PERFORMANCE AND LIFE-CYCLE COST ANALYSIS OF HYBRID WASTE-MODIFIED ASPHALT CONCRETE

Ajani, A. M.[1], Oyedepo, J. O.[2], Oluyemi-Ayibiowu, B. D.[3], Alabi, O. O.[4] and Omomomi, O. J.[5*]

[1]*Department of Civil and Environmental Engineering, The Federal University of Technology, Akure, Nigeria*
[2]*Department of Civil and Environmental Engineering, The Federal University of Technology, Akure, Nigeria*
[3]*Department of Metallurgical and Materials Engineering, The Federal University of Technology, Akure, Nigeria*
[4]*Department of Civil and Environmental Engineering, The Federal University of Technology, Akure, Nigeria*
[5]*Department of Civil and Environmental Engineering, The Federal University of Technology, Akure, Nigeria*
[*]***Corresponding author:*** *omomomioj@futa.edu.ng*

Ajani M.A., Oyedepo J.O., Oluyemi-Ayibiowu B.D., Alabi O.O., Omomomi O.J. (2026): Performance and Life-Cycle Cost Analysis of Hybrid Waste-Modified Asphalt Concrete. FUTA Journal of Engineering and Engineering Technology 20(2), 27-36

Received Date: 24.03.2026 **Accepted Date: 30.04.2026**

Abstract
The increasing demand for sustainable pavement materials has necessitated incorporating waste-derived modifiers to improve performance while reducing environmental impact. This study investigates the mechanical performance and life-cycle cost implications of asphalt concrete modified with lignite, waste polythene (WPT), and worn-out tyre rubber (WOT). Asphalt mixtures were produced with varying proportions of modifiers, and their performance was evaluated using Marshall stability, flow, indirect tensile strength (ITS), rutting resistance, and fatigue tests. The results indicate that the best-performing mixture within the investigated range (7% bitumen, 2% lignite, 2% WPT, and 5% WOT) achieved a Marshall stability of 11.38 kN, representing a substantial improvement over the control mixture, while maintaining a balanced flow of approximately 3.73 mm. The mixture exhibited a 56.5% reduction in rut depth (from 6.2 mm to 2.7 mm) and a 121% increase in fatigue life (from 4.8 × 10^4 to 10.6 × 10^4 cycles), indicating enhanced resistance to permanent deformation and cracking. A 20-year deterministic life-cycle cost analysis (LCCA), conducted using a 10% discount rate, showed that although the hybrid mixture incurred a 1.68% higher initial construction cost (₦90.10 million/km vs ₦88.61 million/km), it resulted in a 22.2% reduction in maintenance cost. This led to a total life-cycle cost reduction from ₦108.02 million/km to ₦105.20 million/km, corresponding to a net saving of ₦2.82 million/km (approximately 2.6%). The findings demonstrate that hybrid modification of asphalt concrete using locally available waste materials significantly enhances mechanical performance and provides measurable long-term economic benefits, making it a viable and sustainable option for road construction in Nigeria.
Keywords: *Hybrid-modified asphalt; Waste polythene (WPT); Worn out tyres (WOT); Lignite filler; Marshall stability; Rutting resistance; Fatigue performance; Life-cycle cost analysis (LCCA).*

Introduction
The exponential growth in traffic volume, axle loads, and urbanisation has imposed an exponentially larger demand on flexible pavement systems, particularly in developing countries like Nigeria (Bamigboye *et al.*, 2021; Abdel-Shafy and Mansour, 2018). Asphalt pavements are subjected to a combination of mechanical and environmental effects, including high temperatures, tensile and moisture variations, which hasten distress cracking, ravelling, rutting, fatigue, and loss of adhesion. These defects shorten the lifespan of roads, increasing maintenance and repair costs. It results in degrading the performance and durability and making this system economically unviable. As a result, a new material system with an improved performance-to-cost ratio is much more desirable. Apart from performance-enhancement issues, rapidly growing solid waste streams, such as plastics and used tyres, pose a major environmental challenge. Rapid urbanisation and industrial growth have led to a large volume of various types of waste, with plastic waste and worn-out tyres accounting for a significant share of daily waste generated (Abdel-Shafy and Mansour, 2018; Allesch and Brunner,

2014). Inefficient waste disposal practices, coupled with an unorganised waste collection system, lead to unmonitored disposal, resulting in issues such as land contamination and blocked drains. The re-utilisation of this waste is viewed as a sustainable strategy that answers the challenges associated with waste management and engineering performance simultaneously. Waste materials have been used as modifiers in pavement engineering to properly improve the mechanical and rheological characteristics of asphalt mixes (Xu *et al*., 2022).

