



Properties of HMA Containing High Density Polyethylene Modified with Reclaimed Asphalt

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ABSTRACT

This paper evaluates the strength performance of hot mix asphalt produced with High Density Polyethylene (HDPE)-modified bitumen and Reclaimed Asphalt Pavement (RAP) which is partially replacing virgin aggregates. Asphalt Institute blending chart was used to determine the quantity of Reclaimed Asphalt Pavement (RAP) incorporated into the mixture. Thermo-gravimetric Analysis and Differential Thermal Analysis (TGA/DTA) were used to determine thermal stability of the High Density Polyethylene (HDPE). Fourier Transform Infrared (FTIR) was used for characterization of the HDPE, bitumen and modified bitumen. Physical test conducted on the RAP and virgin aggregates in accordance with American Society of Testing Materials (ASTM) standards revealed that the aggregates are adequate for use in asphalt production. Marshall method of mix design was adopted for the hot mix asphalt production and testing. With respect to the threshold, the results of Marshall stability showed a 6% increase in the strength of the asphaltic mixture modified with 10% High Density Polyethylene (HDPE). Other Marshall properties tested also showed improvements. Scanning Electron Microscopy and Energy Dispersive X-ray Spectrometry (SEM/EDS) were used for micro-structural examination and composing elements analysis of the asphaltic mixture, respectively. Fibermetric analysis was used to explore the fiber content and pores within the mixture.

Keywords: Bitumen, High Density Polyethylene, Hot Mix Asphalt, Modification, Reclaimed Asphalt Pavement, Strength.

INTRODUCTION

Road transportation constitutes the major form of transportation system in the world. Roads are generally built as rigid pavements or flexible pavements, the topmost layers of these pavements are usually made of a thin cold mix or warm mix or hot mix asphalt. The binder material used in the production of hot mix asphalt is bitumen obtained from fractional distillation of crude

oil (McNally, 2011). High traffic volume, increased axle load and traffic volume changes in daily and seasonal temperatures cause flexible pavements to develop distresses. These distresses majorly disrupt the bonding formed between aggregates and asphaltic binder and thus weakens the bond. The modification of bitumen with various polymers is done typically to improve the performance characteristics of the asphalt concrete, such as adhesion with aggregates, lower susceptibility to

moisture and temperature changes, higher resistance to fatigue and fatigue cracking, higher resistance to wear and tear, as well as cohesiveness. According to Tarsi et al. (2020), Reclaimed Asphalt Pavement (RAP) is defined as a material that is extracted from asphalt concretes of existing flexible pavements, which is made up of non-replenishable resources; namely, the aggregates and the bituminous binder. The incorporation of RAP for construction of new flexible pavements has gained appreciable acceptance in recent times.

Generally, asphalt recycling is a process by which asphalt reclaimed from an existing road is milled. The product of this process is called reclaimed asphalt pavement (RAP) which contains about 95% high-quality aggregate and 5% aged bitumen. In the U.S.A., about 90 million tonnes of Reclaimed Asphalt Pavement (RAP) are generated yearly and 90% of this amount is recycled (Sharma et al., 2021). In Nigeria, however, official statistics of the quantity of RAP generated and recycled yearly are not known according to Ogunrinde et al. (2020).

Studies by Arshad et al. (2018) in Europe and the United States concluded that over 80% of the recycled material is reused in the construction of roads. Polyethylene is the most popular plastic in the world and there are two major types of polyethylene; namely, low-density polyethylene (LDPE) and High Density Polyethylene (HDPE). Its semi-crystalline nature gives excellent chemical resistance, good fatigue and wear resistance and a wide range of properties. A molecule of polyethylene is a long chain of carbon atoms, with two hydrogen atoms attached to each carbon atom. Polyethylene molecules are light in weight and provide good resistance to organic solvents with low moisture-absorption rates (Awwad and Shbeeb, 2007).

LITERATURE REVIEW

Research on the utilization of modified bitumen and reclaimed asphalt pavement in asphalt production is not yet common in Nigeria. The two guiding principles established by the Federal Ministry of Works Nigeria (FMWN, 2013) for recycling of RAP in asphaltic mixture are first, “the mixture containing RAP should meet the same requirements as mixes with all virgin aggregates” and second, “mixes containing RAP should perform equal to or better than virgin mixtures.” Furthermore, the shortage in the supply of

virgin aggregates due to limited availability has resulted in the demand for higher quantities of RAP in asphaltic mixtures (Milad et al., 2020; Sadeeq et al., 2014; Yussof et al., 2019, Murana et al., 2023; Banerji et al., 2023).

A number of polymers and fibre materials, such as polyethylene vinyl-acetate, low density polyethylene (LDPE), polyethylene terephthalate and polystyrene, have been used in asphaltic mixtures (Murana et al., 2018; Aliyu et al., 2015; Murana et al., 2021; Murana et al., 2022). Polymers have been used either as bitumen modifiers through wet process or as fibre reinforcements through dry process. The ultimate goal of incorporating these materials into asphalt mixtures is to increase the service life of the pavement by preventing creep and fatigue failures and reflective cracks (Yasreen et al., 2011).

Previous studies have established that it is more economical to recycle pavement materials to cut down cost of construction according to Jayakody et al. (2017). The use of recycled materials and modified binders in pavement construction reduces cost of construction, along with a reduction in flexible pavement distresses (Roberto et al., 2020; Sorociak and Grzesik, 2019; Milad et al., 2020; Kakar et al., 2021; Alamri et al., 2020; Murana et al., 2020, Murana et al., 2023).

Although studies on the use of reclaimed asphalt pavement (RAP) and High Density Polyethylene (HDPE) exist in literature, the prospect and effectiveness of combining High Density Polyethylene (HDPE) and reclaimed asphalt pavement (RAP) in hot mix asphalt subjected to Marshall testing need to be assessed. This study contributes in that regard by examining the strength performance of hot mix asphalt produced with 25% RAP and 75% virgin aggregate with bitumen modified at 2, 4, 6, 8 and 10% High Density Polyethylene (HDPE), by conducting tests on bitumen and HDPE; namely, FTIR and TGA/DTA, respectively. Marshall properties were also assessed using standard Marshall test procedures and further enhanced with fibermetric analysis and SEM/EDS for micro-structural examination. The distinction of this study from previous studies is quite obvious and cannot be overlooked. The objective of this research is to evaluate the effectiveness of High Density Polyethylene (HDPE) and reclaimed asphalt pavement (RAP) in hot mix asphalt production.

MATERIALS AND METHODS

Materials

The materials used in this research were bitumen, High Density Polyethylene (HDPE), Reclaimed Asphalt Pavement (RAP), fine and coarse aggregates and granite dust. The bitumen and fine and coarse aggregates were obtained from MotherCAT Construction Company at Palladan, Zaria, Nigeria. The bitumen is of 60/70 penetration grade. The fine and coarse aggregates are granite.

