Optimum Gum Arabic Content as Bitumen Modifier in Hot Mix Asphalt

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Abstract

Roads in Nigeria and like any other developing country are hugely plagued with deterioration and damage due to excessive traffic beyond design load, environmental conditions and their interactions as well as low budgetary allocation for routine/preventive maintenance. In order to address the problems, researchers/practitioners in the highway community have engaged in the use of admixtures and waste material to enhance the properties of paving materials while reducing the cost of production. This study investigates the suitability of Gum Arabic (GA) also known as acacia gum to be used as bitumen modifier in Hot Mix Asphalt (HMA). GA is a natural material consisting or hardened sap of various species of acacia. Its glue or binder property makes it a potential material for use as a modifier in HMA. In order to determine the performance of asphalt concrete mix containing GA as modifier, 0%, 2.5%, 5%, 7.5% and 10% GA (by weight of bitumen in asphalt concrete mixture) were added at bitumen contents of 4.5%, 5.5%, 6.5% and 7.5% each. Marshall parameters (stability and flow) and volumetric properties of the asphalt mixtures were used to evaluate the performance of GA as modifier and determine the optimum GA content. The study revealed that asphalt concrete mixture prepared using 2.5% GA at a bitumen content of 6.5% performed better than the control sample (0% GA content) based on the evaluation parameters. This can be recommended for use in surfacing of heavily trafficked flexible pavements.

Keywords
Gum Arabic, Bitumen modifier, Marshall mix design, Hot mix asphalt

1. Introduction
Transportation is cardinal in assessing the growth of any country. Highway transport mode in Nigeria, and many developing countries, accounts for 95% of all transport movements and this is not without the inevitable consequences of pavement failures influenced by material properties, excessive traffic loading and environmental factors (Otuoze and Shuaibu, 2017).

Bituminous pavement surface is susceptible to temperature and loading variation because of its viscoelastic and possibly plastic properties (Rais et al., 2013). The pavement performance in service is significantly affected by the laying temperature of asphalt concrete, which reduces its stiffness. The stiffness of asphalt concrete layers in a pavement structure dramatically influences its structural capacity. As the temperature of asphalt increases, the stiffness decreases, leaving it less able to withstand wheel load (Cuadri et al. 2014). A decrease in asphalt concrete stiffness results in higher stress being transmitted to the base and subgrade layers, thus, affecting the pavement performance.

Conventional asphalt pavements lack the mechanical strength, service requirements and longevity to withstand heavy traffic loading, varying regimes of temperature loading and distresses induced by climatic and environmental conditions (Gökalp, 2021). In addition, the cost of constituent materials that make up the asphalt mixture is another problem, thus, prompting the need to incorporate cheaper/waste materials as partial or whole substitutes for the convectional materials while maintaining/improving the desirable properties of asphalt mixtures.

Researchers and practitioners in the highway community have long been engaged in the use of substitute materials as either partial replacement or modifiers for binder (bitumen) with the objective of improving performance of asphalt concrete. A number of polymers and fiber materials such as thermoplastics – ethylene vinyl acetate (EVA), low density polyethylene (LDPE), high density polyethylene (HDPE) and ethylene-propylene-diene (EPDM) have been used in asphalt mix (see e.g., Hu et al. 2018; Nizamuddin et al. 2020; Ansari et al. 2021). Elastomers like styrene butadiene- styrene (SBS), styrene-butadiene random copolymers (SBR) and styrene-isoprene-styrene (SIS) and poly-butadiene-base materials have also been used (see e.g., Hamzah et al., 2006; Otuoze and Shuaibu, 2017, Zhou et al., 2021).

The use of natural polymer such as Gum Arabic (GA) as bitumen modifier in hot mix asphalt (HMA) has not been explored. However, the binding property of GA has adequately been established in several works (Agnihotri et. Al., 2021).

Gum Arabic is the complex exudate of *Acacia senegal* and *Acacia seyal* tree. Gum Arabic is a complex mixture of glycoproteins and polysaccharides predominantly consisting of arabinose and galactose (Kadowaki et al. 2022). This dried sap which is widely harvested in Africa and Western Asia has immense commercial value as a global commodity as it has found usage in the food industries (Patel and Goyal, 2014), modification of polyethylene terephthalate surfaces (Caykara et al. 2021), coating material (Fardhyanti et al. 2022), nanoparticles dispersing agent (Kadowaki et al. 2022) and anti-corrosive material (Verma and Quraishi 2021).

2. Materials and Methods

2.1 Materials

Conventionally, HMA is a mixture of bitumen (binder), aggregates (fine and coarse) and mineral filler. In this research, Gum Arabic is also incorporated into the mixture as a bitumen modifier. Detailed description on material sourcing and processing is given in the next sub-sections.