Previous research has shown that individual waste materials can improve the properties of asphalt concrete. Plastic-based modifiers generally deliver greater stiffness, while rubber-derived materials enhance modulus value and fatigue life due to viscoelastic behaviour. Xu *et al*. (2022) concluded that the inclusion of waste plastics significantly improves the high-temperature stability of asphalt, reduces costs, and presents significant environmental benefits. Likewise, Khan and Tariq (2025) concluded that the amalgamation of waste LDPE and glass with the asphalt mixture enhances resilient modulus by 78% and increases moisture resistance by an additional 17%, while reducing capital costs by 4.13%. Singh and Gupta (2024) demonstrated that the addition of LDPE to the asphalt mixture resulted in more than a 100% increase in stiffness, up to a 57% increase in fatigue life, and a 17% reduction in costs relative to conventional modified binders. Further to this, Shah *et al*. (2025) found that the life-cycle cost of plastic-waste-modified asphalt was reduced by 10-12% while enhancing mechanical performance. They concluded that the performance of plastic-modified asphalt was highly dependent on the rate of blending, its composition and pre-processing condition. Xu *et al*. (2022) found that stability and low-temperature deficiencies remained challenges even for plastic-modified asphalt. Beyond single modifiers, researchers have used more complex advanced waste materials, such as fibre-reinforced polymers, and scrutinised the effects of optimised type, content, and temperature on the performance of asphalt binder (Murthy *et al*., 2025). Similarly, hybrid modification of an asphalt system with a combination of various modifiers has been explored to achieve synergic property effects. The beneficial effect of combining different materials in double and triple combinations has been demonstrated to produce asphalt with improved properties, including flexibility, stiffness, and strength. Saudy *et al*. (2025) demonstrated that crumped rubber, combined with low-density polyethene, simultaneously improved the fatigue life and flexibility of the asphalt mixture, reducing life cycle cost by 16%. Although the potential of hybrid modification has been established (Xu *et al*., 2022), the knowledge base has not yet encompassed hybrid systems, as well as the wide-index performance and life-cycle cost analysis of such systems. The exact interaction, their composite effect, and the optimal content parameters for optimal performance improvement are not delineated.

In addition, the economic viability of modified asphalt systems is of concern to both researchers and practitioners, as improvements in durability and performance can lead to longer pavement lifespans and less frequent maintenance, thereby reducing long-term costs. These cost savings, however, are often inadequately quantified in relevant engineering literature. The life-cycle cost analysis (LCCA) is a cost analysis technique that provides a systematic approach to evaluating the overall expenses of a pavement system throughout its operational life cycle, including initial material procurement and development, as well as subsequent maintenance requirements. As highlighted by Shah *et al*. (2025) and Saudy *et al*. (2025), when coupled with performance analysis, life-cycle cost development enables informed decisions on the economic and environmental sustainability of different asphalt modification strategies. Similarly, Katanalp and Ahmedzade (2023) demonstrated that incorporating waste-geopolymer composites as asphalt modifiers can lead to financial savings by minimising energy-intensive processes. However, the appropriate level of improvement achievable under these circumstances warrants further investigation. In Nigeria, the design parameters and the economic and environmental impacts are not well studied under field conditions, particularly for hybrid modification systems. For asphalt systems with deteriorating and cost-ineffective performance, there is a lack of studies demonstrating synergistic, systematic modifications to the mechanical behaviour and life-cycle cost analysis of asphalt modified with multiple waste-derived materials.

This paper, therefore, examines the behaviour and life-cycle costs of asphalt concrete mixed with lignite, WPT, and WOT. The aims of the research include: To study the strength and durability properties of hybrid-modified asphalt, (ii) to examine the effect of hybrid-modified asphalt on the life-cycle cost analysis for 20 years. The novelty of this thesis work stems from the fact that this researcher has not yet considered this three-component system (filler, plastic, and rubber) and its full life-cycle analysis to establish a direct link between its composition, behaviour, and, finally, cost.

Materials and Methods

Materials

The materials utilised for the experimental program comprise bitumen, aggregates, lignite, waste polythene (WPT) and worn-out tyre rubber (WOT). As the binder for the asphalt mixes, 60/70 Penetration Grade bitumen sourced from the local manufacturer was employed due to its favourable specifications for use in tropical countries. The binder's basic properties were assumed to be within the limits of typical specifications for paving-grade binders, and the determined pen value was similar to that reported by the manufacturer. The coarse and fine aggregates used were obtained from Akure, Nigeria, and selected to meet the relevant specifications for asphalt production. The procedures for their preparation and characterisation were implemented in accordance with the specifications, and the grading, strength, and durability requirements were incorporated into a typical asphalt mix design. This work employs lignite from Enugu State as a partial replacement for filler. The lignite was dried and ground to a fine powder to make suitable aggregate particles for blending with the bitumen. Waste polythene was cleaned, shredded, and melted, while worn-out tyres were collected, shredded, and subsequently processed to obtain crumb rubber. These waste materials were added to the bitumen binders to evaluate their effects on the hypothesised properties.

Mix Design and Sample Preparation

Asphalt Mixtures were produced incorporating various proportions of bitumen and waste-derived modifiers (WDM). The bitumen contents were set at 4% and 7% by weight of the total mixture, the proportions of lignite and WPT incorporated between 0-8% and the proportions of WOT incorporated between 5-20% as substitutes for filler and binder components, respectively. From 30 mixture combinations generated using Latin Hypercube Sampling (LHS), this technique has controlled the number of asphalt samples while maintaining overall coverage of the design space, potentially reducing the number of experiments required. Design of mixtures and specimen preparation according to conventional Marshall mix design procedures (ASTM D6927; AASHTO T245). The aggregate and binder were heated to the appropriate mixing temperature and mixed to form uniform agglomerates, then compacted at the appropriate mixture density to obtain the base bonds and the required geometry of the specimens. All samples were prepared at controlled laboratory conditions and allowed to cool before testing. The detailed mixture compositions are tabulated below as shown in Table 1

Mechanical and Durability Testing

The asphalt mixture's mechanical and durability characteristics were evaluated using standard laboratory procedures. The Marshall stability and flow values were obtained using the procedures ASTM D6927 and AASHTO T245 to obtain the load-bearing capacity and deformation characteristics, respectively. The indirect tensile strength test was used to evaluate the tensile strength and crack resistance of the asphalt mixtures in accordance with ASTM D6931. Additionally, the wheel-tracking test, based on AASHTO T324 procedures, was used to evaluate the asphalt mixtures' susceptibility to permanent deformation (rutting). Finally, the fatigue performance of asphalt mixtures was evaluated according to AASHTO T321, the repeated-load test procedure, by estimating the number of load application cycles to failure (Nf).

