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A study on the mechanical and field performance properties of polypropylene fibres in asphalt mix

Hassan Suleiman OTUOZE[1]*, Stephen Pinder EJEH[2], Yusuf Dada AMARTEY[3],
Manasseh JOEL[4], Abdumumin Ahmed SHUAIBU[5], Shuaibu Asuku SULEIMAN[6] and
Abdulhafiz Michael ABANDA[7]

[1,2,3,5] *Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria.*
[4] *Department of Civil Engineering, Federal University of Agriculture*, Makurdi, Nigeria
[6] *Samaru College of Agric, Division of Agric Colleges, Ahmadu Bello University, Zaria.*
[7] *Department of Civil Engineering, Federal University of Technology, Minna, Nigeria.*
E-mail(s): [1] hassanotuoze@yahoo.com; [2] engrdrspejeh@yahoo.com;
[3] dadaamartey@yahoo.co.uk; [4] manassehjoel@yahoo.com; [5] abdulshub4u@gmail.com,
[6] asukus@yahoo.com; and [7] abanda_4real@yahoo.com
[*] Corresponding author, phone: +2348032895989

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Abstract

Researchers have been using polymers in asphalt mixes to improve both laboratory and field performance properties of asphalt. Polymer asphalt were known to mitigate traffic distresses and impart upon service life and durability of asphalt pavement. The study focuses on Marshall Test as key laboratory quality control index of asphalt and on simple performance test (SPT) characteristics of High Density Polypropylene (HDPP) waste as measure of durability. The Hot Mixed Asphalt samples were prepared using 0% (control), 0.5%, 1.0% and 1.5% HDPP fibre contents as percentages of the total asphalt mixes. Based on Asphalt Institute recommendations of 10^6ESAL for heavy traffic and optimum bitumen content 6.0% obtained, SPT's were conducted for rutting and indirect tensile strength to simulate field behaviour of the polymer asphalt. An optimum content of 0.5% HDPP enhanced both Marshall properties and SPT's requirements of HDPP asphalt than the conventional asphalt (control) and could mitigate pavement failures.

Keywords

Asphalt Mix; Distress; Polypropylene; Marshall Test; Simple Performance Tests; Indirect Tensile Strength; Rutting

Introduction

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 [1]. Distresses in asphalt pavements are major service problems of roads as the main source of connectivity in low income economies leads to high rates of accident [2]. Increasing vehicular traffic volume and high axle loading increased the economic malady and lack of return on investment as pavement fails to reach the design life and yield returns on investments [3].

Researchers, governments and road agencies have been challenged to improve, strengthen and increase pavement life to yield good service quality and durability requirement [4]. According to [5], pavement distresses and poor performance have led to increased use of fibre reinforcement for bituminous mixtures. A number of fibre materials such as 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. Others are asbestos, glass, carbon and cellulose fibres which also impart on the desired properties of pavement. [6] set the pace on strengthening and extending pavement life when he used wire mesh reinforcement in bituminous mixtures to improve upon resistance to pavement deformation and reflective cracking. Large interests apparently evolved in mitigating failures using different materials and different methods.

According to [7], fibres and polymers in asphalt mixture can help improve resistance to high temperature rutting, medium temperature fatigue and low temperature cracking thereby increasing the durability of pavement structure. In other words additives, such as fibres can increase the amount of strain energy absorbed during fatigue and fracture process of the mix in the resulting composite [8]. Also, fibres provide three-dimensional networking effect in asphalt concrete and stabilise the binder on surface of aggregate particles and prevent from any movement at higher temperature [9].

Among the researches existing researches, [10] studied the behaviour of mixtures of polypropylene and Aramid fibres to evaluate the performance characteristics of a modified asphalt mixture. The results showed that the fibres improved the mixture’s performance in several unique ways against the anticipated major pavement distresses: permanent deformation, fatigue cracking, and thermal cracking. In their test on Stone Mastic Asphalt (SMA) and glass fibre, [11] observed that the fibre has the potential to resist structural distresses that occur in road pavement as a result of increased traffic loading, thus improving fatigue life by increasing the resistance to cracking and permanent deformation especially at higher stress level.