2.1.1 Bitumen

Bitumen used in this research was obtained from Nigerian National Petroleum Corporation (NNPC) refinery, Kaduna, Kaduna State. Table 1 shows the physical properties of the bitumen. The bitumen is a 100/120 penetration grade bitumen and satisfies all standard requirements for use as binder in HMA.

Table 1. Physical Properties of bitumen

Test	Test Method	Code Limit	Test Value	Remark
Penetration @ 25^0c (mm)	ASTM D5 (1997)	100 –120	120	Satisfactory
Softening point (^{0}c)	ASTM D36 (2000)	42 – 49	42	Satisfactory
Flash point (^{0}c)	ASTM D92 (2002)	250	246	Satisfactory
Fire point (^{0}c) min	ASTM D92 (2002)	250	242	Satisfactory
Solubility in tetrachloroethylene (%) min.	ASTM D2042 (2015)	99.5	99.53	Satisfactory
Specific gravity	ASTM D70 (2003)	1.01-1.06	1.01	Satisfactory
Ductility at 25^0c (mm)	ASTM D113 (2017)	100	109.2	Satisfactory
Viscosity at 60^0c (mm^2/sec)	ASTM D4402 (2015)	N/A	146	Satisfactory

2.1.2 Aggregates

Coarse aggregates used in this research are crushed stones obtained from a quarry site along Kaduna – Zaria Road, Kaduna state. The fine aggregate is a river sand obtained from Rahusa block Industry in Zaria, Kaduna state. Table 2 shows the physical properties of the aggregates and their conformity for use as aggregates based on the Nigerian General Specification for Roads and Bridges, FMWH (2016).

Table 2. Physical Properties of Aggregates

Test	Test Method	Code Limit	Test Value	Remark
Aggregate Crushing value (%)	BS 812 p.112 (1990)	Max 25	22.12	Satisfactory
Aggregate Impact Value (%)	BS 812 p.111 (1990)	Max 25	21.31	Satisfactory
Specific gravity (coarse)	ASTM C 127 (2015)	2.55-2.75	2.72	Satisfactory
Specific gravity (fine)	ASTM C128 (2015)	2.55-2.75	2.57	Satisfactory

Sieve analysis is carried out on samples of both aggregates (fine and coarse aggregates) and Figure 1 shows the particle size distribution curve for the fine aggregate. The fine aggregate could be classified as well-graded aggregate. Figure 2 shows that the gradation curve of the coarse aggregate with maximum aggregate size of 20mm.

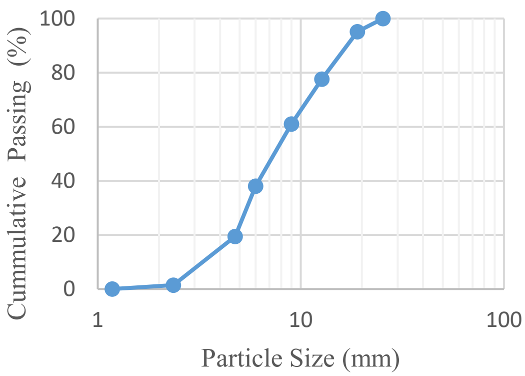

Figure 1. Gradation curve of coarse aggregate

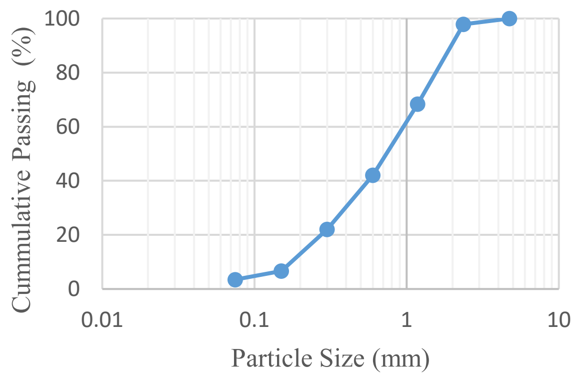

Figure 2. Gradation curve of fine aggregate

FMWH (2016) requires that the two aggregates are proportioned and blended to achieve an all-in-aggregate satisfying certain gradation limit (gradation envelope is as shown in Figure 3). In this research, a trial-and-error proportioning was done to achieve this. The gradation curve of the obtained all-in-aggregate is shown in Figure 3 with the FMWH (2016) gradation envelope.

