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EVALUATION OF BIOPOLYMER MODIFIED HOT MIX ASPHALT

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Abstract: Road construction projects commonly use Hot Mix Asphalt (HMA) because it provides durable results while remaining cost-effective. The production of HMA depends extensively on natural resources including aggregates and bitumen which creates both environmental and economic challenges. Traditional asphalt pavements do not possess sufficient mechanical strength or durability to endure heavy traffic loads and environmental stressors which results in frequent maintenance needs and a service life spanning only 10 to 20 years. This research examines Gum Arabic as a bitumen modifier in HMA production utilizing replacement levels of 2%, 4%, 6%, and 8%. The paving materials comprised coarse aggregate from granite, fine aggregate from sand and filler from stone dust which passed through a 75-micron sieve with all components tested to meet standard specifications. The modification effects of Gum Arabic on physical (density, weight, thickness), engineering (voids filled with bitumen, voids in the mix) and mechanical (stability and flow) properties of asphaltic cores were evaluated using Marshall Stability tests. A 2% substitution with Gum Arabic demonstrated optimal performance by enhancing asphalt characteristics and ensuring both cost-efficiency and sustainability.

Keyword: Gum Arabic, Bitumen Modifier, Marshall Mix Design, Hot Mix Asphalt, Viscosity

1.0 Introduction

The increase in the cost of construction around the world including Nigeria is high. Road construction is one of the major construction carried out. Transportation is essential in the growth of many countries including Nigeria and a good road network greatly improves the economic growth of such countries, Asphalt mixtures are mostly used as the final layer of the road structure (flexible pavement). The average production of Asphalt mixtures in the US is 2.7 million miles of paved roads and highways, ninety-four (94) per cent of which are surfaced with Asphalt [11][12].
Highway transport modes in Nigeria and many developing countries provide ninety-five per cent (95%) of all transport movements not without the inevitable consequences of failure in pavements caused by material properties, excessive traffic loading and environmental factors. [15].
Hot Mix Asphalt (HMA) is a prevalent material in road construction due to its durability and cost-effectiveness. However, in Nigeria, HMA pavements often face challenges such as rutting, cracking, and moisture damage, primarily due to high temperatures and heavy traffic loads.
[11] emphasized that an effective bituminous mix design should result in a pavement that is strong, durable, fatigue- and deformation-resistant, cost-effective, and environmentally friendly. Achieving

this involves evaluating various mix proportions through extensive testing to identify the optimal composition. A well-designed mix must contain the correct bitumen content to ensure durability, provide adequate resistance to shear deformation under high traffic temperatures, and include sufficient air voids for traffic-induced compaction. Additionally, it should offer good workability for proper placement without segregation, resist cracking from axle load flexing, and withstand low temperatures to prevent shrinkage cracking.

In pursuit of improved performance and sustainability, many researchers have investigated the use of renewable materials and industrial waste as stabilizing additives. These innovations not only enhance asphalt concrete strength and durability but also help mitigate environmental impact. Bitumen-producing industries are actively seeking sustainable methods for modifying bituminous mixes to reduce carbon emissions and improve road pavement performance [6].

Gum Arabic is a natural resin extracted from the stems and branches of Acacia Senegal and Acacia trees. It is used as an additive in various industries such as food, pharmaceuticals, cosmetics and textile industries. Researchers have recently explored the possibility of using Gum Arabic as a modifier for asphalt mixtures, to improve the performance and sustainability of asphalt mixtures. The incorporation of Gum Arabic as a bitumen modifier in asphalt mixtures offers significant advantages due to its rheological, mechanical, and environmental properties. Several studies have explored these benefits, which can be categorized as follows:

1.1 Improved Adhesion and Cohesion

Gum Arabic is a highly adhesive substance that is capable of bonding the asphalt binders to the aggregates. This is also helpful in reducing problems such as stripping, where water-negative pressure arises and hence asphalt binder is pulled away from the aggregate surface. With improved cohesion among the various components of the asphalt, inherent even internal strength develops which results in fewer problems of cracking and deformation of the mixture under load which one sees in the life of the pavement [18].