Reclaimed Asphalt Pavement (RAP)

For this research, RAP material was obtained from a dump site generated from ongoing road-construction activities along Abuja–Kano Road (45km from Kaduna Town) in Kaduna State, Nigeria. The construction of Abuja-Kano road is handled by Julius Berger Nigeria, where a representative sample was obtained from the large quantity of RAP generated during construction. Asphalt Institute chart was used for calculating percentages for combined gradation (Table 1). The RAP was sieved through the following set of sieves: 12mm, 9.5mm, 6.4mm, 3.2mm, 1.25mm, 0.6mm, 0.3mm, 0.15mm and 0.075µm.

Table 1. Percentages for combined gradation (Asphalt Institute, 2014)

Material	Blend Percentage	Stockpile Percentage for Determining Combined Gradation
#57 Coarse Agg	20%	20.4%
#8 Coarse Agg	30%	30.6%
Fine Agg	25%	25.5%
RAP	25%	23.5%

High Density Polyethylene (HDPE)

The chemical formula of High Density Polyethylene is $[C_2H_4]_n$ and its chemical structure is depicted in Figure 1. The properties that influenced the choice of HDPE as a modifier are high strength, high impact and chemical resistance, high melting point and ease of malleability. The High Density Polyethylene (HDPE) waste was sourced from open refuse dump plastics inside Ahmadu Bello University campus. The HDPE was treated with ethanol to remove dirt, air-dried for 72 hours, cut into pellets and ground into fiber using the milling machine.

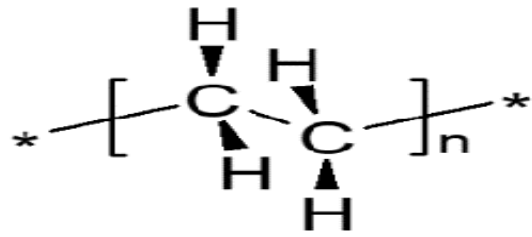


Figure (1): Chemical structure of High Density Polyethylene (Prasad et al., 2021)

Methods

The followed methodology in this research is presented in Figure 2.

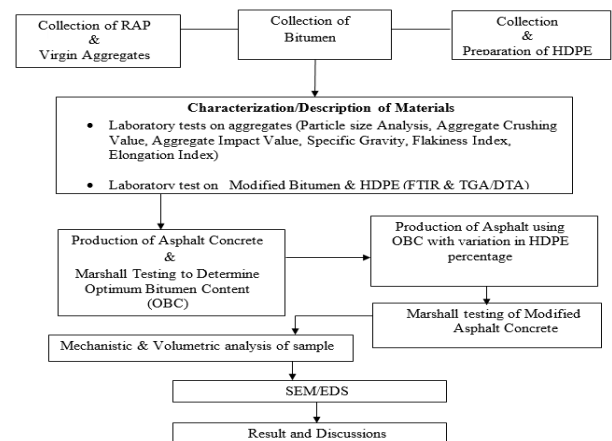


Figure (2): Methodology flowchart

Test on Aggregates

The following tests were performed on the aggregates.

i. Particle-size Distribution

Particle-size distribution of aggregates was done by sieving. The sieving of aggregates is done to determine the distribution of different sizes of aggregate in a given batch aggregate. The test was conducted in accordance with ASTM C136/C136M-19 (2019).

ii. Aggregate Crushing Value (ACV)

Aggregate crushing-value test was conducted to estimate the resistance of aggregate to crushing under gradually-applied traffic loading. The test was conducted in accordance with BS EN 1097-2 (2020).

iii. Aggregate Impact Value (AIV)

Aggregate impact-value test is used to assess the resistance of an aggregate to impact and shock.

The test was conducted in accordance with BS EN 1097-2 (2020).

iv. Specific-gravity Test

Specific-gravity test is used to determine impermeable and permeable pores of an aggregate. The test was conducted in accordance with ASTM C127-15, 2015; ASTM C128-15 (2015).

v. Elongation Index

Elongation-index test is a method of characterization of coarse aggregate used in flexible-pavement design. Test for elongated aggregates is mandatory, as elongated aggregates are susceptible to breakage under heavy traffic loading. The test was conducted in accordance with ASTM D4791-19 (2019).

vi. Flakiness Index

Flakiness-index test is a test method used for characterization of aggregate particles in flexible-pavement design. Test for flaky particles is necessary, as flaky aggregates are undesirable and may cause weakness within the mixture matrix. The test was conducted in accordance with BS EN 933-3 (2017).

Tests on Bitumen and HDPE

For characterization of the bitumen and HDPE, the following tests were performed.

i. Fourier Transform Infra-Red (FTIR)

Fourier transform infrared-spectroscopy test is mainly used to inspect the structure and functional groups of chemical molecules. It is also used to indicate the occurrence of chemical changes in blended materials. For this study, ThermoFisher scientific

Agilent Cary 630 spectrometer was used in accordance with ASTM D6348-12 (2020), where the wavelength ranged from 4000 to 650 cm^{-1} . The wavenumber is plotted against the transmittance percentage.

ii. Thermogravimetry (TGA) Analysis

Thermogravimetry (TGA) analysis is a technique chiefly used to appraise the physical properties of a material under monitored-heat temperature. Differential thermal analysis (DTA) is used to measure a material's heat capacity; i.e., the temperature at which a material is transformed physically (phase transition). For this study, PerkinElmer STA 8000 simultaneous thermal analyzer was used in accordance with ASTM D6370-99 (2019).

Tests on Hot Mix Asphalt

The following tests were performed on the asphalt samples

i. Marshall Stability and Flow

Marshall stability is the maximum load that a compacted asphalt specimen can withstand before a deformation at a standard temperature of 60°C with a load applied at a constant rate of 50mm/min. The stability and flow are read from the dial gauges. The flow which is measured in 0.25mm units is the deformation that the specimen has undergone at the maximum load. The test was conducted in accordance with ASTM D6927-05 (2015). Figure 3 shows the Marshall stability and flow experiment process.



Figure (3): Experiment process (a) Threshold sample curing (b) HDPE-modified sample and (c) Marshall testing setup

ii. SEM/EDS

Scanning Electron Microscopy (SEM) is a technique that uses a high-energy beam to create an image-resolution surface. Energy Dispersive Spectroscopy (EDS) is a technique used to identify elemental composition of a material's surface. SEM/EDS shows the surface micro-structural arrangement between aggregates and bitumen materials. It also aids in qualitative and quantitative elemental analysis. The test was conducted in accordance with ASTM E2809-22, (2022).

RESULTS AND DISCUSSION

Particle-size Distribution

The particle-size distribution test on aggregates is

done to determine the gradation of a given batch of aggregates used for asphalt-concrete production. The particle-size distribution of combined coarse aggregate, fine aggregate and mineral filler for RAP and natural aggregates is shown in Figure 4 and tabulated in Table 2. It can be noted from Figure 4 that the selected batch of aggregates is within the limits specified by FMWH. (2016), as it is within the envelope's upper limit and lower limit. The results of the particle-size distribution test show a well-graded aggregate that can properly interlock and contribute to the strength of the asphalt concrete.

