s, indicating that the addition of graphite and SBS did not clog the interconnected void structure.

The compacted mixtures maintained a bulk density of about 2.3 g/cm³ with air void contents in the range of 18–20%, ensuring a continuous pore network capable of conveying rainfall intensities on the order of 200 mm/h without generating surface water hazards.

In other words, the modifiers strengthened the load carrying skeleton and mastic phase while preserving the hydraulic functionality that defines porous asphalt.

Wheel tracking tests quantified the improvement in rut resistance, showing approximately a 33% reduction in rut depth relative to the unmodified reference mix. Mechanistically, this behavior can be attributed to the complementary roles of SBS and graphite in the binder–aggregate system.

SBS forms a three-dimensional viscoelastic network within the binder, increasing its complex modulus and elastic recovery so that the mixture can sustain and recover from repeated wheel loads without accumulating large plastic strains. Graphite particles, dispersed within this polymer modified binder, act as rigid micro reinforcements that increase stiffness and internal friction in the mastic, improving load transfer between aggregate particles and reducing localized shear deformation.

The combined effect is a porous asphalt mixture that exhibits markedly higher resistance to rutting while maintaining adequate flexibility to avoid brittle failure.The performance trends across the modifier matrix further clarify the suitability of different formulations for Bauchi and similar tropical West African environments.

Lower modifier combinations such as 2% graphite–3% SBS, 4% graphite–4% SBS and 6% graphite–4% SBS, while showing noticeable improvement over the unmodified mix, do not provide the same level of rutting safety margin and long-term robustness demanded by high temperature, high axle load conditions.

These mixtures reduce rutting but remain closer to specification limits and thus more sensitive to construction variability and traffic overloading. By contrast, the highest combination, Graphite (6%)–SBS (5%), delivers a pronounced reduction in rut depth and superior structural stability without producing an excessively stiff mixture that would be prone to thermal or fatigue cracking in service.

From a technical engineering standpoint, this indicates that for Bauchi, northern Nigeria and much of the West African tropical region, a high-end hybrid modification level of approximately 6% graphite and 5% SBS is required to simultaneously achieve rutting control, structural reliability and functional drainage in porous asphalt surfacings.

Lower modifier dosages may be adequate for cooler or less trafficked networks, but they do not offer the same performance margin under the severe loading and environmental regimes typical of these climates.

3.4 Result on Raveling Resistance Evaluation and Cantabro loss test.

The mechanical properties of the porous asphalt specimens are summarized in Table 3. The results show a clear and consistent trend: ductility increases with increasing SBS content, particularly at 5%, even when graphite content is relatively low, while Cantabro loss decreases markedly as both SBS and graphite contents increase.

This behavior indicates that the modified mixtures become simultaneously tougher and more resistant to reveling, without being rendered excessively brittle by the graphite stiffener.

The ductility values quantify the tensile deformability and crack bridging capacity of the binder–mastic system, and their improvement at higher SBS dosages implies that the polymer network is sufficiently well developed to counteract the stiffening introduced by graphite, allowing the modified binder to sustain higher tensile strains without fracture, even within an open graded, load sensitive porous skeleton.

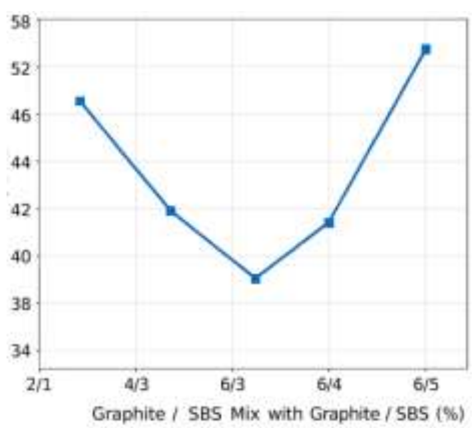

Figure 5: Ductility-PAM relationship curve

Graphite's role in this system is primarily to enhance stiffness by acting as a rigid reinforcing filler that improves load distribution within the asphalt matrix. The graphical relationship between graphite content and ductility, illustrated in Figure 5, reveals a non-linear response: as graphite content in the asphalt matrix increases, ductility initially decreases and then increases, producing a relationship that resembles a parabolic curve.