1.2 Enhanced Moisture Resistance

By applying gum Arabic along with asphalt, the mixture may become more impervious to moisture damage. By being hydrophilic and adhesive gum Arabic forms a protective layer that significantly reduces the chances of water weakening the asphalt-aggregate bond [16].

Rheological Modifications

Gum Arabic can reduce the rheological (flow) properties of asphalt binders through which the asphalt gains its elasticity and viscosity which can easily get damaged. In this way, the asphalt can be more resistant to deformation due to high temperature and at the same time can become more elastic in the cold condition. The use of gum Arabic can boost the temperature distribution of the binder and thus it will be more resistant to rutting (at high temperatures) and to cracking (at low temperatures) [17][5].

1.3 Enhanced Resistance to Fatigue

Gum Arabic may improve asphalt's resistance to fatigue cracking under heavy traffic loads by increasing its elasticity and resilience. Pavements' service life may be increased as a result [18].

There are challenges and limitations with the use of gum Arabic as an asphalt modifier such as optimizing the dosage and compatibility of gum Arabic with various bitumen, and evaluation of its long-term performance under various environmental and loading conditions.

2.0 Materials and Method

2.1 Materials

Hot Mix Asphalt is a mixture of bitumen which serves as the binder, fine aggregates, coarse aggregates and stone dust as filler. Gum Arabic is incorporated as an admixture (bitumen modifier).

2.1.1 Coarse Aggregate

The coarse aggregate used was locally sourced granite from the environment of federal university of agriculture Abeokuta, Ogun State, conforming to standard specifications and particle sizes.

2.1.2 Fine Aggregate

The fine aggregate used was locally sourced from the environment of federal university of agriculture Abeokuta, Ogun State, conforming to standard specifications and particle sizes.

2.1.3 Filler

The filler used was locally sourced stone dust from the environment of federal university of agriculture Abeokuta, Ogun State, passing through a sieve size of 75 microns conforming to standard specifications. Particle size distribution test was carried out on the coarse aggregate, fine aggregate and filler.

2.1.4 Bitumen

Bitumen was sourced and ordered from Ikorodu, Lagos State. The bitumen is a 60/70 penetration grade bitumen, and the following preliminary tests, specific gravity, Penetration test and flash point were carried out to ensure it conformed to standard requirement.

2.1.5 Gum Arabic

Gum Arabic was obtained in its raw form, and was added in bits as modifier to the bitumen at 2%, 4%, 6%, and 8%.

2.2 Mix Design

Asphalt concrete mixtures were designed using the Marshall Mix design method, following the mix proportions specified for heavily trafficked pavements in [19]. To determine the optimum bitumen content, 15 samples were prepared for the Marshall Test, with three samples at each bitumen content level ranging from 4% to 6% in 0.5% increments. The optimum bitumen content was identified as 5%. This 5% bitumen content (equivalent to 60 grams) was then used to establish the optimum modifier content. For this purpose, 15 hot mix asphalt samples were produced, with three samples at each modifier content level varying from 0% to 8% in 2% increments. These samples were subjected to the Marshall Test to assess the impact of the modifier on the asphalt concrete properties.

Table 1: Determination of optimum bitumen content (OBC)

Test property	Bitumen Content (%)
Max. Stability (KN)	4%
Max. Bulk density (g/cm)	6%
Air voids at 4%	4.50%
OBC = (4+6+4.5)/3 = 5%	

