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AN EXPERIMENTAL STUDY ON THE USE OF POLYPROPYLENE WASTE IN BITUMINOUS MIX

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ABSTRACT

The work focuses on assessing the Marshall properties of High Density Polypropylene (HDPP) waste and its potentiality to mitigate pavement failures due to environmental and traffic loading. Based on design, 4.5, 5.0, 5.5, 6.0 and 6.5% bitumen contents were arbitrarily selected to prepare one hundred and five (105) Marshall specimens having respectively 0, 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0% HDPP waste in Polymer Modified (PM) asphalt concrete. The specimens were tested for stability, flow, compacted density of the mix (CDM) and void analysis. Optimum parameter for Marshall properties obtained are 27.68kN, 2.54mm, 2.45g/cm^3, 3.39%, 16.2% and 74.10% respectively for stability, flow, CDM, VIM, VMA and VFB. The results revealed enhanced engineering properties of 2% HDPP at an optimal bitumen content of 5.5% and could satisfy strength and durability requirements of heavy traffic situation.

Keywords: *High Density Polypropylene, Bitumen, Asphalt, Strength*

NOTATIONS:
HDPE: High Density Polyethylene
LDPE: Low Density Polyethylene
VIM: Void in Mix
VFB: void Filled with Bitumen
VMA: Void in Mineral Aggregate
CDM: Compacted Density of Mix
EAL: Equivalent Axle Load
PM: Polymer Modified

1. INTRODUCTION

Transportation in all history has remained the cornerstone of civilization and an index of economic growth and development of every nation [1]. Highway transport mode in Nigeria, like many developing countries, accounts for 95% of all transport movements and this is not without the inevitable consequences of pavement failures induced by material properties, excessive traffic loading and environmental factors [2 – 4].

Though, long term cost puts rigid pavement at comparative cost advantage, flexible pavement still remains the choice of low income countries because of its lower initial cost of construction. Although, about N1.4 trillion had been appropriated for investment in the road sector infrastructures between 1999 and 2012 by Nigerian federal government [1], distresses like ravelling, cracking, rutting, creep, corrugation, stripping and pot-holing are some of the major service problems of the roads leading to high rates of accident [5].

Pavement is the structural materials laid down on an area intended to sustain vehicular or foot traffic, such as a road or walkway and its structure normally consists of a few layered materials arranged from the topmost (surfacing) in the order of strength to ensure adequate stability under traffic loads [6]. A number of factors such as poor materials selection and quality, design and construction lapses, climatic factors; maintenance negligence and excessive traffic loading are responsible for pavement failures [7]; [5]. Increasing vehicular traffic volume on roads as the main source of connectivity and inefficient stake of government on public transport has increased the economic malady and lack of return on investment as pavements fail to reach the design life [8]. Also, constant overload beyond 80 kN (Nigerian legal axle limit) by trucks has made design projection life meaningless [9]. In view of that, efforts to strengthen and increase pavement life have become enormous challenge to government, road agencies and researchers.

It is important to use mixes flexible enough at low service temperature to reduce excessive failures like pavement cracking and to be stiff enough at high service temperature to prevent creep, rutting which are time and temperature dependent [10]. Pavement distresses and poor performance of bituminous mixtures under increased traffic volume and heavy axle loading have led to increased development and usage of bitumen modifier

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[11] and fibre reinforcement [12] for bituminous mixtures.

A number of polymers and fibre 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. 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[11]. Others are asbestos, glass, carbon and cellulose fibres which also impact on the desired properties of pavement and suffice to mitigate the distresses. The materials have been used either as bitumen modifier called wet process [13]; [14]. or fibre reinforcement called dry process [15]. The ultimate goal of introducing the materials into asphalt mix is to increase the service life of the pavement by preventing creep and fatigue failures and reflective cracks.