Life-Cycle Cost Analysis (LCCA)

A deterministic life-cycle cost analysis (LCCA) was used to determine the economic performance of the selected asphalt mixtures over a 20-year design period at a real discount rate of 10%, as defined in the Pavement Economic Evaluation guidelines (Federal Highway Administration, 1998; AASHTO, 2017). The functional unit used was 1 km of a two-lane flexible pavement wearing course, 7.3 m wide and 50 mm thick, with an asphalt hotmix requirement of around 858 tonnes per km. The initial construction costs were obtained using current local prices, while periodic maintenance was modelled as resurfacing. Two asphalt mixtures representing two typical pavement sections were selected for economic analysis. The control mixture was conventional and unmodified and the hybrid mixture was modified (extension of the typical design life of the section). Based on the expected pavement performance (resurfacing durability), resurfacing intervals of 7 years and 9 years were assumed for the control and hybrid asphalt mixtures, respectively. Resurfacing costs were therefore scheduled for years 7 and 14 for the control section, and for years 9 and 18 for the hybrid section, over a 20-year performance period for both mixtures. Cost data were presented in Naira (₦) values at 2026 prices. Net Present Value (NPV) and total life-cycle costs (LCC) were used as economic measures, and thus, the total LCC was given by:

$$NPV = \sum\nolimits^{n}_{t=0} (B_t - C_t) / (1 + r)^t \qquad (1)$$

$$LCC = \sum\nolimits^{n}_{t=0} C_t / (1 + r)^t \qquad (2)$$

where:

B_t is benefits at year t (taken as zero in this cost-based analysis)
C_t is cost at year t
r is discount rate (10%)
t is year of analysis
n is total analysis period (20 years)

Table 1: Experimental Design Matrix of Asphalt Mixtures

S/N	Sample ID	BT (%)	L (%)	WPT (%)	WOT (%)	FA (%)	CA (%)
R1	BT4FA23CA73	4	0	0	0	23	73
R2	BT4L2WOT5WPT2FA25CA69	4	2	2	5	25	69
R3	BT4L8WOT15WPT6FA12CA54	4	8	6	15	12	54
R4	BT4L4WOT10WPT4FA15CA70	4	4	4	10	15	70
R5	BT4L6WOT20WPT2FA10CA66	4	6	2	20	10	66
R6	BT4L2WOT10WPT6FA20CA58	4	2	6	10	20	58
R7	BT4L8WOT5WPT4FA14CA65	4	8	4	5	14	65
R8	BT4L4WOT15WPT2FA18CA57	4	4	2	15	18	57
R9	BT4L6WOT5WPT6FA16CA63	4	6	6	5	16	63
R10	BT4L2WOT20WPT4FA19CA51	4	2	4	20	19	51
R11	BT4L8WOT10WPT2FA17CA59	4	8	2	10	17	59
R12	BT4L4WOT20WPT6FA22CA44	4	4	6	20	22	44
R13	BT4L6WOT5WPT4FA21CA60	4	6	4	5	21	60
R14	BT4L2WOT15WPT2FA23CA54	4	2	2	15	23	54
R15	BT4L8WOT5WPT6FA24CA43	4	8	6	5	24	43
R16	BT7FA21CA72	7	0	0	0	21	72
R17	BT7L2WOT5WPT2FA25CA59	7	2	2	5	25	59
R18	BT7L8WOT15WPT6FA12CA52	7	8	6	15	12	52
R19	BT7L4WOT10WPT4FA15CA60	7	4	4	10	15	60
R20	BT7L6WOT20WPT2FA10CA60	7	6	2	20	10	60
R21	BT7L2WOT10WPT6FA20CA45	7	2	6	10	20	45
R22	BT7L8WOT5WPT4FA14CA62	7	8	4	5	14	62
R23	BT7L4WOT15WPT2FA18CA54	7	4	2	15	18	54
R24	BT7L6WOT5WPT6FA16CA40	7	6	6	5	16	40
R25	BT7L2WOT20WPT4FA19CA52	7	2	4	20	19	52
R26	BT7L8WOT10WPT2FA17CA56	7	8	2	10	17	56
R27	BT7L4WOT20WPT6FA22CA41	7	4	6	20	22	41
R28	BT7L6WOT5WPT4FA21CA57	7	6	4	5	21	57
R29	BT7L2WOT15WPT2FA23CA51	7	2	2	15	23	51
R30	BT7L8WOT5WPT6FA24CA50	7	8	6	5	24	50

Note: BT = Bitumen content; L = Lignite; WPT = Waste polythene; WOT = Worn-out tyre rubber; FA = Fine aggregate; CA = Coarse aggregate