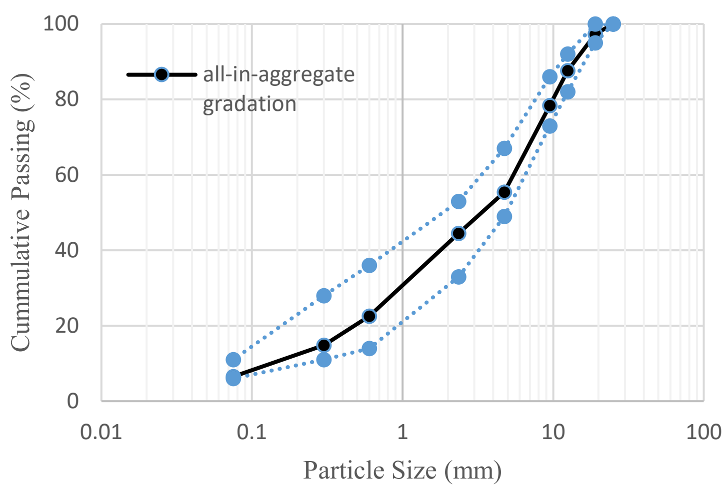

Figure 3. Gradation curve of all-in-aggregate

2.1.3 Filler

A brand of Portland limestone cement obtained from open market in Zaria was used as filler in the hot mix asphalt. Conformity of the brand to Portland limestone cement was ascertained through conformity tests prescribed in BS EN 196:3 (2016) and reported in Table 3. The cement is then sieved through BS sieve No. 200 to ensure only particles with diameter less than 75 µm are used as filler.

Table 3. Results on conformity test on filler material

Test	Test method	Code limit	Test value	Remark
Initial setting time	BS EN 196 p.3 (2016)	>45 mins	89 mins	Satisfactory
Final setting time	BS EN 196 p.3 (2016)	<10 hrs	2 hrs 31 mins	Satisfactory
Soundness	BS EN 196 p.3 (2016)	<10 mm	4 mm	Satisfactory
Specific gravity	ASTM C188 (2017)	3.15	3.15	Satisfactory

2.1.4 Gum Arabic

Gum Arabic in its raw form was obtained from open market in Funtua, Katsina state. It is ground to obtain particles less than 75 µm. The choice of particle size is strictly guided by the desire of achieving sample homogenization when the modifier is added to the bitumen. Table 4 shows the oxide composition of the modifier. When introducing the modifier to the bitumen, the methodology prescribed by Porto et al., (2019) was adopted.

Table 4. Oxide composition of Gum Arabic

Oxide	SiO_2	SO_3	K_2O	CaO	TiO_2	MnO	Fe_2O_3	CuO	GeO_2	Al_2O_3
Concentration (%)	13	0.54	16.9	28.5	0.51	19.0	7.14	1.7	2.9	9.8

2.2 Mix design

Marshall mix design method was used to prepare asphalt concrete mixes using mix proportions prescribed for heavily trafficked pavements in FMWH (2016). To determine the optimum bitumen content (OBC), 12 samples (3 at each bitumen content between 4.5 – 7.5% in increments of 1%) were prepared for Marshall test in accordance to Asphalt Institute (1997). The OBC was determined as 6.5% as shown in Table 5.

Table 5. Determination of optimum bitumen content

Test property	Bitumen content (%)
Max. stability (kN)	6.5
Max. bulk density (g/cm^3)	7.5
Median % air voids	5.5
OBC = (6.5+7.5+5.5)/3 = 6.5%	

This optimum binder content (6.5%) is then used to determine the optimum modifier (gum Arabic) content. For this, 12 samples of HMA were prepared (3 at each modifier content ranging between 2.5 – 7.5% in increments of 2.5%). These samples were subjected to Marshall test to evaluate the effect of the modifier on the asphalt concrete Marshall values and volumetric properties.

3. Results and Discussion

In this section, results of Marshall tests on HMA samples containing the modifier are presented and discussed. Properties of the HMA samples assessed are stability, flow, bulk density, Percent air voids (or voids in mix, VIM), voids in mineral aggregate (VMA) and voids filled with bitumen (VFB).

Stability is defined as the maximum load carried by a compacted specimen tested at 1408F at a loading rate of 2 in./min. The two primary factors in determining the stability are the angle of internal friction of the aggregate and the viscosity of the bitumen. The sudden increase in stability at 2.5% GA content could be attributed to increase in viscosity of the asphalt mastic (Figure 4). Beyond this modifier content, a decreasing trend could be observed in stability values of HMA samples. This decrease could likely be as a result of change in rheological properties of the bitumen occasioned by excess amount of polysaccharide (in the modifier). Similar decrease in viscosity caused by excess polysaccharide content has been reported in Porto et al., (2019).