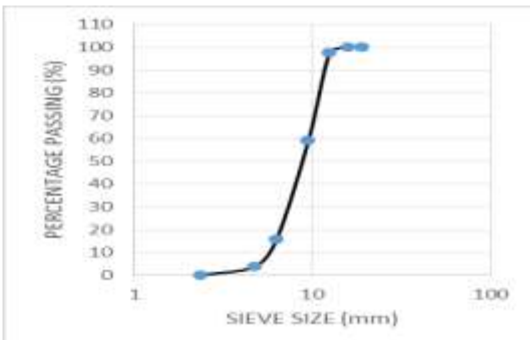
3.0 Results and Discussion

3.1 Particle size distribution

Figure 1 shows the gradation curve for the coarse aggregate; the coarse aggregate is classified as a poorly graded soil with aggregate size > 12.5mm but < 16mm. Figure 2 shows the gradation curve for the fine aggregate; the fine aggregate is classified as poorly graded soil. Figure 3 shows the gradation curve for the filler; the filler is classified as a poorly graded soil with a coefficient of Uniformity (Cu) = 0.94< 4 and coefficient of gradation (Cc) = 1.00 = 1.

Table 2: Physical properties of aggregates and filler.

Test	Test Method	Test value	Remark
Aggregate Impact Value	[3]	7.37	Satisfactory
Specific Gravity (Coarse)	[2]	2.68	Satisfactory
Specific Gravity (Fine)	[2]	2.31	Satisfactory
Specific Gravity (Filler)	[2]	2.33	Satisfactory



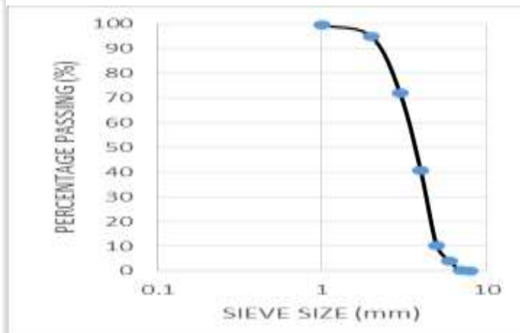
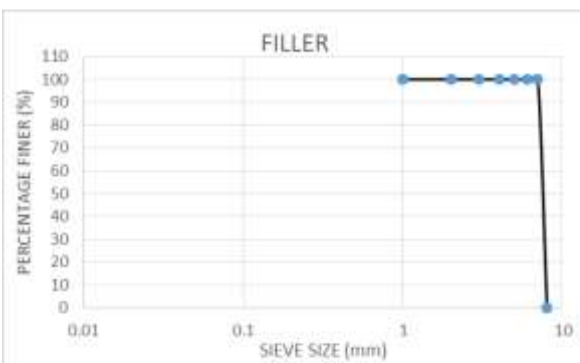


Figure 1: Gradation curve of coarse aggregate Figure 2: Gradation curve of fine aggregate



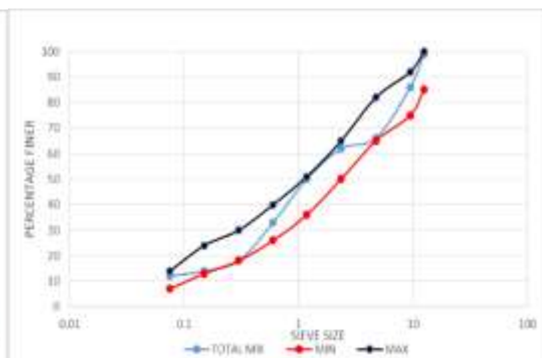


Figure 3: Gradation curve of filler Figure 4: Gradation curve for all-in-aggregate

According to [19] the aggregates and filler were proportioned and blended to achieve an all-in-aggregate satisfying the gradation limit. A trial and error proportioning was done in this research for the achievement of this as shown in Figure 4.

3.2 Bitumen preliminary test

The results from these tests are presented in table 2, and it can be seen from table 2 that the penetration value is acceptable for [8] method at 25°C measures 67 mm. The flash point and fire point are further confirmed, 260°C and 290°C tested with [9] test method, respectively; stable and safe under high-temperature scenario. In addition, the specific gravity as per the [4] is 1.07, which also confirms its suitability for road construction and other uses.