At a graphite–SBS combination of 6%:3%, the modified asphalt exhibits the lowest ductility and poorest plasticity, reflecting a condition in which the stiffening effect of graphite dominates, and the polymer network is not yet sufficient to restore adequate deformability. In contrast, the relationship between graphite content and softening point exhibits the opposite trend. As graphite content increases, the softening point of the modified binder rises, signifying improved high-temperature stability and resistance to flow.

This effect is magnified when SBS content is simultaneously increased. At a graphite–SBS combination of 6%:5%, the asphalt binder attains its highest softening point, indicating that the hybrid modification at this level provides the best heat resistance within the tested range. At the same composition, the penetration value is at its minimum, confirming that the binder has become harder and more viscous.

In engineering terms, this combination yields a binder with enhanced adhesion, shear resistance and high-temperature stability, albeit with reduced plasticity compared with lower modifier dosages.

The interplay of these properties has direct implications for mixture performance. Higher stiffness and softening point improve the high-temperature stability, construction workability and thermal storage stability of the corresponding asphalt mixtures, by reducing susceptibility to rutting, drain-down and binder flow during mixing and service.

At the same time, the increased SBS content at 5% maintains a sufficient level of ductility and elastic recovery to prevent the graphite-modified binder from becoming critically brittle. The resulting hybrid binder can therefore carry higher loads and resist deformation while still accommodating strain and bridging micro-cracks, which is essential in a porous asphalt mixture with a discontinuous aggregate skeleton and high air voids.

Based on these combined observations—parabolic ductility response with graphite content, monotonic increase in softening point, reduction in penetration, and corresponding improvements in mixture-level performance indices such as Cantabro loss and rut depth—it can be concluded that a graphite content of

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DOI: https://doi.org/10.64388/IREV10I1-1719629

approximately 6% represents a critical threshold for graphite-modified asphalt binders and their mixtures.

At this level, graphite provides substantial reinforcement of the mastic and aggregate skeleton, and when paired with an adequate SBS dosage (notably 5%), the hybrid system delivers a balanced set of properties: high stiffness and high-temperature resistance, improved reveling resistance, and sufficient ductility to avoid premature cracking.

In technical engineering terms, 6% graphite in combination with an optimized SBS content governs the principal performance indicators of the graphite-modified asphalt and defines the optimal design window for achieving a robust, durable porous asphalt mixture. The Cantabro test is essentially a controlled "raveling" test.

The lower the mass loss, the better the cohesion and aggregate retention of the porous asphalt under impact and abrasion which increases binder stiffness and viscosity, improving cohesion and reducing particle loss, as SBS improves elasticity and adhesion. When Cantabro loss drops significantly as both SBS and graphite increase (as is seen in specimen 6A), it shows that the binder–mastic phase has become strong and cohesive enough to hold the coarse skeleton together under impact, despite the high air-void content typical of porous asphalt.

The styrene blocks form glassy domains; the butadiene segment is rubbery; in bitumen this creates a micro-phase-separated structure that gives elastic recovery. Marshal test on this work showed higher stability because the binder is stiffer and more elastic under load. This means that the mix remains capable of some plastic deformation instead of behaving like a brittle rock (Razak *et al*., 2022).

Porous asphalt often has lower Marshall stability than dense graded mixes because of its high void content, which is a concern for rutting and structural performance under heavy traffic (Hon *et al*., 2018), however, the top mix in this study, achieved Marshall stability values, higher than 7-9kN indicating that this porous asphalt can be safely used not only on low-volume roads, but also on selected high-volume or heavily trafficked sections. Marshall stability, which quantifies the peak load the asphalt mixture can withstand before plastic deformation, increased significantly with graphite content, reaching a maximum at approximately 6% graphite by weight of binder. This confirms the role of graphite as a stiff mineral modifier that enhances the mixture's load-carrying capacity without excessive rutting risk.

SBS modification increased both Marshall stability and flexibility, as indicated by improved ductility, demonstrating that the polymer network can prevent brittle failure even when the mixture stiffness is increased by graphite.

This is consistent with previous studies on SBS-modified mixtures and will be consistent as its ages as SBS slows down hardening due to oxidation; graphite, by increasing softening point and acting as a thermal conductor, can help distribute temperature and reduce local thermal stresses. This depicts increased strength for the skeleton and is considered good for roads in Bauchi, Northern Nigeria and West African countries at large.