Approximately 30,000,000 tons of HDPP was consumed worldwide in 2001 and the products generate monumental waste disposal and environmental problems after their use [16].In Nigeria, polypropylene production has been largely dependent on the two local petrochemical industries in Eleme and Warri with production capacities of 90,000 and 35, 0000tons per annum respectively [43]. Polypropylene (PP) is known to have good heat and chemical resistance; resistance to deformation at elevated temperatures, high stiffness, surface hardness and toughness at normal temperature [17].The differences between HDPP and LDPP are the densities and crystalline or amorphous structure depending on the desired phase. The focus of this research is to evaluate the potentials of HDPP waste which is more abundant and readily available than LDPP to mitigate pavement distresses. The research is aimed at assessing the possibility of using HDPP waste to improve engineering properties of asphalt concrete.

2. LITERATURE REVIEW

2.1 Bitumen

[18] depicted bitumen as having "colloidal system, with asphaltenes forming the centres of micelle and having a more pronounced aromatic nature. The asphaltenes are assumed to be surrounded by lighter constituents of less aromatic nature, and there were no distinct interphases between micelles and the medium surrounding it". Micelles may be visualized in terms of surfactants or compounds that lower surface or interfacial tension and an aggregation of colloids or surfactant molecules coming together from association of several unit cells [19].

Basically, three constituent mixtures are largely identified in bitumen – asphaltenes, asphaltic resins and oily constituents (aromatics and saturates).The acronym (SARA's) was conveniently used by [20]; [21] to depict the presence of saturates (S), aromatics (A), resins (R), and asphaltenes (As) in bitumen.

2.2 Characterisation of Polypropylene Material

Polypropylene is one of the most widely used polymers in the world because of the widespread availability and low manufacturing cost. The reactivity of propylene is a result of the olefinic double bond in methyl-ethylene ($H_2C=CHCH_2$), which gives rise to addition reactions. With respect to the regularity of the methyl group placement relative to the other methyl groups along the chain backbone otherwise called the stereospecificity of the polymerization, [22] provided the models of three limiting classifications of stereospecificity in PP – isotactic polypropylene (iPP), syndiotactic polypropylene (sPP) and atactic polypropylene (aPP).