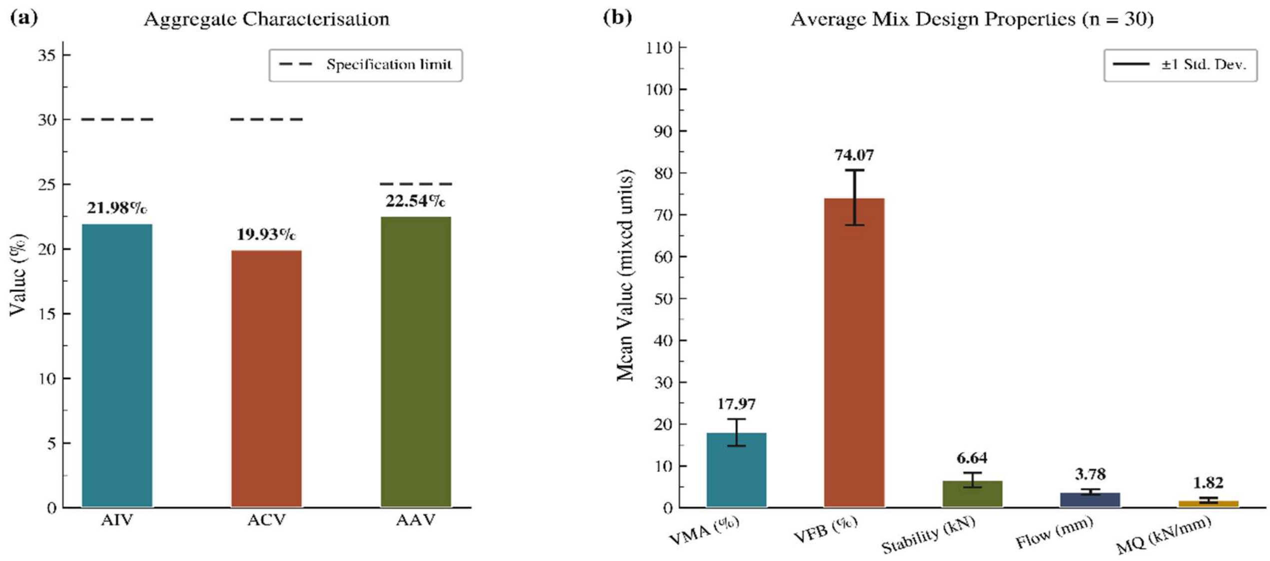

Figure 1: Aggregate properties and material characteristics

Results and Discussion

Material Characterisation and Suitability

The properties of the materials used are shown to meet the requirements for asphalt production. Penetration was measured at 62-68 (0.1 mm), falling within the specified limits of 60-75. This suggests the bitumen is neither too hard nor too soft for asphalt production. The ductility value was noted as 102-116cm, which exceeds the minimum 100cm requirement. This indicates the material will have adequate flexibility and elasticity under applied loading to help reduce pavement cracking. The softening point is given as 50–55 °C, and the viscosity is >2400 cP. This indicates the material will provide adequate resistance to deformation at elevated temperatures and good workability. Analysis of the aggregate's tests indicates strong mechanical performance. The ACV was 19.93%, the average. The test limit is 25-30% for the base and wearing courses of this type of material. The AIV was 21.98, well below this limit. 22.54% of the AAV value indicates that the material will have adequate wear resistance. The material properties are listed in Table 2, and Figure 1 shows the aggregate conditions.

Volumetric Behaviour of Asphalt Mixtures

The volumetric characteristics of the mixtures reflect a much more definite response to the hybrid modification. VMA ranges from approximately 13.2% to 22.2% with the mean value of approximately 18.0%, while VFB varies from 62.5% to 86.3% with an average value of approximately 74.1%. The study of the control mixture shows that R1 has VMA and VFB of approximately 15.4% and 66.9%, respectively, within specification limits. A transition is clearly visible going past sample R16 point, where the values of VMA and VFB increase to approximately 20-22% and 78-86% respectively, which could be explained by the fact that the number of voids inserted into the structure is better filled with the binder, thus creating a very stable structure between binder and aggregate. Sample R17 appears to lie slightly above the mean value (VMA ≈ 21%, VFB ≈ 80–82%), indicating an optimum aggregate structure capable of filling and interacting, implying improved aggregate-binder interaction. These volumetric properties varied for all the mixtures (Figure 2).

Mechanical Performance

The mechanical properties of the asphalt mixtures were assessed using various Marshall stability parameters. The Marshall stability test measures the load-bearing capability of the specimens, ranging from 4.0 to 11.38 kN (mean 6.64 kN). Most mixtures fall within the one standard-deviation band of the means, indicating considerably stable load-bearing parameters. R17 has the highest Marshall stability occurring above the upper deviation band, predicting a significant change in load-bearing ability. The flow rate of the mixtures is indicated by the Marshall flow with values ranging from 2.3-4.7 mm (mean 3.78 mm). Most of the samples fall within the variability band thus predicting deformations to be within reasonable limits. R17 has a flow rate very close to the mean of 3.7; thus, predicting a significant change in load-bearing ability does not cause deformations. Measurement of the Marshall quotient levels (an indication of other deformation and stiffness) ranges from 1.0-3.4

kN/mm (mean 1.82 kN/mm), with most of the samples around the overall mean, and R17 higher than the upper deviation band. Trends observed with the Marshall quotient are indicated in Figure 3a-c).