The bitumen is of excellent quality and reliable for use in asphaltic mixtures as all test values are within specified limits.

Table 3: Physical properties of Bitumen

Test	Test Method	Test Value	Remark
PENETRATION @ 25ºc (mm)	[8]	67	Satisfactory
FLASH POINT (ºC)	[9]	260	Satisfactory
FIRE POINT (ºC)	[9]	290	Satisfactory
SPECIFIC GRAVITY	[4]	1.07	Satisfactory

3.3 Marshall test

The results of the Marshall test on the Properties of the modified hot mix asphalt samples examined are discussed and presented as follows: Marshall Stability, flow, bulk specific gravity, percentage air voids, voids in mineral aggregate, and voids filled with bitumen.

3.3.1 Marshall Stability

Figure 5 shows the pattern in Marshall Stability for the modified hot mix asphalt (HMA), , which first rises gradually with the addition of gum Arabic content from 0% to 2% but then drops from 2% to a content of 8%. Marshall Stability represents the maximum load a compacted asphalt specimen can sustain. Improved viscosity of the asphalt mastic can be the reason for the sharp increase in stability at a content of 2%. At lower concentrations (0%–2%), gum Arabic seems to cause the improvement in the cohesiveness among the particles in the mix, resulting in optimum load distribution and higher resistance against deformations and shear forces.

But with more than a 2% content in gum Arabic, the binder itself becomes too viscous. That increased viscosity creates a softening effect on the asphalt blend, making the blend more pliable but less resistant against heavy loads prior to being deformed. Increased gum Arabic content more than 2% diminishes the internal friction and the mechanical interlocking among the aggregates and thereby results in a decrease in Marshall Stability.