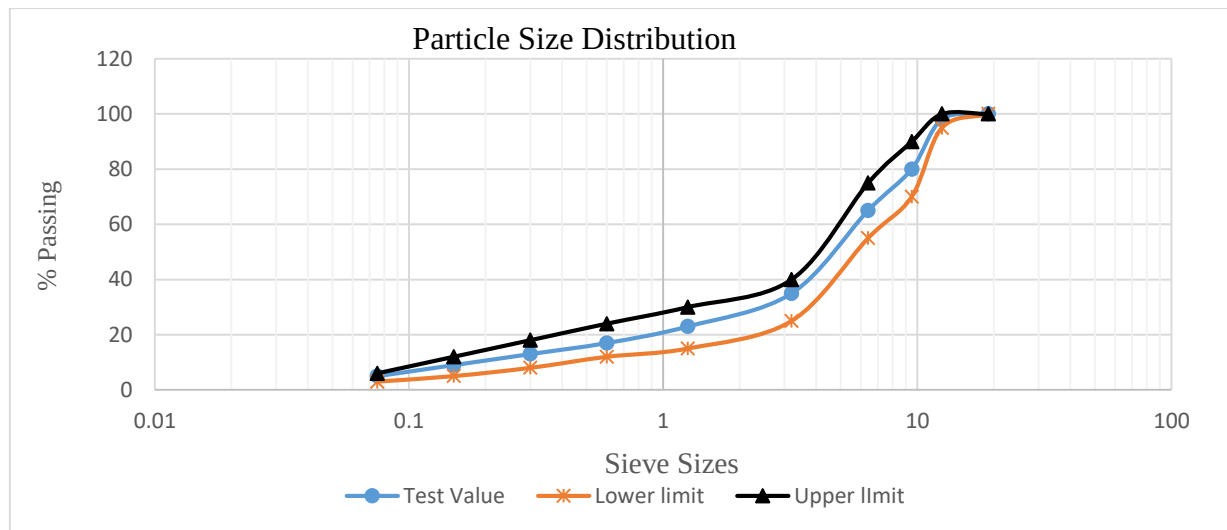


Figure (4): Particle-size distribution

Table 2. Asphalt job mix design in accordance with FMWH (2016)

Sieve Size (mm)	Upper limit	(%) Passing	Lower limit	(%) Retained	25% RAP Content	Total of RAP	75% NA	Total of NA	Grand Total Aggregate (%)
19	100	100	100	0	0	0	0	0	0
12.5	95	98	100	2	0.5	5.58	1.5	16.74	22.32
9.5	70	80	90	18	4.5	50.22	13.5	150.66	200.88
6.4	55	65	75	15	3.75	41.85	11.25	125.55	167.4
3.2	25	40	40	25	6.25	69.75	18.75	209.25	279
1.25	15	23	30	17	4.25	47.43	12.75	142.29	189.72
0.6	12	17	24	6	1.5	16.74	4.5	50.22	66.96
0.3	8	13	18	4	1	11.16	3	33.48	44.64
0.15	5	9	12	4	1	11.16	3	33.48	44.64
0.075	3	5	6	4	1	11.16	3	33.48	44.64
Pan				5	1.25	13.95	3.75	41.85	55.8
Total					25	279	75	837	1116

Note: RAP = Reclaimed Asphalt Pavement. NA = Natural Aggregates.

Physical Properties of Aggregates

The physical-property tests on aggregates are done to determine strength, angularity and surface charge. The results of aggregate physical-property tests for virgin aggregate and RAP are presented in Table 3. The specific-gravity test results for virgin-aggregate testing are 2.83, 2.72 and 2.91 for coarse aggregate, fine aggregate and granite dust, respectively, while specific gravity for coarse and fine aggregates for RAP is 2.66 and 2.31. The elongation and flakiness indices for virgin aggregate and RAP are 17.38, 21.40, 22.52 and 23.18%,

respectively. The aggregate crushing and impact values or virgin aggregate and RAP are 20.57, 23.11 and 15.98%, respectively. The results obtained from the physical-property tests have revealed the capacity of the aggregate to withstand loading and resist deformation. The values obtained from physical test on RAP did satisfy the first part of guiding principles established by the Federal Ministry of Works Nigeria (FMWN, 2013) for recycling of RAP in asphaltic mixture which states that “the mixture containing RAP should meet the same requirements as mixes with all virgin aggregates”.

Table 3. Physical properties of aggregate with standard specifications

Properties	Test Values		FMWH (2013) Standard Spec.		Remarks
	RAP	Virgin Aggregate	Min.	Max.	
Specific Gravity (coarse)	2.66	2.83	2.5	3.0	Satisfying
Specific Gravity (fine)	2.31	2.77	N/S	N/S	Satisfying
Specific Gravity (filler)	-	2.91	N/S	N/S	Satisfying
Flakiness Index (%)	23.18	21.40	N/S	35	Satisfying
Elongation Index (%)	22.52	17.38	N/S	25	Satisfying
Aggregate Crushing Value (%)	15.98	20.57	N/S	30	Satisfying
Aggregate Impact Value (%)	20.18	23.11	N/S	35	Satisfying

N/S = Not Specified.

Results of FTIR

Figure 5 (a-c) depicts Infrared spectra of HDPE, unmodified bitumen and modified bitumen, respectively. The peak values of HDPE (Figure 5a) are 2918.5, 2851.4, 1461.1, 1375.4 and 719.4 cm^{-1} , as tabulated in Table 4. The peaks at 2918.5 and 2851.4 cm^{-1} represent C-H stretching of aliphatic group, while those at 1461.1 and 1375.4 cm^{-1} represent C-O bending and C-O stretching of ethylene group, respectively, and that at 719.4 cm^{-1} represents C-H rocking of CH_2 ethylene group. This is in concurrence with the works of Weigel and Stephan (2018) and Yaro et al. (2021). For unmodified bitumen (Figure 5b), the peak values are 2920.05, 2851.26, 1601.71, 1455.65, 1375.54, 865.75, 811.30 and 744.30 cm^{-1} . The peaks at 2920.05 and 2851.26 cm^{-1} represent C-H stretching of CH_2 aliphatic group, while that at 1601.71 represents C=C stretching of C=C aromatic group, those at 1455.65 and 1375.54 cm^{-1} represent C-H bending of CH_2 aliphatic group,

those at 865.75 and 811.30 cm^{-1} represent C-C bending of CH aromatic group, whereas that at 744.30 cm^{-1} represents C-H bending of C-H aromatic group. This is in agreement with the works of Shivasharana and Kesti (2019) and Prasad et al. (2021). For the modified bitumen (Figure 5c), incorporation of HDPE changed the intensity of infrared spectra; some infrared spectra increased with minor noticeable changes in wavenumbers in comparison with the spectra of the unmodified bitumen. The change in wavenumber indicates that a chemical reaction has occurred between the bitumen and the HDPE. The peak values of the modified bitumen are 2922.2, 2851.4, 1599, 1457.4, 1375.4, 868.5, 812.6 and 745.2 cm^{-1} . The peak values of the modified bitumen suggest that the HDPE uniformly disperses inside the bitumen. The decrease of C=C stretching from wavenumber 1601.71 to 1599 cm^{-1} suggests that strong physical forces exist between HDPE and bitumen compared to chemical forces.