Table 2: Summary of Bitumen Properties

PARAMETERS	A	B	C	RESULTS	SPECIFICATION	TEST METHOD	REMARK
Penetration @ 25 °C	68	64	62	65	60-75	EN 1426, IS 1203 and ASTM D-5	Meets Specification
Ductility @ 25 °C	102	110	116	109	100 MIN.	IS 1208 and ASTM D-113	Exceeds Specification
Softening Point	50	52	55	52	52-60	EN 1427, IS 1205 and ASTM D-36	Meets Specification
Specific Gravity @ 25 °C	0.98	0.98	0.98	0.98	0.98-1.06	ASTM D-70	Meets Specification
Loss on Heating (wt%)	0.12	0.14	0.15	0.14	0.2 MAX.	ASTM D-6	Meets Specification
Viscosity	2770	2685	2645	2700	2400 MIN.	IS 1206 (Part 2) and ASTM D-2171	Exceeds Specification
Flash and Fire Point	258	269	275	267	≥250	EN ISO 2592 and ASTM D-92	Exceeds Specification

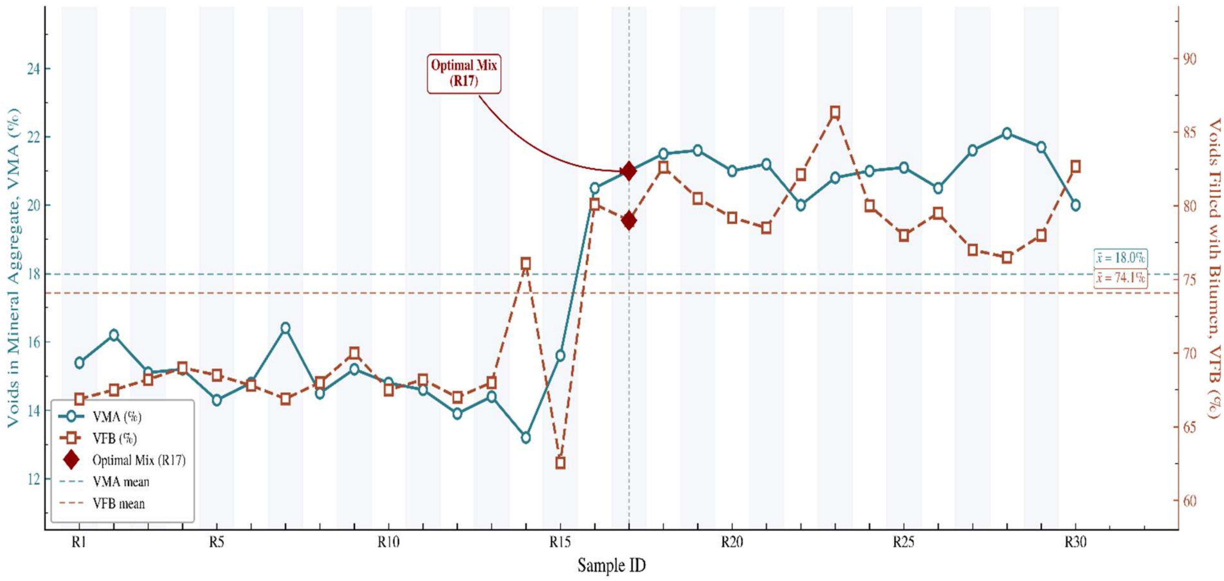

Figure 2*:* Combined volumetric and Marshall properties

Rutting and Fatigue Behaviour

The rutting and fatigue performance of these mixtures appears to be predominantly governed by a stiffness-controlled behaviour. Rut depth varies between approximately 2.7 mm and 7.1 mm, with R1 (control mixture) having relatively high deformation (6.2 mm). Sample R17 (optimised mixture) has a rut depth of approximately 2.7 mm, representing a ~56.5% reduction. The fatigue life of the control mixture is approximately 4.8×10^4 cycles, while that of R17 is approximately 10.6×10^4 cycles. This represents an improvement of approximately 121%. The mechanical and volumetric parameters exhibited poor correlations, with R^2 values of approximately 0.02 (stability-flow), 0.03 (stability-VMA), and 0.009 (flow-VFB). This suggests that deformation behaviour can be improved, but it is not solely governed by volumetric properties. Sample R17 was outside the data cloud (high stability, modest flow) and ranked more highly in internalstructure and load distribution. These relationships, as well as the respective improvements in rutting and fatigue performance, are plotted in Figure 4a-c.