Asphalt mixes generally improved in stiffness when 0.5% of the fibres were used to evaluate viscosity and complex shear modulus of fibre reinforced [4]. A great deal of enhancement on visco-elasticity which reduced the phase angle between stress and strain due to reduction in total and permanent strains were recorded. This leads to high resistance to permanent deformation in the fibre reinforced binders.

Specific industrial materials used for pavement strengthening are expensive. 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 [12]. 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 [13]. The differences between HDPP and LDPP are the densities and crystalline or amorphous structure depending on the desired phase.

The research is directed at evaluating potentials of converting HDPP waste into fibres for asphalt reinforcement to mitigate pavement distresses and the field performances. Various tests conducted are Marshall Test for laboratory control of quality as well as indirect tensile strength and rutting for simple performance test (SPT’s) criteria. Studies have shown that crack bridging activation and matrix micro-structural mechanical behaviour are SPT’s and age related and as such, the study focuses on synergy of both Marshall and SPT properties to evaluate the impact of PP fibre on strength, service and durability of asphalt mix.

Material and method

Test on bitumen

Table 1 shows ductility, penetration, softening point, specific gravity, solubility and flash and fire point tests are evaluations of grade, purity and safety respectively.

Table 1. Consistency, Purity and Safety Tests Values of Bitumen Sample

Test Conducted	ASTM Code	Code Values	Test Values
Penetration at 25^0C, 0.1 mm	ASTM D5-97	60-70	67.7
Penetration Index (PI)	-	-2 to +2	-0.338
Softening point (^{0}C)	ASTM D36-95	46-56	50.5
Flash point (Cleveland open cup) (^{0}C)	ASTM D92-02	Min. 232	295.2
Fire point (Cleveland cup) (^{0}C)	ASTM D92-02	Min. 232	306.5
Ductility at 25^0C (cm)	ASTM D113	Min. 50	122.4
Specific gravity at 25^0C (g/cc)	ASTM D70	0.97 -1.02	1.022
Solubility in trichloroethylene (%)	ASTM D2042	Min. 99	99.02

The tests conducted were according to relevant recommendations of code standards for the 60/70 penetration bitumen and were found to meet requirements of good control of quality of bitumen used.

Preliminary tests on mineral aggregates

Table 2 shows aggregate quality control in accordance to their respective code recommendations.

Table 2. Preliminary Test Values of 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
Specific Gravity of Mix Aggregates (Gsb) (g/cc)	ASTM C127	-	2.71

Strength characterization, shape, moisture absorption and gravity tests were conducted on aggregates to assess and were within ranges of code specifications to certify the aggregates good for the mix.

Consistency tests of cement filler

Tests conducted on cement filler include specific gravity, setting time and soundness using relevant codes and Table 3 shows the values obtained.

Table 3. Preliminary Test Values of Cement Filler

Test Conducted	Code Used	Code limit	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

The tests, having satisfied the quality of cement filler showed to it will impart on density and bond enhancement and improve the overall strength and stability of asphalt.

Aggregate material sampling, grading, proportioning and blending

Aggregate materials were sampled according to the recommendation of BS EN932-1 (2003) and particle size distribution was done according to BS EN 933-1 (2003). The passing sieve diameter (PSD) for Coarse, fine aggregates and cement filler are shown in Tables 4.

Table 4. Combined Aggregate Mix and Range of Specification Requirements

Sieve Size (mm)	Percentage Retained	Cumulative Percentage Retained	Cumulative Percent Passing	Percent 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	-	-

Combined aggregates fall within aggregate envelop safe zone formed by standard specification range and could be adjudged good for aggregate parking and interlocking.