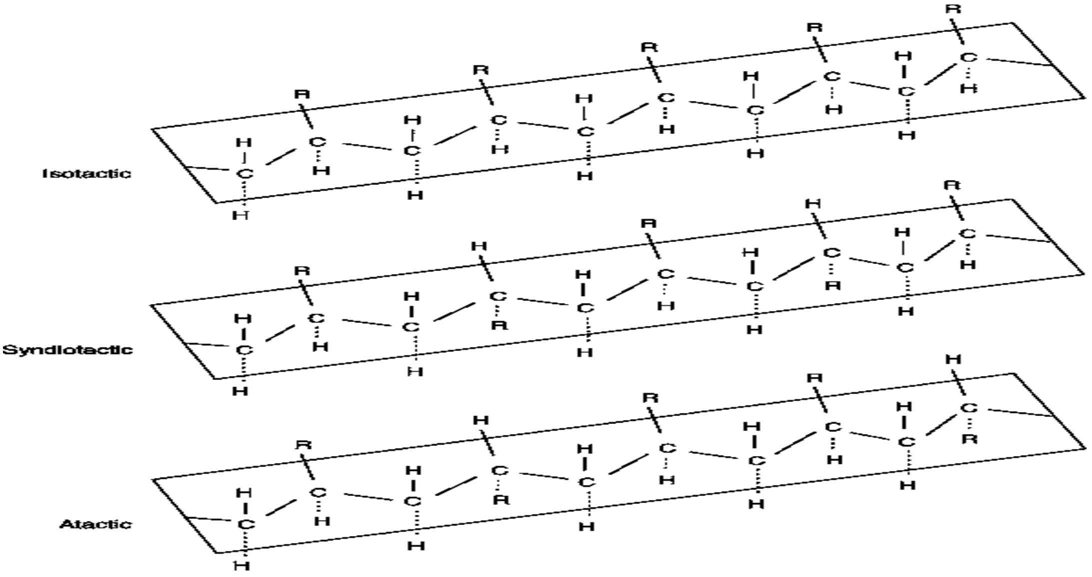


Figure 1: Strucures of (iPP), (sPP) and (aPP) {Source: [22]}

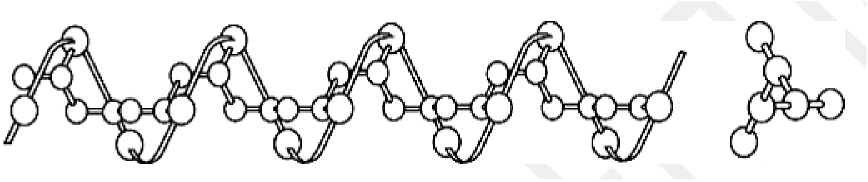


Figure 2: Conformation chain of (iPP) - {Source: [23]}

The isotactic polypropylene (iPP) has all of the methyl groups having the same configuration with respect to the polymer backbone while syndiotactic polypropylene (sPP) has the methyl groups have alternating configurations. The atactic polypropylene (aPP) has a random configuration. iPP is overwhelmingly the most commercially significant form of PP for most products [23]and[24]Figure 1 shows the Strucures of (iPP), (sPP) and (aPP) isomers [22]. Figure 2 is the depiction of chain conformation of isotactic polypropylene (iPP). The density (ρ) of iPP in the α- form shows variation between the limit of 100% amorphous (ρa=0.850 to 0.855 g/cm^3) and 100% crystalline (ρc=0.936 to 0.946 g/cm^3) [25].In this way, the measured mass density ρ gives a measure of the crystallinity. Density gradient techniqueis mostly used to measure ρ-values [26].

3. METHODOLOGY

Preliminary tests were conducted on bitumen coarse and fine aggregates and filler in Department of Civil Engineering Ahmadu Bello University, Zaria. to ascertain whether they meet the qualities viable for use as satisfying the various code standards requirements.

3.1 Preliminary Test on HDPP Modified Bitumen

Tests were conducted to determine the consistency, purity and safety of unmodified and HDPP polymer modified bitumen (0–3%). The tests conducted were according to the recommendations of the American Society for Material Testing (ASTM) relevant code standards for the 60/70 penetration bitumen used. As shown in Table 1, the tests conducted are ductility, penetration, softening point, specific gravity, solubility and flash and fire point tests. Also, thin film oven test (TFOT) was included in the characterization of HDPP bitumen to evaluate the short term ageing which affects the durability of the mix.

3.2 Preliminary Tests on Mineral Aggregates

Strength characterization, shape, moisture absorption and gravity tests were conducted on aggregates to assess their quality. Table 2 shows the results of the tests with their respective code recommendations.

Table 1: Results of Consistency, Purity and Safety Tests of Bitumen

Test Conducted	ASTM Code	Code Used	Test Result for % HDPP						
			0	0.5	1.0	1.5	2.0	2.5	3.0
Penetration at 25 ˚C, 0.1mm	ASTM D5-97	60-70	67.7	62.9	53.8	45.2	38.5	30.9	22.5
Penetration Index (PI)	-	-2 to +2	-0.338	+0.239	+0.222	0.526	+1.516	+1.881	2.146
Softening point (˚C)	ASTM D36-95	46-56	50.5	53.6	55.3	58.7	66.0	71.3	77.8
Flash point (Cleveland open cup), ˚C	ASTM D92-02	Min. 232	295.2	311.4	317.0	322.6	330.9	335.6	342.5
Fire point Cleveland cup), ˚C	ASTM D92-02	Min. 232	306.5	317.2	326.8	334.7	341.5	349.6	358.4
Ductility at 25˚c, cm	ASTM D113	Min. 50	122.4	107.2	88.6	72.4	54.3	42.8	22.6
Specific gravity at 25˚C (g/cc)	ASTM D70	0.97 - 1.02	1.022	1.015	1.011	1.008	1.005	1.003	1.001
Solubility in trichloroethylene,%	ASTM D2042	Min. 99	99.02	-	-	-	-	-	-
Properties of residue Thin Film Oven Test (TFOT) - {Heating for 5hrs at 163 ^{o}C}									
Ductility at 25˚c, cm	ASTM D113	Min. 50	59.2	56.4	54.0	52.5	50.5	48.7	46.5
Retained penetration (% of original)	ASTM D5	Min. 54	78.3	72.6	65.9	59.4	56.0	50.2	44.8
Loss on heating (% by mass)	ASTM D6-95	Max. 0.5	0.23	0.25	0.38	0.41	0.42	0.46	0.59