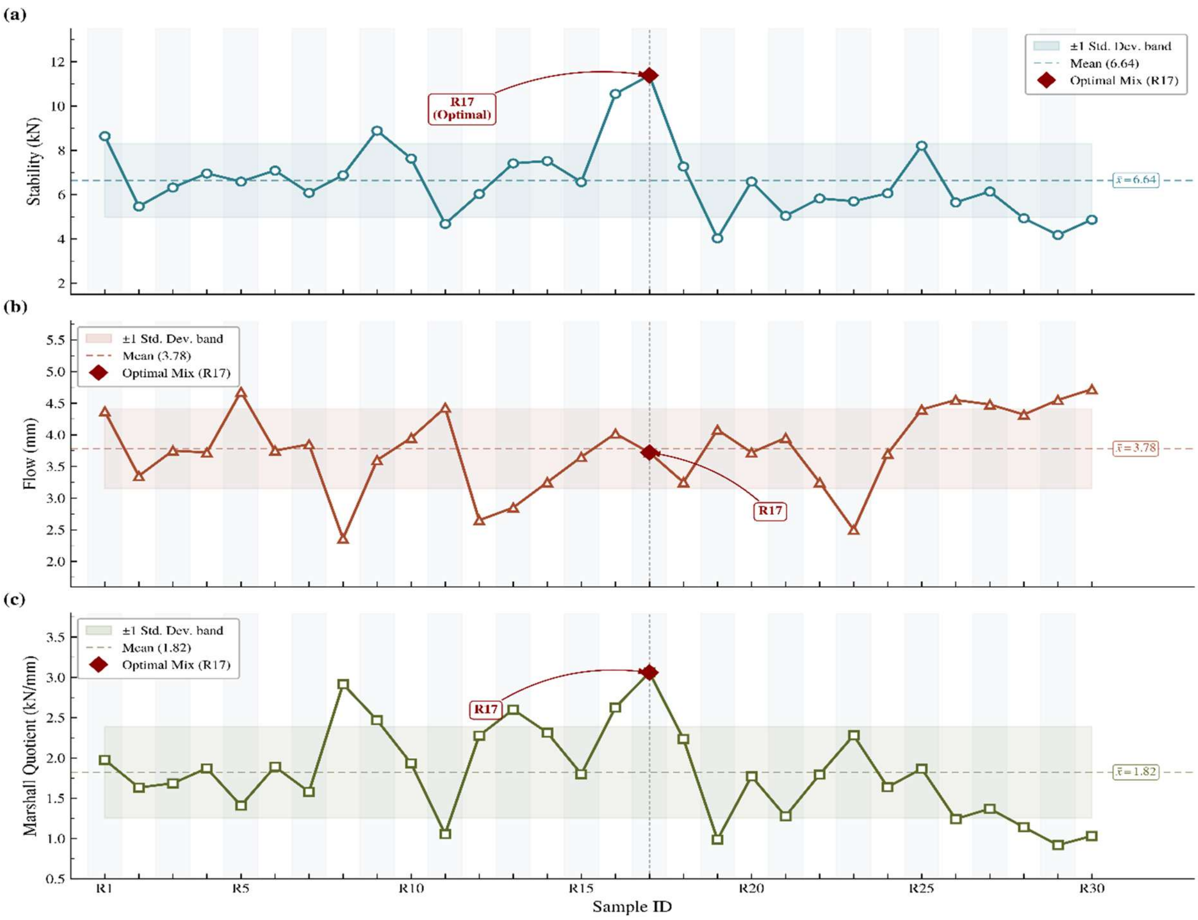

Figure 3: Strength and stiffness performance

Life-Cycle Cost Analysis (LCCA)

The economic analysis of the mixtures was based on the calculated cumulative discounted life-cycle cost. The cash-flow values are presented in Table 3, while the cost trend is shown in Figure 6. Figure 7 shows the results of the sensitivity analysis. The hybrid mixture used in the lifecycle cost analysis was sample R17, which provided the best overall mechanical performance among the mixtures tested. The initial construction cost of the hybrid mixture is 90.10 million/km, 1.49 million/km (1.68%) higher than that of the conventional mixture (88.61 million/km). However, the hybrid mixture has the advantage of longer maintenance-lifecycle intervals, thus fewer interventions are necessary over the analysis period. The conventional mixture is resurfaced at year 7 and year 14, with discounted costs of ₦12.83 million/km and ₦6.58 million/km; the total discounted cost for maintenance is ₦19.41 million/km. The hybrid mixture is resurfaced at years 9 and 18, with discounted costs of ₦10.60 million/km and ₦4.50 million/km; the total discounted maintenance cost is ₦15.10 million/km, saving ₦4.31 million/km (22.2%). The intersection of the cost curves at a value between years 7 and 8 indicates the breakeven point, when the hybrid mixture becomes less expensive. The total life-cycle cost of the mixtures at year 20 is ₦108.02 million/km for the conventional mixture and ₦105.20 million/km for the hybrid mixture, thus saving ₦2.82 million/km (about 2.6%). Overlay cost variation has the most effect on net present value (ΔNPV ≈ ₦4.4 million/km), followed by overlay interval (ΔNPV ≈

₦3.3 million/km) and discount rate (ΔNPV ≈ ₦2.0 million/km); the order of magnitude effect of its variation on the NPV is overlay cost > overlay interval > discount rate.