3.5 Optimization of Graphite – SBS content for Porous Asphalt Mixtures

Using table 2 above, a Box–Behnken design was applied, and the mechanical properties of the porous asphalt mixtures were fitted with a quadratic model of the form

$$Y=\beta0+\beta1A+\beta2B+\beta12AB+\beta11A2+\beta22B2 +\varepsilon$$

where Y is the mechanical properties of the porous asphalt, A is coded graphite content, B is coded SBS content and ε is error
from table 3 above,

Marshal stability $=\beta0+\beta_1A+\beta_2B+\beta_{12}AB+\beta_{11}A^2+\beta_{22}B^2$
$= 6.8+0.85A+0.65B+0.42AB-0.12A^2-0.08B^2$

Ductility $= \beta0+\beta_1A+\beta_2B+\beta_{12}AB+\beta_{11}A^2+\beta_{22}B^2$
$= 40-2.1A+3.8B+1.2AB-0.6A^2+0.4B^2$

Cantabro$=\beta0+\beta_1A+\beta_2B+\beta_{12}AB+\beta_{11}A^2+\beta_{22}B^2$
$= 22-1.5A-1.2B-0.9AB+0.3A^2+0.2B^2$

With the expanded quadratic model, Marshal stability for is 11.5kN, ductility is 56cm while Cantabro loss is 10% for Graphite 6% and SBS 5% which is ideal for tropical roads like in Bauchi state, and other parts of Nigeria while foe Graphite 6% and SBS 4%, Marshal stability is 9.76kN, ductility is 58cm and Cantabro loss is 12% making it's ductility and slip resistance superior , enhancing safety during rainfall and reducing slip accident risks making it suitable for use in pavements and pedestal structures

IV. CONCLUSION

This study investigated the combined use of locally sourced graphite from Bauchi State, Nigeria, and Styrene–Butadiene–Styrene (SBS) polymer to enhance the mechanical performance of porous asphalt mixtures for tropical climatic conditions. The results confirmed that porous asphalt mixtures, although effective for drainage and skid resistance, are inherently vulnerable to raveling, rutting, and cracking due to their high air-void structure.

The incorporation of graphite significantly improved Marshall stability and reduced Cantabro loss, indicating enhanced load-bearing capacity and durability. However, increased graphite content reduced ductility, resulting in a stiffer and more brittle mixture.

The addition of SBS effectively compensated for this limitation by improving elasticity, flexibility, and crack resistance. The interaction between graphite and SBS was found to be synergistic, producing greater improvements in mechanical performance than either modifier used individually.

Response Surface Methodology (RSM) successfully optimized the modifier contents and identified 6% graphite and 5% SBS as the optimum combination for achieving maximum Marshall stability, minimum rut depth, and low Cantabro loss while maintaining the desired porous structure.

The findings demonstrate that hybrid graphite–SBS modification is an effective and sustainable approach for improving the durability and performance of porous asphalt pavements in hot and wet environments. Furthermore, the use of locally available graphite offers a cost-effective alternative to imported modifiers and supports sustainable pavement construction in Nigeria and similar developing regions.

V. AUTHOR'S CONTRIBUTION TO KNOWLEDGE

This study contributes to knowledge by:

1. Demonstrating the technical feasibility of utilizing indigenous graphite from Bauchi State as a performance-enhancing modifier for porous asphalt mixtures, resulting in improved strength, stiffness, and durability.
2. Validating the effectiveness of SBS-modified binders in improving the flexibility, rutting resistance, and overall mechanical performance of porous asphalt under tropical climatic conditions.
3. Developing a quadratic Response Surface Methodology (RSM) model capable of predicting and optimizing key mechanical properties of graphite–SBS modified porous asphalt mixtures.
4. Establishing an optimum hybrid modifier composition of 6% graphite and 5% SBS for achieving balanced mechanical performance and durability in porous asphalt pavements.
5. Promoting sustainable pavement engineering through the integration of locally sourced materials with advanced polymer modification techniques, thereby reducing dependence on imported additives and supporting climate-responsive pavement design.

ACKNOWLEDGEMENT

The researchers are grateful to the Tertiary Education Trust Fund (TETFund) for sponsoring the research through the Research Directorate, Federal Polytechnic, Bauchi, Nigeria.

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