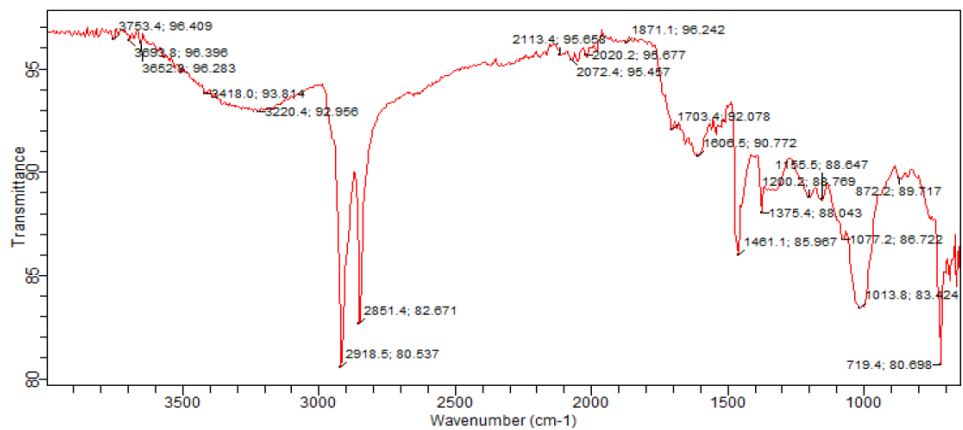


Figure (5a): Infrared spectra of HDPE

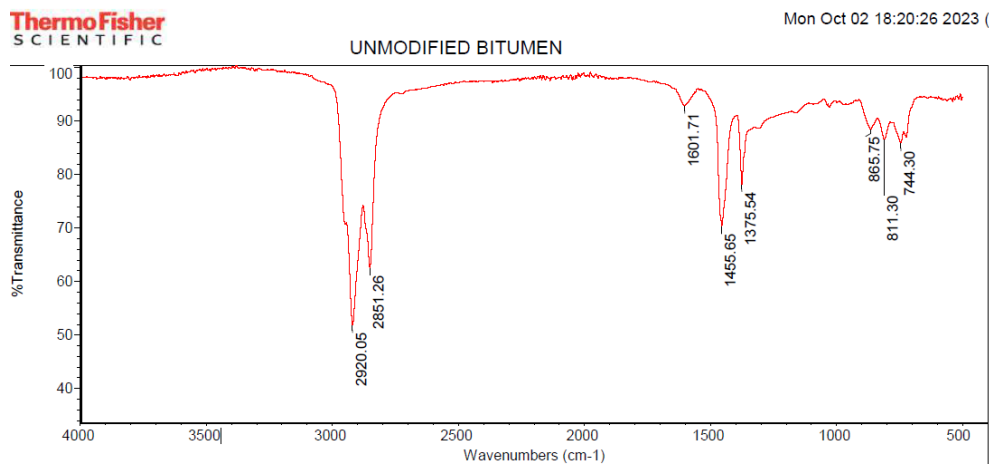


Figure (5b): Infrared spectra of unmodified bitumen

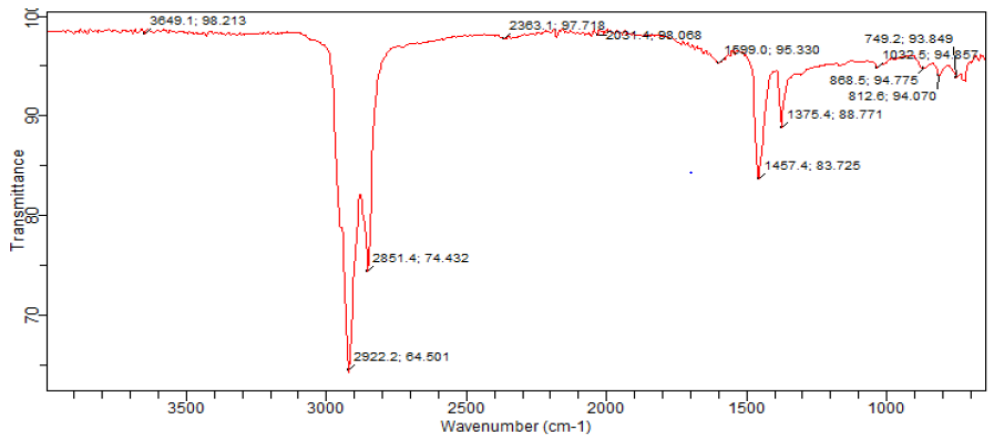


Figure (5c): Infrared spectra of HDPE-modified bitumen

Table 4: Wavenumbers and functional groups

HDPE		Unmodified Bitumen		Modified Bitumen	
Wavenumber (cm ⁻¹)	Functional Group	Wavenumber (cm ⁻¹)	Functional Group	Wavenumber (cm ⁻¹)	Functional Group
2918.5	CH Stretching Aliphatic	2920.05	CH ₂ Stretching Aliphatic	2922.2	CH ₂ Stretching Aliphatic
2851.4	CH Stretching Aliphatic	2851.26	CH ₂ Stretching Aliphatic	2851.4	CH ₂ Stretching Aliphatic
1606.5	C=C Stretching Aromatic	1601.71	C=C Stretching Aromatic	1599	C=C Stretching Aromatic
1461.1	CH ₂ Bending Ethylene	1455.65	CH ₂ Bending Aliphatic	1457.4	CH ₂ Bending Ethylene
1375.4	CH ₂ Stretching Ethylene	1375.54	CH ₂ Bending Aliphatic	1375.4	CH ₂ Stretching Ethylene
1013.8	C=C Stretching Vinyl	865.75	CH Bending Aromatic	868.5	CH ₂ Stretching Ethylene
719.4	CH ₂ Rocking Ethylene	811.30	CH Bending Aromatic	812.6	CH ₂ Bending Ethylene
		744.30	CH Bending Aromatic	749.2	CH Stretching Aromatic

Results of Thermo-gravimetric Analysis

Thermo-gravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) of HDPE are depicted in Figure 6. For the thermo-gravimetric test, an amount of 14.209g of HDPE was subjected to a stepwise isothermal-heating temperature of 30.00°C to 950°C at 10.00°C/min. The HDPE underwent a one-degradation step with the onset-degradation temperature at 302.31°C and final-degradation temperature at 461.96°C with weight loss of 75%. This behaviour of HDPE is influenced by the structure of the material and the bonds

between the atoms that hold the structure together. The result of the TGA test indicates that the material has a high thermal stability which translates to a high resistance rate to decomposition and as such can be safely used below the degradation temperature as a modifier in bitumen to improve its thermal stability. BS EN 12591 (2009) recommends that the maximum temperature of bitumen at any stage of mix preparation is 180°C for 50/70 penetration grade. The residual mass at the end of 461.96°C-DTA/TGA was 25%. A similar result was reported by Awad et al. (2019).