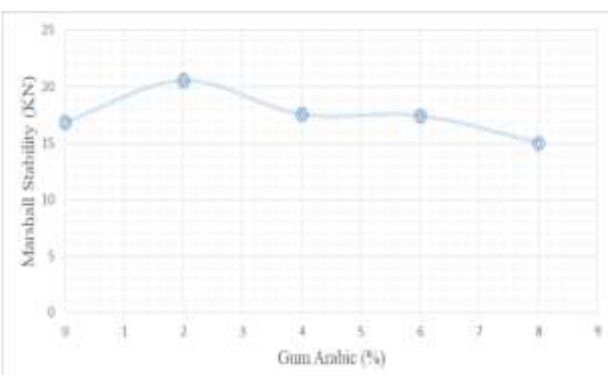


Figure 5: Marshall Stability of modified HMA

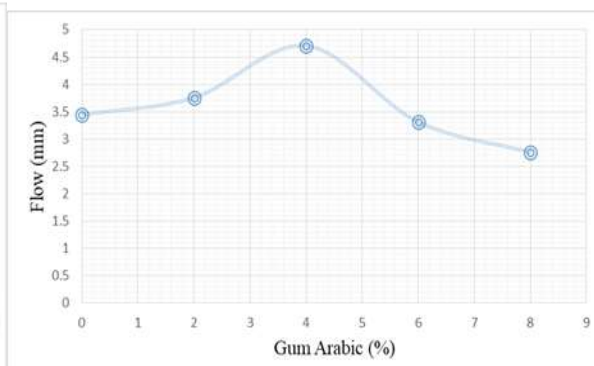


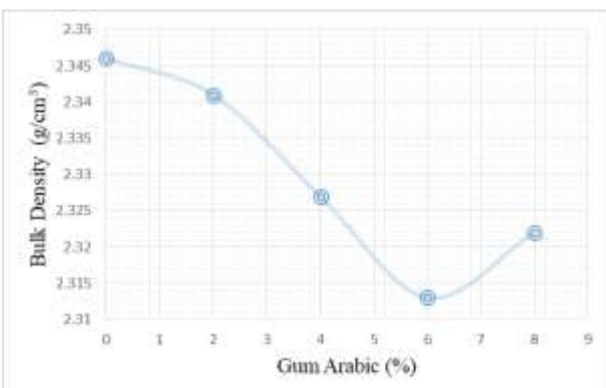
Figure 5: Marshall flow of modified HMA

3.3.2 Marshall Flow

Figure 6 illustrates a progressive increase in flow from 0% to 4% gum Arabic content, suggesting that the asphalt mixture becomes more flexible and ductile, allowing greater deformation before failure. At lower concentrations, gum Arabic appears to soften the asphaltic core, enhancing its flexibility. This effect may be due to gum Arabic functioning as a flexible binder, enabling the mixture to withstand higher deformation under load without immediate failure.Beyond 4%, however, the flow begins to decline, indicating a transition toward reduced ductility and increased brittleness. Flow, which measures the vertical deformation of the hot mix asphalt (HMA) at failure, is an indicator of stability. As gum Arabic content continues to rise, it starts to excessively bind the aggregate, leading to a stiffer mixture. This increased stiffness restricts deformation, causing a reduction in flow. Since asphalt with higher viscosity generally exhibits lower flow, the observed decrease in flow between 4% and 8% can likely be attributed to the rising viscosity of the binder.

3.3.3 Bulk Specific Gravity

Figure 7 illustrates that the bulk specific gravity of the asphalt mix decreases between 0% and 6% gum Arabic content, after which it begins to rise. Bulk specific gravity plays a crucial role in determining the strength of hot mix asphalt (HMA). Notably, maximum stability was observed at 2% gum Arabic, coinciding with a drop in bulk specific gravity. This suggests that at lower concentrations, gum Arabic may increase void content by reducing compaction and mix density. This effect is likely due to gum Arabic's reduced binding capability compared to traditional asphalt binder, resulting in more air voids within the structure. Despite the decrease in specific gravity, the mix retains strength, indicating the potential for a lightweight yet stable asphalt formulation. At 6% gum Arabic, the bulk specific gravity begins to rise, suggesting improved compaction and a shift toward more binder-like behavior. As gum Arabic content increases beyond this point, it appears to fill voids more effectively, increasing density. These variations in specific gravity directly impact flow behavior: reduced gravity enhances flexibility and deformation (higher flow), while increased gravity beyond 6% results in a stiffer, less deformable mix with lower flow values.



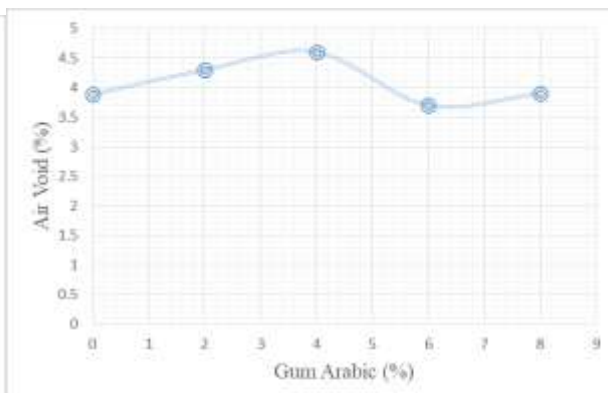


Figure 6: Bulk specific gravity of modified HMA Figure 8: Air voids of modified HMA

3.3.4 Air Void

The Air voids percentage in an asphalt mix refers to the empty spaces between the aggregate particles that are not filled with binder. These voids are critical for durability, compaction, and the overall performance of the pavement. From Figure 8, it is observed that the air voids in the hot mix asphalt (HMA) increase linearly from 0% to 4% and then begin to reduce from 4% up to 6%, where it rises again. The increase in air voids, especially early on, suggests less effective compaction due to the lower viscosity of gum Arabic, leading to a reduction in the load-bearing capacity, as seen in the corresponding drop in Marshall Stability after the peak (4%) and the easy deformation of the mix, hence the increase in flow. The reduction in air voids present could likely be due to the gum Arabic saturating the mix and reducing void spaces.