3.3 Consistency Tests on Cement Filler

Tests conducted on cement filler include specific gravity, setting time and soundness and Table 3 shows the results.

3.4 Aggregate Material Sampling, Grading, Proportioning and Blending

3.4.1 Aggregate Sampling and Determination of Particle Size Distribution (PSD)

Aggregate materials were sampled according to the recommendation of BS [27] and particle size distribution was conducted according to [28].The result of PSD for Coarse and fine aggregates and cement filler are shown in Tables 4.

3.5 Design Bitumen Content

The method of [29]was used to estimate expected Design Bitumen Content (DBC) given by:

$$DBC = 0.035a + 0.04b + Kc + F \qquad (1)$$

Since a is the % of mineral aggregate retained on the 2.36mm sieve = 55.5%, b is the % of aggregate passing 2.36mm sieve and retained on 0.075mm sieve = 38%, c is the= % of mineral aggregate passing the 0.075mm sieve = 6.5%, K is the 0.18 for 6-10% passing the 0.075mm sieve = 0.18 and F is the 0-2% for absorption of bitumen = 0.7

Therefore,

$$DBC = 0.035\,(55.5) + 0.04(38) + 0.18(6.5) + 0.7 = 1$$
$$= 5.332 = 5.5\%\ (appr)$$

The recommendation of [29]requires two other points at 0.5% above and below the optimum DBC which serves as the optimum. Thus, the ranges of bitumen content to be adopted in the mix are 4.5, 5.0, 5.5, 6.0 and 6.5%.

Table 2: Result of Preliminary Test on Aggregate materials

Test Conducted	Code Used	Code Limits	Test Result
Aggregate Crushing Value (%)	BS 812 Part 112	Max. 25	22.8
Aggregate Impact Value (%)	BS 812 Part 111	Max. 25	16.3
Aggregate Los Angeles Abrasion Value (%)	ASTM C131	Max. 30	18.9
Specific Gravity (Coarse Aggregate) (G_c) g/cc	ASTM C127	2.55 – 2.75	2.70
Aggregate Moisture Absorption (%)	BS 812 Part 2	Max. 2	1.4
Coarse Aggregate Flakiness Index	BS812 Part 105	<35	26
Specific Gravity (Fine Aggregate) (G_f) g/cc	ASTM C128	2.55 – 2.75	2.63
Bulk Specific Gravity of Total Aggregate (Gsb), g/cc	ASTM C127	-	2.71

Table 3: Result of Preliminary Test on Cement Filler

Test Conducted	Code Used	Code Specification	Result Obtained
Specific gravity	ASTM C188	3.15	3.15
Initial Setting time (minutes)	BS EN 196 Part 3	Min. 45	98
Final Setting time (minutes)	BS EN 196 Part 3	Max 375	230
Soundness (mm)	BS EN 196 Part 3	Max. 10	3.5