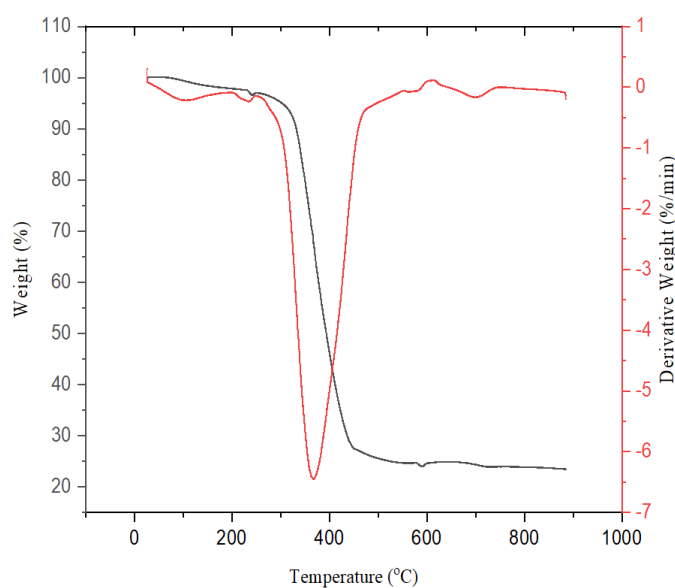


Figure (6): Thermogram of HDPE

Marshall Stability Results

The results of Marshall stability with variation of HDPE content are displayed in Figure 7. The results of Marshall stability show a 28, 35, 39 and 24% decrease in strength at 2, 4, 6 and 8% HDPE content, respectively, in comparison to the threshold. The stability values dropped from 10.9kN to 7.9, 7.05, 6.05 and 8.25kN. However, a 6% increase in strength was recorded at 10% HDPE content. The increment in strength could be attributed to sufficient quantity of HDPE that

rejuvenated the RAP. All mixes containing HDPE-modified bitumen and RAP satisfy the FMWH (2016) minimum Marshall stability requirement of 3.5kN. Higher stability indicates better resistance to rutting and shoving (Awan et al., 2022). The Marshall stability values also satisfied the second part of the guideline principles established by (FMWN, 2013) for use of RAP in asphalt mixtures which stipulates that “mixes containing RAP should perform equal to or better than virgin mixtures”.

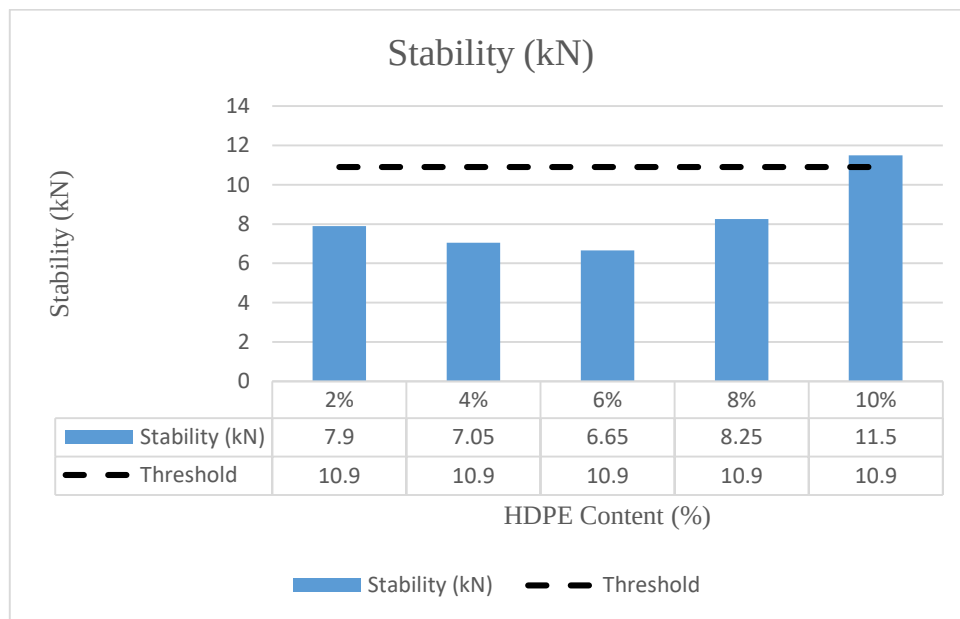


Figure (7): Variation of stability with HDPE content

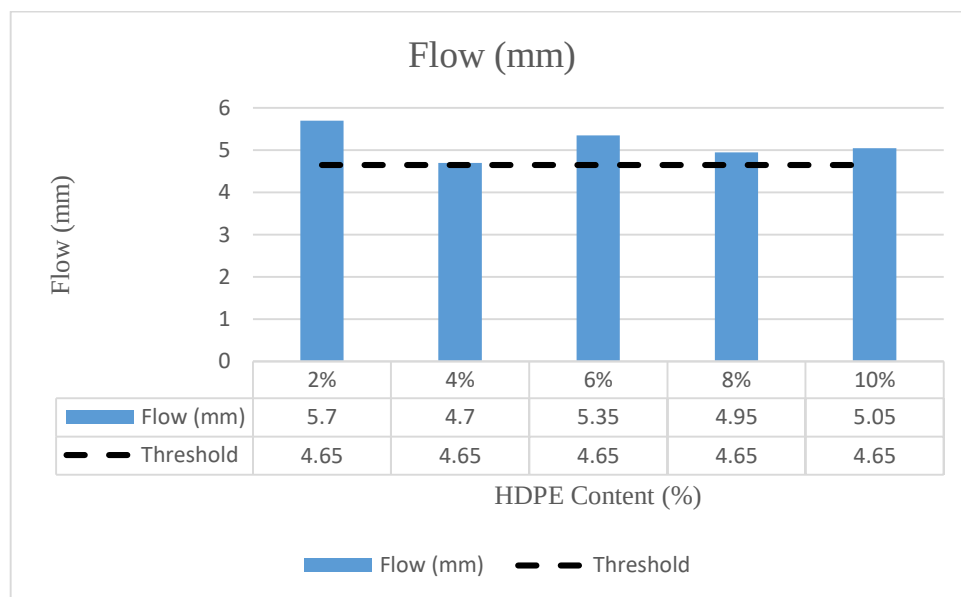


Figure (8): Variation of flow with HDPE content

Marshall Flow Results

The results of Marshall flow with variation of HDPE content are displayed in Figure 8. Murana et al. (2019) described flow as the sum total of deformity occurring at maximal load. Flow values indicate the ability of the asphalt concrete to evenly adapt to loads and settlements under heavy loading conditions. From the flow results obtained, it was noticed that all modified hot mix asphalt had higher flow values than the threshold. Furthermore, the flow values of modified hot mix asphalt were outside the requirement of 2mm-4mm range set by FMWH (2016). This suggests that HDPE did not improve the overall viscosity of asphalt concrete. Flow is an interpretive guide for assessing the possibility of rutting in asphalt mixtures.