3.3.5 Voids in Mineral Aggregate (VMA)

The Voids in Mineral Aggregate (VMA) measures the volume of empty space between the aggregate particles in compacted asphalt. From Figure 9, the initial increase in VMA from 0% to 4% is due to higher viscosity, and the peak at 4% gum Arabic indicates the point where the binder content is optimal for coating aggregates, resulting in slightly higher voids within the aggregate structure. As the binder content increases, the excess gum Arabic starts filling more void spaces between the aggregate particles, leading to a decrease beyond 4%, suggesting that the mix has become more saturated with binder, reducing the voids between the aggregate particles. The decrease in VMA after the peak correlates with a drop in stability, suggesting that the gum Arabic is reducing voids but potentially weakening the structure by oversaturating the mix. Higher VMA corresponds to higher flow values, as the mix becomes less dense and more prone to deformation when the binder does not sufficiently fill the voids.

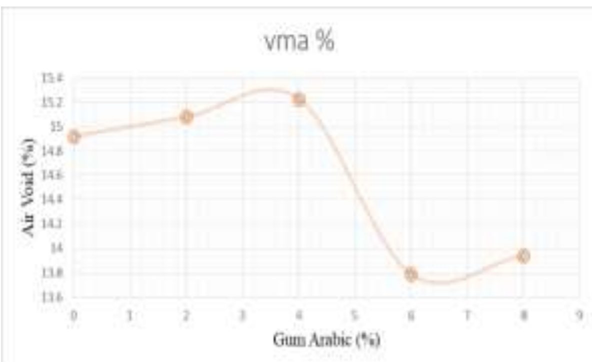


Figure 7: Voids in mineral aggregate

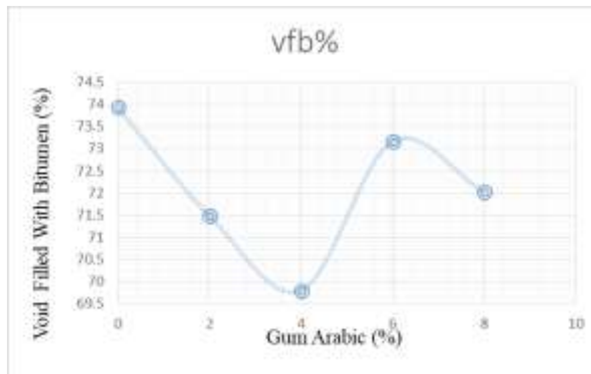


Figure 8: Voids filled with bitumen

3.3.6 Voids Filled with Bitumen (VFB)

Voids Filled with Bitumen (VFB) refers to the percentage of the voids in the mineral aggregate (VMA) that are occupied by bitumen, playing a vital role in the durability and impermeability of asphalt mixtures. VFB is inversely related to VMA, meaning that as VMA increases, VFB tends to decrease. From Figure 10, the VFB begins at 73.93% with 0% gum Arabic and decreases to 69.8% at 4%, after which it increases between 4% and 6%, followed by another decline. These fluctuations reflect the varying effectiveness of gum Arabic in filling the internal voids of the aggregate matrix.

At lower binder contents (0–4%), gum Arabic may not adequately coat the aggregate particles or fill the voids, resulting in reduced VFB. As the binder content increases beyond 4%, the gum Arabic appears to distribute more evenly and act more effectively, increasing the VFB and improving the mix's internal cohesion. However, beyond 6%, excessive binder may lead to oversaturation, which can reduce VFB again. The rise in VFB after 4% correlates with increased Marshall Stability, indicating a stronger, more stable mix. Conversely, when VFB decreases, the mix becomes more pliable and less stiff, leading to higher flow values and reduced structural integrity.