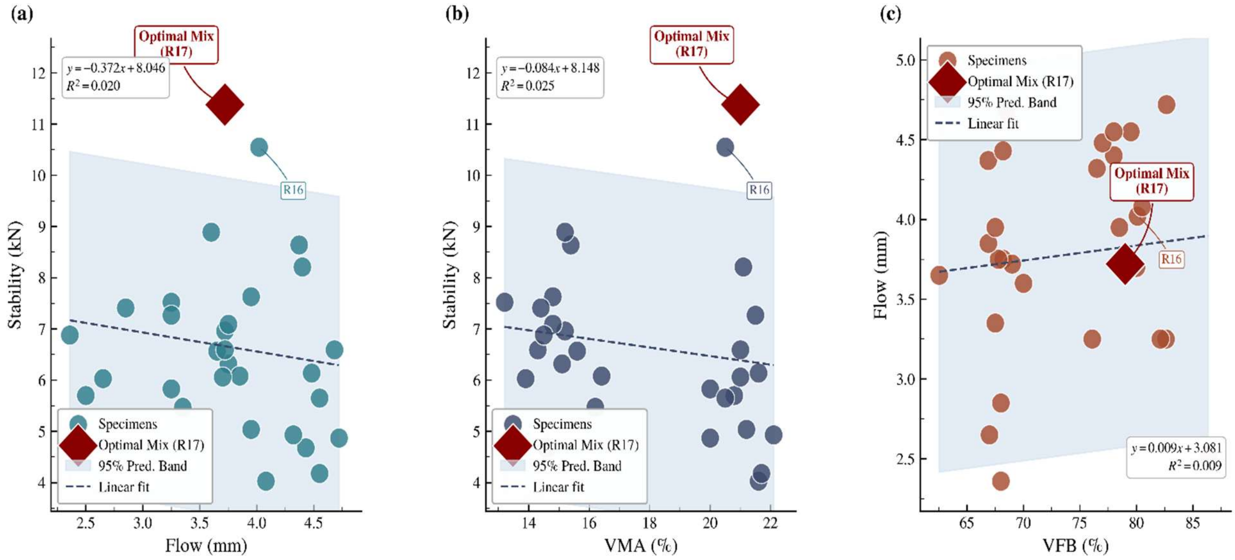

Figure 4: Rutting and fatigue performance

Table 3: Discounted Cash-Flow Schedule for Life-Cycle Cost Analysis (₦ million, r = 10%)

(a) Conventional mixture (R16) – 7-year resurfacing interval

Year	**Activity**	**Nominal Cost (₦ million)**	**Discount Factor**	**Present Value (₦ million)**
0	Initial construction	88.61	1.0000	88.61
7	Overlay	25.00	0.5132	12.83
14	Overlay	25.00	0.2630	6.58
	Total PV			108.02

(b) Hybrid mixture (R17) – 9-year resurfacing interval (base case)

Year	**Activity**	**Nominal Cost (₦ million)**	**Discount Factor**	**Present Value (₦ million)**
0	Initial construction	90.10	1.0000	90.10
9	Overlay	25.00	0.4241	10.60
18	Overlay	25.00	0.1799	4.50
	Total PV			105.20

Note: The second overlay for the hybrid mixture occurs at year 18 (9 + 9) within the 20-year analysis period. No additional intervention is considered within the analysis horizon.

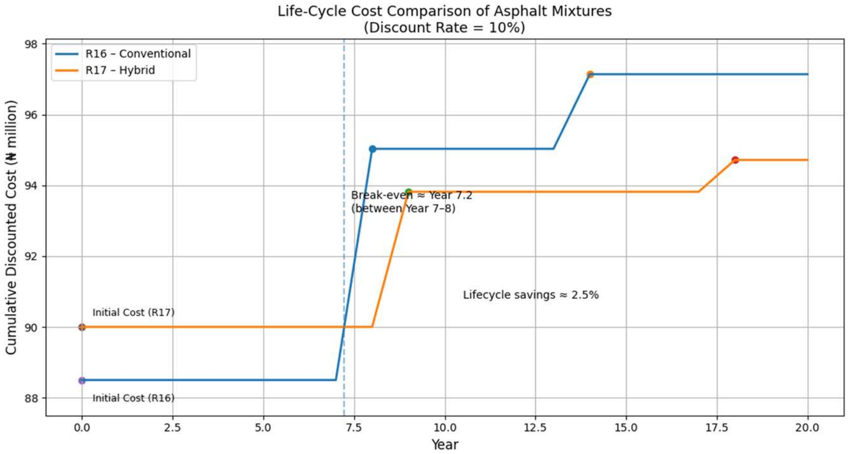

Figure 6: Cumulative discounted life-cycle cost

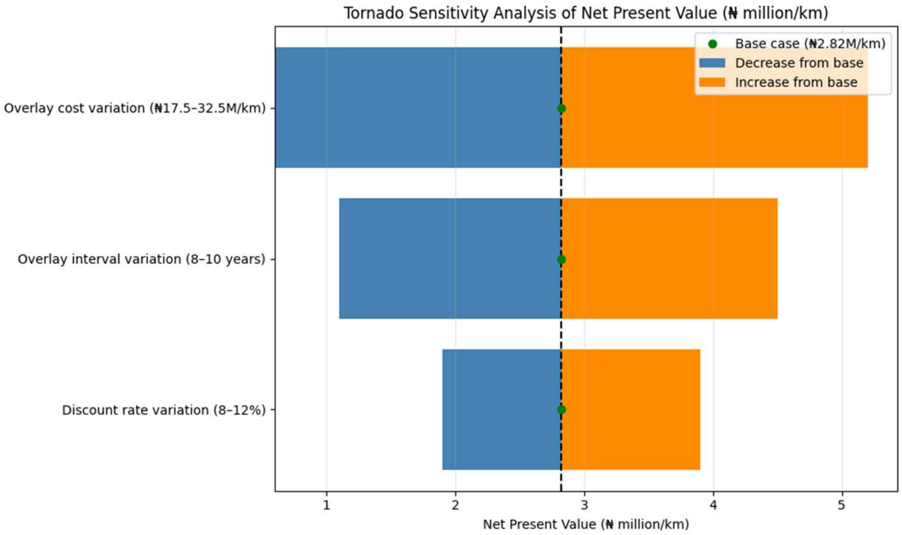

Figure 7: Tornado sensitivity plot

Conclusion

This study investigates the mechanical behaviour and life-cycle cost effects of a lignite, waste polythene (WPT), and worn-out tyre rubber (WOT)-modified asphalt mixture. Based on experimental and economic analysis, the key findings are as follows:

- Hybrid modification presents significant improvements in the asphalt mechanical properties. The optimum system (7% bitumen + 2% lignite + 2% WPT + 5% WOT) produced a mixture with a Marshall stability of 11.38 kN, which is approximately 182% higher than the control mixture and an acceptable flow (≈ 3.73 mm);
- The durability behaviour has improved considerably with a 56.50% reduction in the rut depth (6.2 mm to 2.7 mm) and a 121% increase in fatigue life (from 4.8×10^4 to 10.6×10^4 cycles);
- The better performance can be explained in terms of the synergic impact of the hybrid system, the lignite increased the asphalt filler packing and road stiffness, the WPT facilitated binder characteristics, and the WOT improved its elasticity and fatigue resistance, leading to better load balancing;
- Cost-effectiveness analysis indicated that the hybrid design panel to construct mixture had slightly higher initial costs (+1.68%) but in return the system showed a significant reduction in maintenance costs (-22.2%), achieving a life-cycle cost reduction from ₦108.02 million/km to ₦105.20 million/km for the system, saving ₦2.82 million/km (2.6%) during the 20-year study period;

- Mechanical performance improvements can be translated into the economic performance shown in the present study, indicating the viability of hybrid modification for asphalt.

In summary, this investigation demonstrates that incorporating lignite, WPT, and worn-out tyre rubber in a hybrid form yields an optimal combination of strength, durability, and life-cycle cost performance. In the future, the long-term performance of the hybrid asphalt system should be validated under real-world conditions through full-scale application and through probabilistic life-cycle cost analysis under different traffic loads and climatic regimes.

References

Abdel-Shafy, H. I., and Mansour, M. S. M. (2018). Solid waste issue: Sources, composition, disposal, recycling, and valorisation. *Egyptian Journal of Petroleum*, 27(4), 1275–1290. https://doi.org/10.1016/j.ejpe.2018.07.003

Allesch, A., and Brunner, P. H. (2014). Assessment methods for solid waste management: A literature review. *Waste Management and Research*, 32(6), 461–473. https://doi.org/10.1177/0734242X14535653

AASHTO T245 (2018). *Resistance to plastic flow of asphalt mixtures using Marshall apparatus*. American Association of State Highway and Transportation Officials.

AASHTO T321 (2017). *Determining fatigue life of compacted asphalt mixtures using repeated flexural bending*. American Association of State Highway and Transportation Officials.

AASHTO T324 (2019). *Hamburg wheel-track testing of compacted asphalt mixtures*. American Association of State Highway and Transportation Officials.

ASTM D6931 (2017). *Standard test method for indirect tensile strength of asphalt mixtures*. ASTM International.

ASTM D5 (2020). *Standard test method for penetration of bituminous materials*. ASTM International.

ASTM D36. *Standard test method for softening point of bitumen (Ring-and-Ball apparatus)*. ASTM International.

ASTM D70 (2020). *Standard test method for specific gravity and density of semi-solid bituminous materials*. ASTM International.

ASTM D92 (2020). *Standard test method for flash and fire points by Cleveland open cup tester*. ASTM International.

ASTM D113 (2020). *Standard test method for ductility of bituminous materials*. ASTM International.

ASTM D2171 (2020). *Standard test method for viscosity of asphalt by vacuum capillary viscometer*. ASTM International.

ASTM D6927 (2021). *Standard test method for Marshall stability and flow of asphalt mixtures*. ASTM International.

Bamigboye, G. O., Bassey, D. E., Olukanni, D. O., Ngene, B. U., Adegoke, D., Odetoyan, A. O., Kareem, M. A., Enabulele, D. O., and Nworgu, A. T. (2021). Waste materials in highway applications: An overview on generation and utilization implications on sustainability. *Journal of Cleaner Production*, 283, 124581. https://doi.org/10.1016/j.jclepro.2020.124581

Federal Highway Administration (FHWA). (1998). *Life-cycle cost analysis in pavement design*. U.S. Department of Transportation.

Katanalp, B. Y., and Ahmedzade, P. (2023). Rheological evaluation and life cycle cost analysis of geopolymer-based asphalt modification. *Journal of Materials in Civil Engineering*, 35(11). https://doi.org/10.1061/JMCEE7.MTENG-159

Khan, M. U., and Tariq, M. (2025). Transforming plastic and glass waste into high-performance hot mix asphalt additives. *International Journal of Pavement Research and Technology*. https://doi.org/10.1007/s42947-025-00656-8

Murthy, S. B., Biligiri, K. P., and Pandurangan, V. (2025). Carbon and glass fibre composite waste-modified asphalt binders: Compatibility assessment, dosage optimisation, and performance evaluation. https://doi.org/10.1080/14680629.2025.2599472

Saudy, M., Guirguis, M., Saeed, A., Elshenawy, A., Elkaramany, F., Dawoud, N., Darwish, M., and AbouZeid, M. (2025). Crumb rubber and LDPE-modified asphalt pavement assessment: Mechanical, environmental, and life cycle cost analysis. *Sustainability*, 17(13), 5785. https://doi.org/10.3390/su17135785

Shah, S. K., Gao, Y., and Abdelfatah, A. (2025). Plastic-waste-modified asphalt for sustainable road infrastructure: A comprehensive review. *Sustainability*, 17(21), 9832. https://doi.org/10.3390/su17219832

Singh, A., and Gupta, A. (2024). Mechanical and economical feasibility of LDPE waste-modified asphalt mixtures. *Scientific Reports*, 14, 25311. https://doi.org/10.1038/s41598-024-75196-5

Xu, F., Zhao, Y., and Li, K. (2022). Using waste plastics as asphalt modifier: A review. *Materials*, 15(1), 110. https://doi.org/10.3390/ma15010110