Unit-weight Results

The results of unit weight with variation of HDPE content are displayed in Figure 9. Unit weight indicates the degree of compaction achieved. The results of the unit-weight test showed a continuous decrease with increase in HDPE content. The unit weight values recorded are 2.33, 2.32, 2.31, 2.30 and 2.29g/cm³. Comparison of the unit weight of threshold to the unit weight of modified asphaltic mixtures shows a decrease at 4, 6, 8 and 10% HDPE content. The reduced unit weight is not unconnected to the increase of fiber contents from HDPE, making the mixture denser and causing a subsequent improvement of Marshall stability.

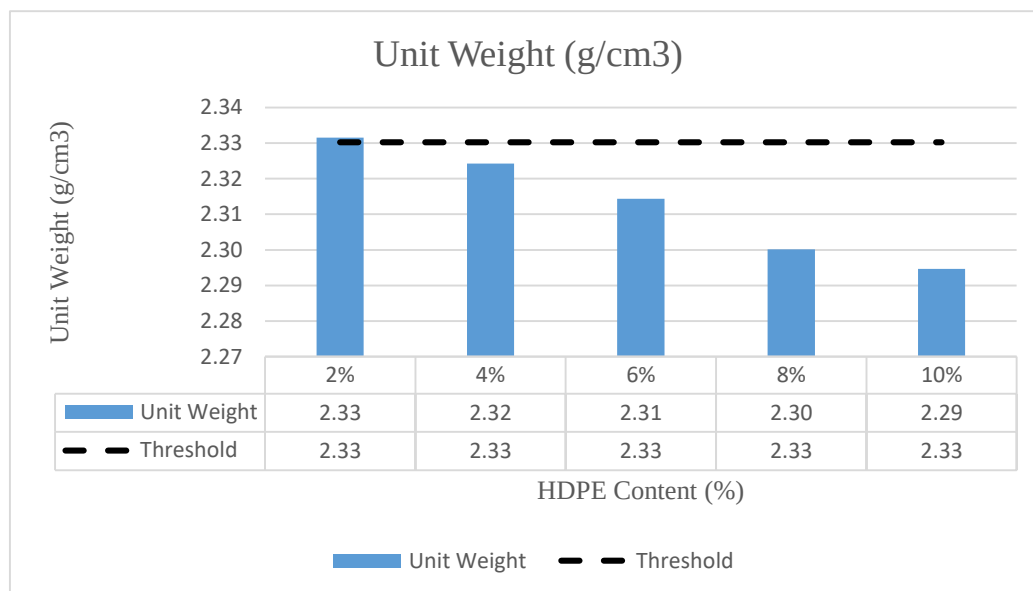


Figure (9): Variation of unit weight with HDPE content

Voids in Mineral Aggregate (VMA) Results

The results of voids in mineral aggregate with variation of HDPE content are displayed in Figure 10. Voids in mineral aggregate are referred to as the voids between aggregate particles in the compacted mixture. The values of voids in mineral aggregate recorded are 22.82, 23.06, 23.38, 23.85 and 24.03%. The values of voids in total mixture for the modified mixture improved with respect to the threshold (22.86%) except for 2% HDPE content. The values of voids in mineral aggregate are inversely related to the values of the unit weight. Voids in mineral aggregate represent an indicator of asphalt content and directly relates to durability performance of the mixture.

Voids in Total Mixture (Pa) Results

The results of voids in total mixture with variation of HDPE content are displayed in Figure 11. The results of the voids in total mixture showed an increase with the increase in HDPE content, as the voids in total mixture recorded are 4.12, 4.42, 4.82, 5.41 and 5.63%. All values of voids in total mixture for the modified mixes are higher than the values of the threshold (4.17%) except for 2% HDPE content. The results obtained from this analysis indicate the ability of the modified mixture to resist ingress of moisture within the matrix of the mixture. The higher the Pa values, the lower the voids in the mixture. The values of voids in total mixture for 2, 4 and 6% are within the FMWH (2016) requirement range of 3%-5%.

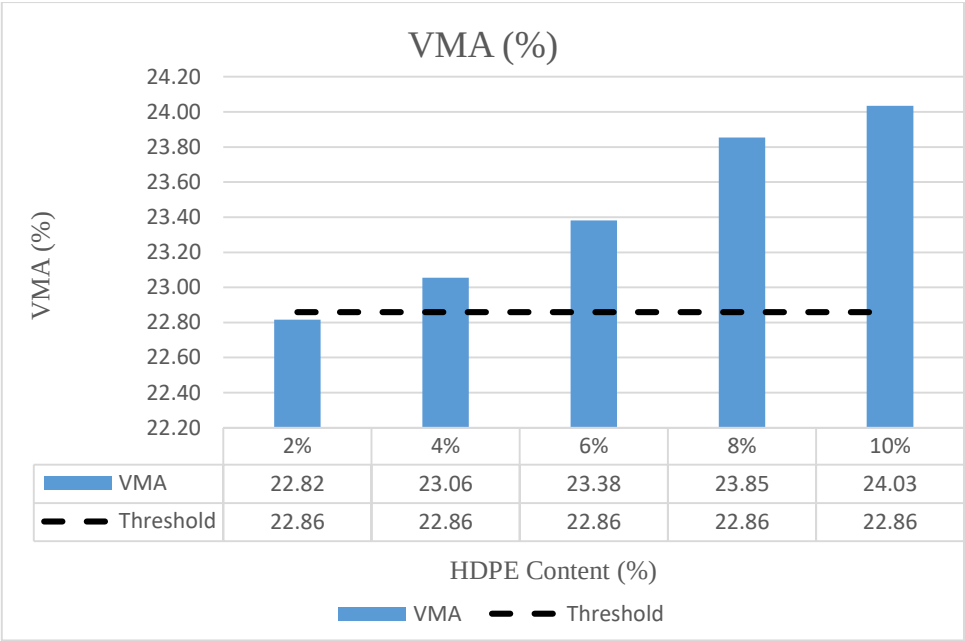


Figure (10): Variation of VMA with HDPE content

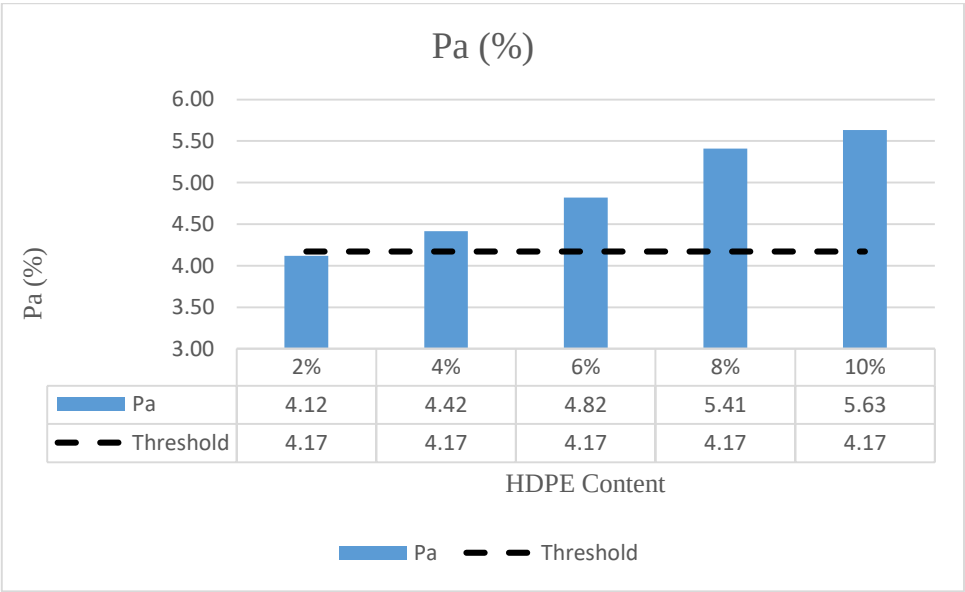


Figure (11): Variation of Pa with HDPE content

Voids Filled with Bitumen (VFB)