3.4 SEM and EDX Results

Plate 1 reveals a microstructure dominated by clumped, irregularly shaped particles with rough surfaces. These particles are tightly agglomerated, forming a dense and compact structure. In the absence of gum Arabic, the material displays minimal porosity and a rigid, uneven surface, indicating high particle cohesion and limited void spaces. In contrast, Plate 2 shows a more porous structure with small voids dispersed throughout. Although still relatively compact, the material

presents a smoother, more uniform texture, suggesting that the addition of gum Arabic begins to alter the internal structure by reducing particle agglomeration and introducing some void content. Plate 3 exhibits a significant transformation in microstructure. With 6% gum Arabic, the material becomes notably porous and fibrous, characterized by visible streaks or aligned fibers. This indicates a substantial reduction in density and a more fragile internal framework. Larger and more defined voids are evident, marking a stark contrast to the dense structure observed at 0%.
Overall, increasing gum Arabic content leads to greater porosity and structural alignment. The surfaces become smoother and less compact, with particles appearing less clustered. The progressive incorporation of gum Arabic significantly modifies the material's microstructure, potentially influencing its mechanical behavior by making it lighter and more flexible, but possibly less durable.

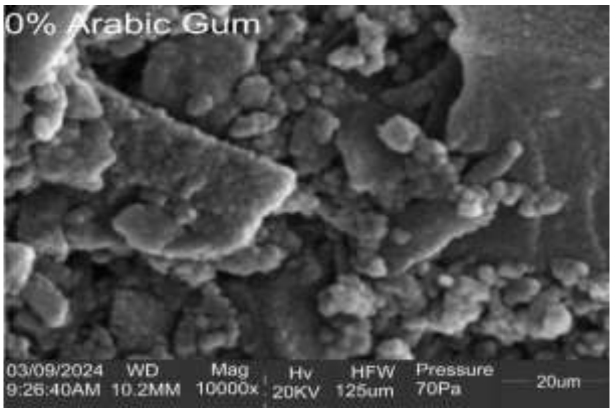


Plate. 1 : SEM Image for 0% gum Arabic

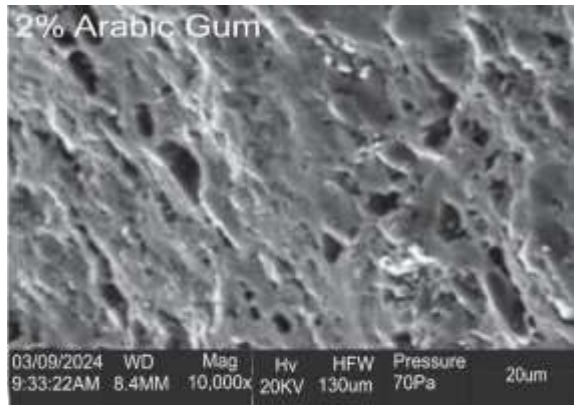


Plate. 2: SEM Image for 2% gum Arabic

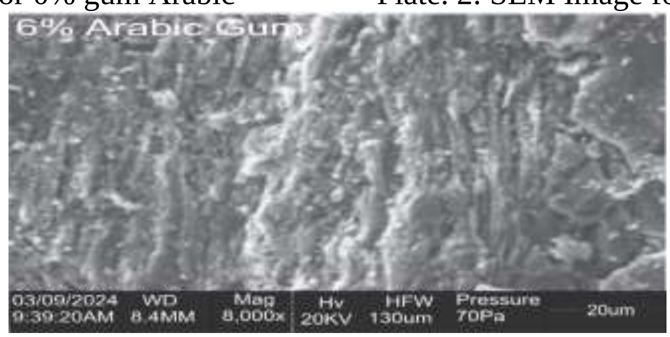


Plate. 2: SEM image for 6% gum Arabic as partial replacement for bitumen

Table 4: Summary of properties of modified HMA.