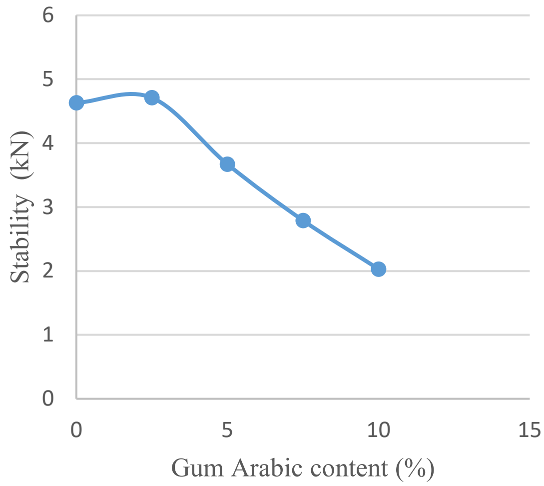

Figure 4. Marshall stability of modified HMA

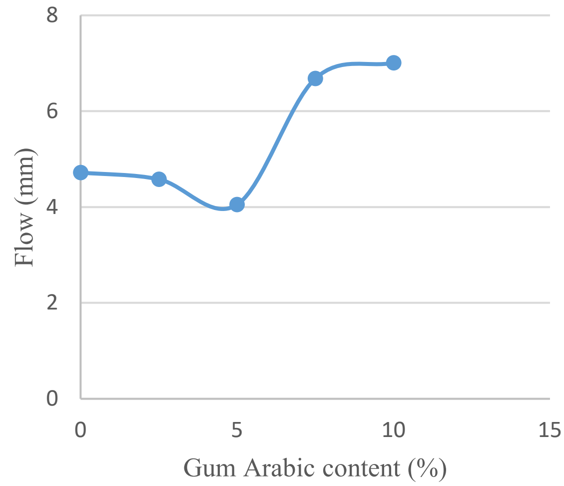

Figure 5. Flow of modified HMA

Flow is the vertical deformation of the HMA sample at failure. Viscosity of HMA binder also strongly influences flow of HMA samples. Generally, more viscous asphalt mixes tend to have lower flow values. Figure 5 shows how this HMA property varies with GA content. The initial decrease in flow between 0-5% GA content could be attributed to increase in viscosity of the bitumen by the modifier. Flow values of HMA samples prepared with GA content above 5% exceeded that of the control sample. This could be attributed to loss in viscosity occasioned by saturation of the bitumen with polysaccharide. The bulk specific gravity of a HMA sample is an important volumetric property that influences the strength of HMA. Generally, higher unit weight values are desirable which indicate greater strength. However, with lightweight construction, even greater strengths could be achieved with lower unit weight values. Comparing Figures 4 and 6, an increase in stability (strength) is recorded at 2.5% GA content. However, this increase is accompanied by a decrease in unit weight of the sample at the same GA content. The modifier could be said to have an effect of increasing the void spaces in the asphalt concrete without detrimental effect on strength.

This assertion is further strengthened with the fact that the plot of voids in mix (Figure 6 and 7) shows an increase in the total voids in the mix at this modifier content. A certain percentage of voids is desirable in compacted HMA to allow for movement of unabsorbed bitumen (through spaces created by the voids) during post-construction compaction of pavement by traffic and weather-induced asphalt expansion. The durability of an asphalt pavement is a function of this HMA property. The lower the air-voids content, the denser the mix (less permeable). Too high air-voids content will provide passageways for air and water and leads to durability problems. Too low air-voids content is also undesirable as it leads to bleeding; where the unabsorbed bitumen bleeds out to the surface of the mix.