The results of voids filled with bitumen with variation of HDPE content are displayed in Figure 12. Voids filled with bitumen approximate the part of voids in mineral aggregate filled with bitumen. The values of voids filled with bitumen for the modified mixes are 81.95, 80.85, 79.38, 77.33 and 76.57% for 2, 4, 6, 8 and 10% HDPE content, respectively. The results of the voids filled with bitumen showed a continuous reduction with the increase in HDPE content. All values of voids

filled with bitumen for the modified mixes are lower than the values of the threshold (81.75%). The reduction in VFB translates to an increase in the durability of asphalt concrete. This trend of results can be attributed to the uniform dispersion of HDPE in bitumen, which improved bitumen viscosity, causing an increased coating of bitumen around the aggregate. The results are within the range of 75%-82% specified by FMWH (2016).

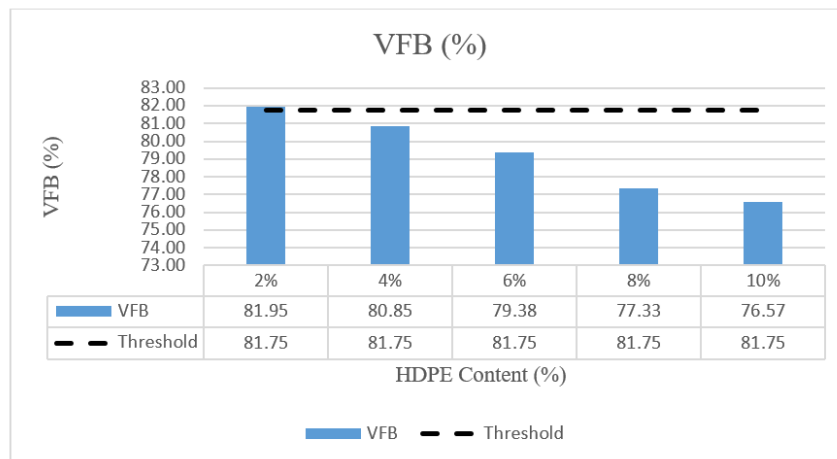


Figure (12): Variation of VFB with HDPE content

Micrograph Analysis of Hot Mix Asphalt Sample

The micrograph of threshold and HDPE modified hot mix asphalt are depicted in Figures 13 and 14, respectively. Scanning electron microscopy (SEM) was carried out at 537 μ m scale and 1000 μ m magnification. The morphology of the modified hot mix asphalt with 10% (optimum) HDPE content showed a better structural interlocking arrangement matrix in comparison with the threshold, corroborating the results obtained in the void-density analysis. Energy dispersive spectroscopy (EDS) revealed three major elements; namely, carbon, nitrogen and silicon. Carbon showed an increase in atomic concentration from 82.66% to 88.56%. This suggests that HDPE enriched the carbon content of the mixture. On the other hand, atomic concentration of nitrogen and silicon decreased from 12.07 and 2.17% to 6.96 and 1.98%, respectively. These three main elements play a major role in the hardening process of hot mix asphalt, which is validated by the FTIR analysis.

In this comparative analysis, fiber and pore sizes were also investigated. The fiber and pore histograms are presented in Figures 15 and 16, respectively. The fiber and pore histograms were taken at the same resolution and magnification as SEM. The fiber content of the modified asphalt ranged from 2.13 μ m to 18.85 μ m which is higher than the fiber content recorded at the threshold that ranged from 1.66 μ m to 16.92 μ m, indicating the appearance of more surface area of fiber from HDPE. The increased fiber content can be attributed to the increase in Marshall stability observed at 10% HDPE content. Furthermore, fibermetric analysis showed modified hot mix asphalt sample pore sizes ranging from 0.10 μ m² to 182.88 μ m². This is a decrease in comparison to pore sizes of threshold ranging from 0.41 μ m² to 188.59 μ m². Reduction in the pore size can be attributed to the influence of HDPE fibers and this is confirmed by the improvement recorded in density-void analysis. Smaller pore sizes translate to a denser mixture and an enhanced durability.