Table 4: Combined Material Mix and Range of Specification Requirements

Sieve Size (mm)	Percentage Retained	Cumulative Percentage Retained	Cumulative Percentage Passing	Range of Percentage Passing (ASTM D3515)
25.00	-	-	100	100
19.00	2.7	2.7	97.3	95 – 100
12.50	9.7	12.4	87.6	82 – 92
9.50	9.2	21.6	78.4	73 – 86
6.30	12.7	34.3	65.7	-
4.75	10.3	44.6	55.4	49 – 67
2.36	10.9	55.5	44.5	33 – 53
1.18	12.0	67.5	32.5	-
0.60	10.0	77.5	22.5	14 – 36
0.30	7.7	85.2	14.8	11 – 28
0.15	6.2	91.4	8.6	-
0.075	2.1	93.5	6.5	6 – 11
Pan	6.5	100	-	-

3.6 Marshall Specimen Compaction

According to [30], specimen compaction is a function of design traffic category. Application of 35, 50 and 75 blows respectively on each side of specimen depicts light (<10^4EAL), medium (10^4 to 10^6 EAL) and heavy traffic (>10^6EAL) categories. VIM in the specimen correlates with the degree of compaction. Though, a VIM range of 3 to 5% which supports use of additives is suggested by [31]a moderate VIM of 4% shows that excessive cracking supported by upper limit (5% VIM) and plastic flow and bleeding supported by the lower limit (3% VIM) can be mitigated. [32] recommends 5% VIM for 75 blows if traffic is in excess of $5*10^6$ EAL.

4. ANALYSIS AND DISCUSSION

4.1 Bitumen test

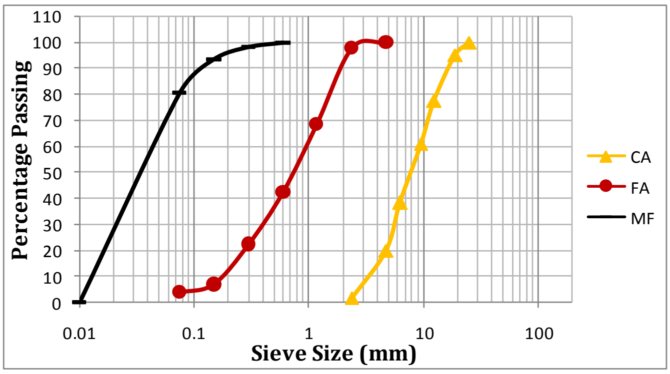
The test conducted on unmodified bitumen and HDPP modified 60/70 penetration bitumen used satisfied various codes requirements for ductility, penetration, softening point, specific gravity, solubility and flash and fire point tests. The factors that can affect ageing of bitumen are temperature, exposure to oxygen, UV light, chemical components and bitumen structure [33]. As the consequences of ageing, volatilization followed by oxidation and minor cases of polymerization impart on short and long term ageing of the bitumen binder during its service. From TFOT conducted to simulate short term ageing, 0 to 2.5% HDPP modified bitumen did not have considerable loss of volatiles which agrees with [34], but 2.5% HDPP content led to changes in physical and rheological characteristics exhibited by loss of ductility, elasticity and retained penetration. Considering the recommendations of penetration grades bitumen [32], an optimum HDPP content of 2.0% meets TFOT requirements for retained penetration, ductility and loss in mass.

4.2 Preliminary Tests on Mineral Aggregates

According to Aggregate suitability affects physical and mechanical properties and durability of asphalt [35]. Mineralogy cum petro-graphic nature of rock formation as well as shape and size impart on strength, traffic wear and weather resistance of aggregates in asphalt [36, 37].Strength tests carried out on mineral aggregates presented in Table 2 satisfied relevant codes recommendations adjudging that the material is strength, tough, dense and abrasion resistant and can stand the test of both serviceability and durability requirements of asphalt mixtures within the designed life.