Properties	Wearing course Specification [19]	0%	2%	4%	6%	8%
Marshall stability (KN)	Min 8.0	16.87	20.56	17.55	17.45	15.04
Flow (mm)	2 – 4	3.446	3.759	4.708	3.313	2.76
Bulk Specific Gravity	2.20 - 2.50	2.346	2.341	2.327	2.313	2.322
Voids in Mix (V.I.M) %	3 – 5	3.89	4.3	4.6	3.7	3.9
Voids in Mineral Aggregate (VMA) %	Min 13	14.92	15.08	15.23	13.79	13.94
Voids filled with bitumen (VFB) %	65 – 75	73.93	71.49	69.8	73.17	72.02

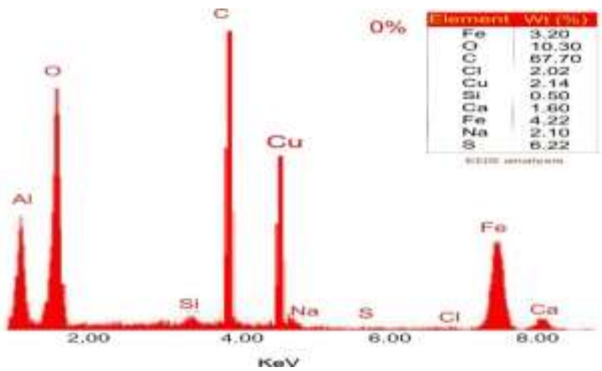


Plate 4: EDX image for 0% gum Arabic

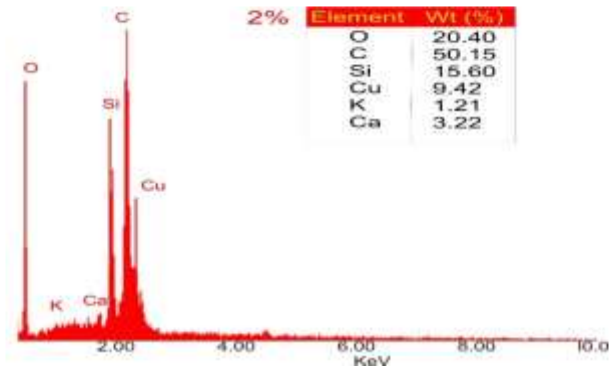


Plate 5: EDX image for 2% gum Arabic

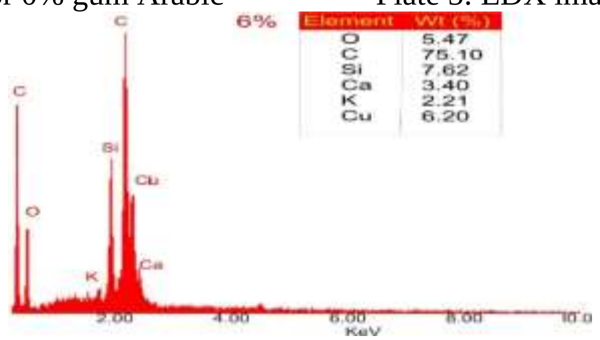


Plate 6: EDX image for 6% gum Arabic

4.0 Conclusion

This research examined the evaluation of biopolymer modified hot mix asphalt (HMA). A preliminary laboratory test was carried out on all materials to determine their suitability for use in hot mix asphalt (HMA) according to standard specifications after which hot mix asphaltic cores were produced according to the Marshall Mix design method. The bitumen modifier (Gum Arabic) affects the Hot Mix Asphalt production, it increases the binding properties between the aggregate and the bitumen thereby increasing the stability and flow of asphalt mixture at lower concentrations although at higher concentration, it reduces both stability and flow. The bitumen modifier, Gum Arabic also reduced the bulk specific gravity at lower concentrations with no adverse effect on the strength resulting in lightweight aggregate.

Hot mix asphaltic core samples prepared with bitumen modifier (gum Arabic) at 2% showed the best performance in comparison with the control sample with 0% gum Arabic content and meets the performance requirements for use in flexible pavement surfacing. The modifier can be further researched upon so it can be adopted in commercial production of Hot Mix Asphalt as it leads to a reduction in production cost.

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