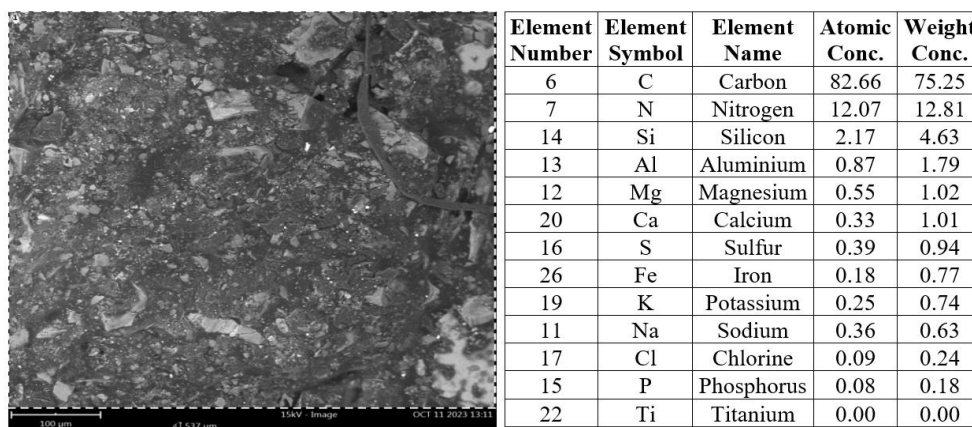


Figure (13): SEM/EDS of threshold

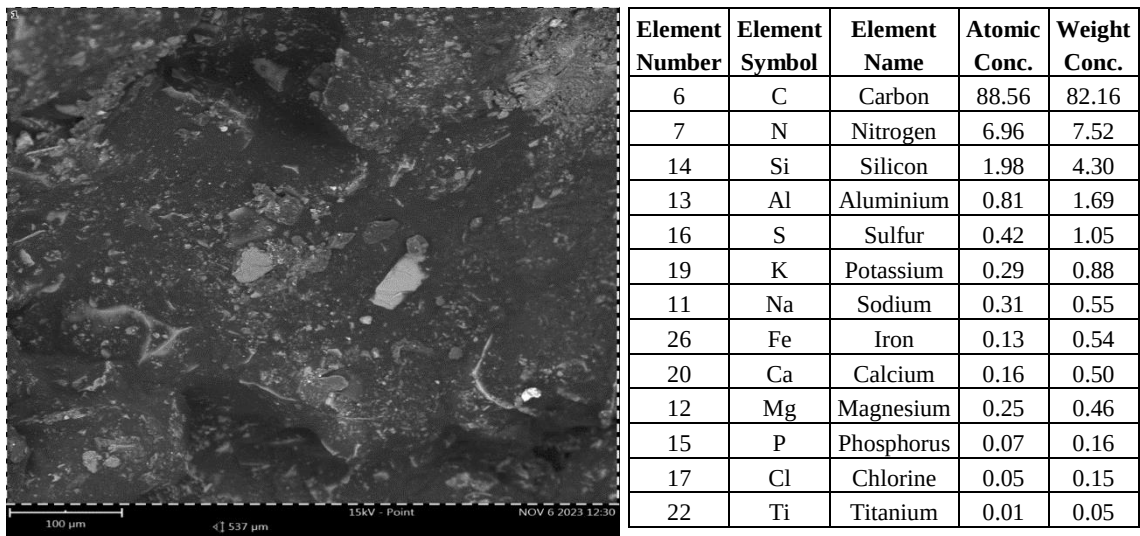


Figure (14): SEM/EDS of modified HMA

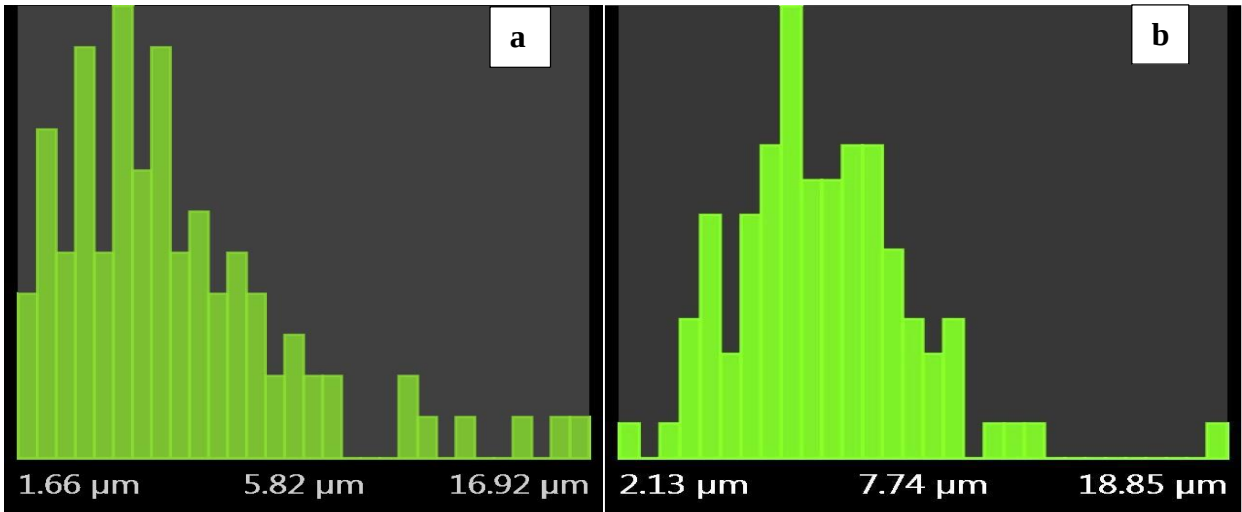


Figure (15): Fiber histogram of (a) Threshold and (b) Modified HMA

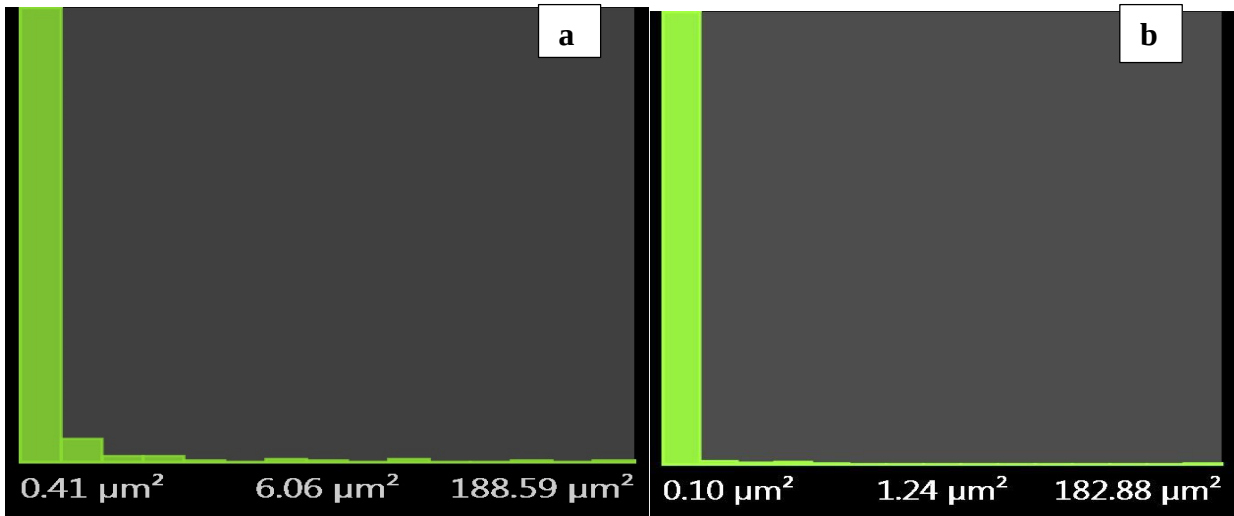


Figure (16): Pore histogram of (a) Threshold and (b) Modified HMA

CONCLUSIONS

This study presents a laboratory-based investigation into the performance evaluation of asphalt concrete produced with HDPE modified bitumen incorporating RAP. The following conclusions were drawn based on the results of the research.

- The physical properties of Reclaimed Asphalt Pavement (RAP) are analogous to the properties of virgin aggregate, as they are within the acceptable limits specified by FMWH (2013). The aggregates are considered durable for use in asphalt concrete production.
- FTIR analysis on HDPE confirmed HDPE as primarily made up of hydrocarbon. The HDPE was successfully incorporated into the bitumen and changes in functional group structure and peaks

validate the assumed incorporation.

- The 6% improvement in the performance of Marshall stability indicates higher load bearing capacity, improved resistance to shoving, rutting, temperature susceptibility, fatigue failure, water and moisture ingress.
- Micrograph of the modified HMA showed an improved structural packing arrangement of particles, with alteration in the atomic concentration of elements, which implies an improved service life performance, such as resistance to raveling, rutting and cracking.
- For further research, rheological properties of HDPE modified bitumen incorporating RAP should be studied, since the science of rheology deals with flow and deformation of materials and the interrelationship between time, force and deformation.

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