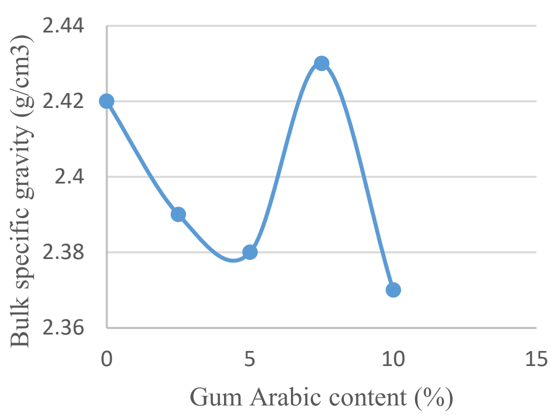

Figure 6. Bulk specific gravity of modified HMA

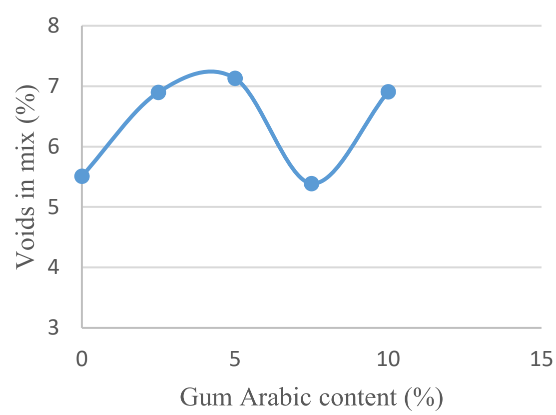

Figure 7. Voids in mix (VIM) of modified HMA

Voids in mineral aggregate (VMA) represents the volume of intergranular void space between the aggregate particles of a compacted asphalt concrete. This volume includes the air voids and effective binder content, expressed as a percent of the total volume of the sample. Figure 8 shows how this HMA design parameter varies with modifier content. The initial increase in VMA could be attributed to the increase in viscosity of the bitumen which increases the bitumen-film thickness on coated aggregates. After the saturation of the bitumen with modifier (beyond 5%), a decrease in VMA is observed (Table 6).

Table 6. Requirement of HMA for use in flexible pavement surfacing (FMWH, 2016)

Property	Binder course	Wearing course
OBC (%)	4.5 – 6.5	5.0 – 8.0
Stability (kN), not less Than	3.5	3.5
Flow (mm)	2 – 6	2 – 4
Voids in total Mixture (%)	3 – 8	3 – 5
Voids filled with Bitumen (%)	65 – 72	75 – 82

Figure 9 on the other hand, shows the variation of VFB with GA content. Since VFB is largely depended on VMA, and has a strong correlation with VIM, it is expected that an increase in air voids (Figure 8) should be accompanied by a decrease in VFB since most of the voids in the compacted asphalt are occupied by air. However, requirements on VFB are usually put in place to avoid less durable HMA resulting from thin films of binder on the (coated) aggregates.

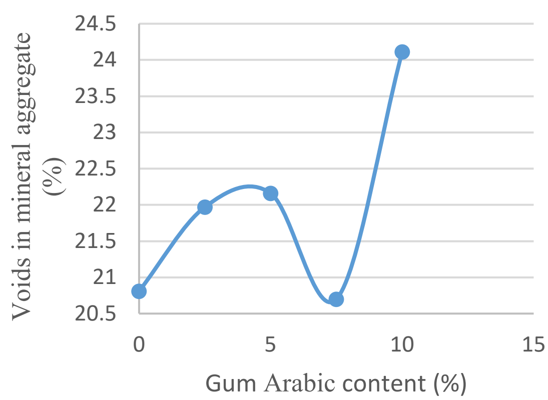

Figure 8. VMA of modified HMA

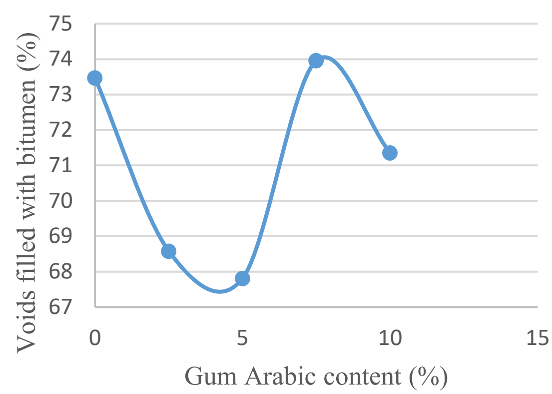

Figure 9. VFB of modified HMA

4. Conclusion

In this research, the influence of gum Arabic as a bitumen modifier in hot mix asphalt was investigated. Hot mix asphalt was prepared according to the Marshall mix design method. Preliminary tests were performed on all constituent materials to determine their conformity for use in hot mix asphalt according to relevant standards. The tests revealed that all the constituent materials are suitable for use in HMA.

Results on Marshall analysis show that Gum Arabic at lower concentrations increases the stability and reduces flow of HMA. This improvement is attributed to increase in viscosity caused by presence of polysaccharide in GA. However, at greater concentrations of GA, an excess amount of polysaccharide resulted in decrease in stability and increase in flow of HMA samples. On volumetric properties, GA at lower concentrations increases the air voids in compacted HMA samples forming stronger lightweight asphalt concrete.

HMA samples prepared with modified bitumen containing 2.5% GA showed superior performance compared to the control sample (0% GA content) and satisfy the performance requirements for use in flexible pavement surfacing (Table 6).

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