4.3 Aggregate Grading and Blending

The results of coarse and fine aggregates and filler material grading are shown in Figures 3. The figure is the combined aggregate envelope and the distribution of various materials. Figure 4 shows the blending of the materials which have been sandwiched between the envelope of the ranges of passing sieves sizes specified by [38].Aggregate grading is the foremost and most crucial factor affecting rutting and permanent deformation. Good bond enhancement of materials, interlocking friction grip and good packaging density are predicated upon the characteristics, nature and grading of aggregates [39]. The nature of aggregate skeleton imparts upon the matrix of the mix and structural benefit of strength and durability that withstand stresses from vehicle tire [40]. Grading in Figure 4 passes through the middle of the envelop while the closer the curve to lower limit, the more strength is compromised even as the voids reduces. Conversely, aggregate curve closer to the upper boundary of the envelop entrains more voids whole could affect the rate of oxidation and ageing of asphalt. As in Figure 4, the combined grading which passes through the middle of the grading envelop supports job mix formula and is considered to be rutting resistant [38, 40].



Figures 3: Grading curve for mineral materials

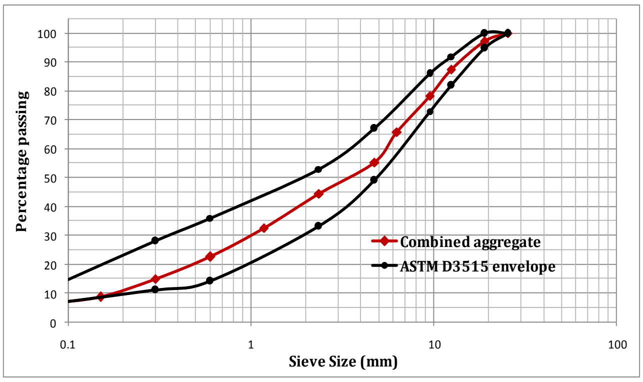


Figure 4: Combined aggregate envelope

CA: Coarse Aggregate, FA: Fine Aggregate and MF: Mineral Filler

4.4 Marshall Test Results for HDPP Polymer Modified Asphalt

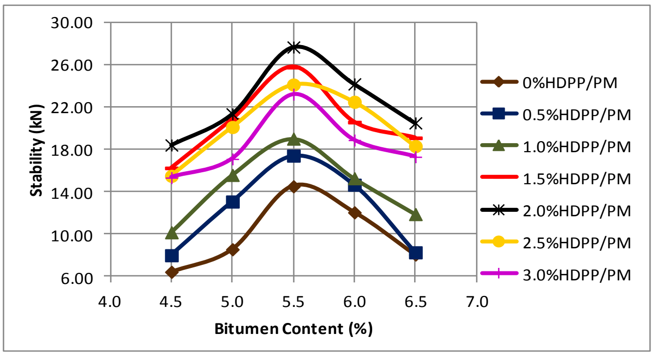
The results of stability, flow and volumetric analysis (VIM; void in mix, VMA; void in mineral aggregate and VFB; void filled with bitumen) for wet process (polymer bitumen) and dry process (fibre reinforced) asphalt concrete are shown in Figures 5 to 10. The summary of the findings as follows:

1. The result of stability steadily increased; reaching the optimum as HDPP content increased. The optimum stability for wet process is 27.68kN and this occurred at 2.0% HDPP content. The inclusion of HDD Paccounted for an improvement of 90.63% in strength compared to 0% HDPP (control). This agrees with the work of [41]. The optimum bitumen content is 5.5%. The initial increase is as a result of increase in surface tension which coagulates the loosely bonded molecular structure of bitumen. Beyond the optimum, the polymer bitumen becomes more plastic than viscoelastic.
2. The Compacted Density of Mix (CDM)of the mix decreased as HDPP increased. This is because incorporating HDPP which is less dense compared to the other components of the mix lowers the unit weight of the compacted asphalt mix irrespective of the percentage voids attained. The optimum bitumen content is 5.5%.Optimum CDM translates into adequate void which supports good internal strength and deformation to the optimum of stress bearing capacity [41].Before the optimum, the voids increases exposing the mix early oxidation of bitumen leading to stripping and cracking, but above optimum CDM, rutting is triggered by increasing bitumen content because of deformation susceptibility of bitumen even at ambient temperature [39]
3. Since the range of specification requirement of [30] for VIM is 3 – 5% and the average (i.e. 4.0% VIM) is usually preferred, Increasing HDPP content from 0 to 3.0% lowers what may be adjudged optimum bitumen and thus, reduced bitumen consumption as increasing HDPP increase toughness and lowering the voids entrained in the mix. Higher VIM values beyond the upper range 5% causes oxidation of bitumen and results to quick ageing and loss of durability while lower than 3.0% VIM causes fatigue cracking [32]. Optimum VIM strikes the balance between two extreme scenarios of stiffness leading to premature cracking on one side and excessive deformation flow because of excessive bitumen on the other [39]. Thus, an optimum VIM of in between the range of 3-5% would forestall against the two unfavourable failure scenarios – stiffness cracking and deformation.
4. The flow results at optimum bitumen content of 5.5% decreased from 2.8mm to 2.3mm respectively for increasing HDPP contents of 0 to 3.0% because of increasing interfacial tension created by surface tension and colloids of bitumen and polymer that forms increasing micelles of unit cells [19].This trend lowers deformation as micelle units galvanises the strength of the intermolecular bonds in the asphalt matrix even at increasing temperature defines its deformation resilience that lowers creep and rutting. When HDPP is high, the mixture becomes phase inversed leading to flocculation and destabilisation [42]. At this stage of phase separation, a transition from viscoelasticity phase to plastic phase mix occurs because of high stiffness which causes premature cracking [41].
5. Initially, as bitumen content increases, the value of VMA generally decreases down to ‘refusal density’. The optimum VMA occurs at the minimum point around the optimum bitumen content. Beyond this ‘refusal density’, a further increase in bitumen content increases VMA as a consequent of aggregate structure becoming overfilled with bitumen leading to deformation [28]. A minimum VMA of 12.0% at average 4.0% VIM is recommended by Marshall criteria for nominal aggregate size of 1” (25mm). For all HDPP contents of 0 to 3.0%, optimum VMA increased. These values meet the recommendation of the code [30]. VMA increased because the film thickness of coated aggregate and effective bitumen content that does not include absorbed bitumen increased. The optimum bitumen content is 5.5%.
6. At optimum bitumen content of 5.25%, the VFB for 0 to 2.0% HDPP asphalt concrete meet the Marshall criteria for heavy traffic whose values range between 65 to 75% VFB, according to code specification [30]. Higher values of VFB often lead to bleeding of bitumen and corrugation of asphalt pavement.

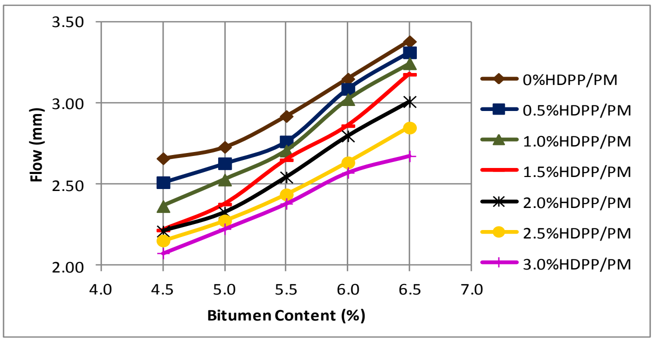
5. CONCLUSION

The following conclusions could be made from the research:

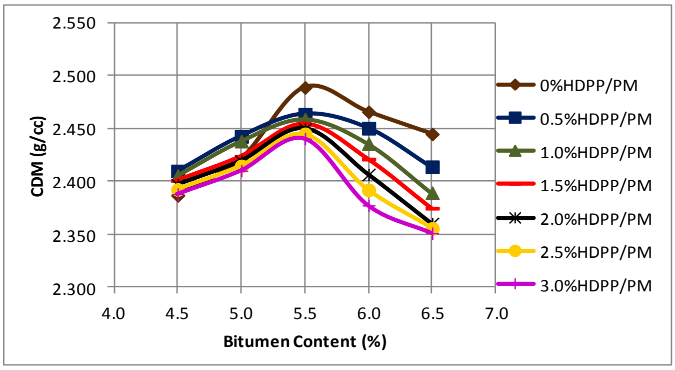
1. Thin Film Oven Test (TFOT) conducted for both pure and PM asphalt showed adequate age resistances for 0 to 2.5% HDPP contents that can withstand traffic loading, favorable service conditions and durability of asphalt.
2. For Marshall parameters for HDPP PM asphalt, 2.0% HDPP content gave improved stability increase of 92.5% and flow resilience or reduction of 13.0%.



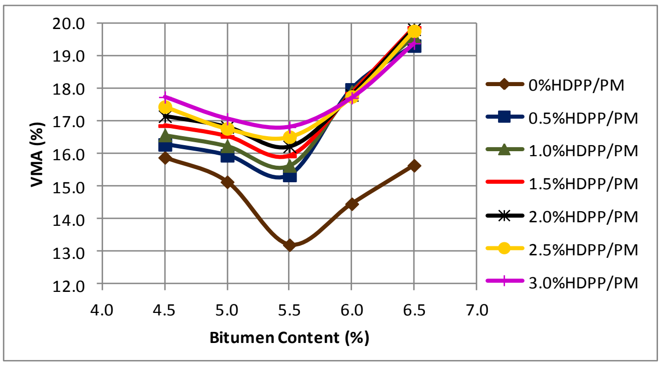
Figures 5: Relationship between Stability and Bitumen Content



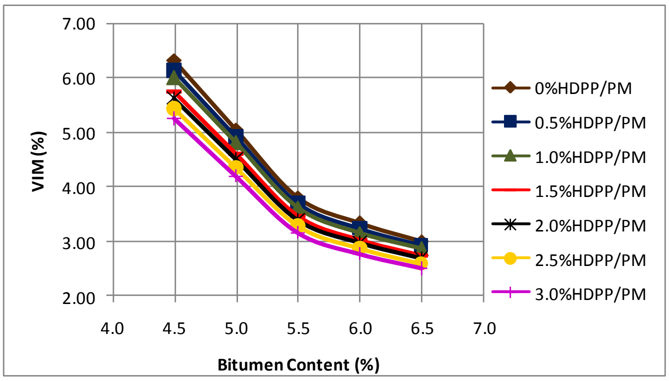
Figures 6: Relationship between Flow and Bitumen Content



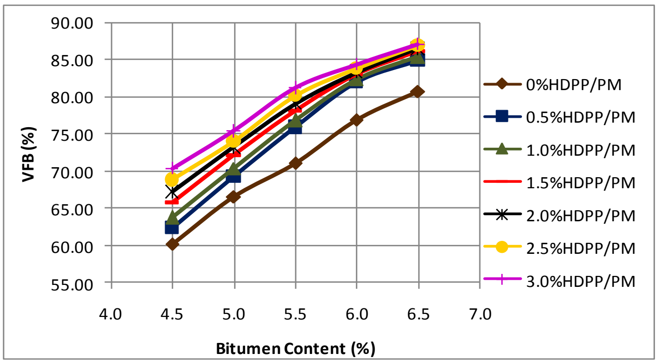
Figures 7: Relationship between CDM and Bitumen Content



Figures 8: Relationship between VMA and Bitumen Content



Figures 9: Relationship between VIM and Bitumen Content



Figures 10: Relationship between VFB and Bitumen Content

3. The void properties (VMA, VIM and VFB) are enhanced to resist moisture susceptibility and improve on durability.
4. The Results of both Marshall parameters and void analysis obtained are better enhanced with improved properties than 0% HDPP (control) and meets the Marshall specifications for Asphalt Institute, (1997) for heavy traffic situation of more than 10^6 ESAL considered and hence, could mitigate pavement distresses.

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