Marshall Test experimental plan and specimen preparation

Asphalt Institute (1994) recommendations were used to prepare specimens weighing 1200g weight, 101.5mm diameter and 63.5mm height compacted with 75 hammer blows on each side to simulate heavy traffic situation of greater than 10^6 ESALs. The specimens are tested for bulk specific gravity in accordance with [14]. The specimens are kept immersed in water in a thermostatically controlled water bath at 60^0C for 30 to 40 minutes and then transferred within 30 seconds to the Marshall Test head and tested for both Marshall stability and flow in accordance with ASTM D1559 (2001). The volumetric tests carried out are CDM, VMA, VIM and VFB. Theoretical Maximum Specific Gravity of the Mix (G_{mm}) were determined using ASTM D 2041-95 and Bulk Specific Gravity or Compacted Density of the Mix (CDM) using ASTM D1188-96. ASTM D3203-94 was used to estimate Void in the Mix (VIM). ASTM D1559 (2004) was used to determine the stability and flow of specimens.

Indirect tensile strength (ITS) test

The test comprises measurement of compressive load, vertical and radial displacements. It is used to determine the loading values for resilient modulus, fracture energy and fatigue resistance tests. It was carried out following the recommendations of ASTM D4123-2005a and ASTM D6931-2012 at a temperature of 25^0C. The values obtained for ITS of asphalt are shown in Table 5.

Table 5. Indirect Tensile Strength of HDPP fibre asphalt

HDPP Content	Specimen Identity	Peak load at failure (N)	ITS (kPa)	Avg. ITS (kPa)
0% HDPP	1	13,455	1341.91	1339.78
	2	13,391	1322.89	
	3	13,928	1354.55	
0.5% HDPP	1	14494.5	1418.45	1441.79
	2	14935.5	1459.33	
	3	14838.5	1447.59	
1.0% HDPP	1	6282.5	620.63	595.75
	2	6363	621.72	
	3	5637.5	544.88	
1.5% HDPP	1	2288	219.11	230.92
	2	2595	246.26	
	3	2389	227.40	

Rutting of asphalt mix

Rutting resistance of the asphalt mixes was determined using Asphalt Pavement Analyser (APA) and load repetitions of 10,000 cycles to permanent deformation and at 50^0C following the recommendations of NCHRP Report 508:2003 [15] and AASHTO T324. Rutting was carried out as part of field performance criteria. The values for rutting test are shown in Table 6.

Table 6. Rutting evaluation values of asphalt mix (mm)

No of Cycles	0%	0.5%	1.0%	1.5%	No of Cycles	0%	0.5%	1.0%	1.5%
0	0.00	0.00	0.00	0.00	400	2.03	2.17	3.87	9.11
25	0.22	0.45	0.52	1.21	425	1.76	2.30	4.75	11.04
50	0.48	0.71	1.14	2.64	475	2.15	2.33	5.38	11.18
75	0.81	0.90	1.92	4.46	500	2.36	2.47	5.48	11.86
100	0.91	0.99	2.15	5.01	600	2.75	3.50	8.21	16.80
125	0.95	1.16	2.25	5.23	1000	3.35	3.92	9.08	18.82
150	1.00	1.26	2.37	5.50	2000	4.62	5.19	10.16	21.28
175	1.05	1.42	2.49	5.78	3000	5.00	6.11	11.45	25.05
200	1.22	1.56	2.89	6.71	4000	5.95	6.63	12.47	30.50
225	1.27	1.59	3.43	6.68	6000	6.87	7.38	13.10	30.26
250	1.47	1.72	3.49	7.22	7000	6.96	6.73	14.34	31.63
275	1.60	1.74	3.59	7.31	8000	7.33	7.44	17.83	34.22
300	1.69	1.96	3.71	8.23	9000	6.29	7.74	21.23	37.11
325	1.70	2.05	3.71	8.61	10000	7.65	8.96	23.56	39.63
350	1.81	1.95	3.74	8.19	Max rut depth	7.73	8.96	23.56	39.63
375	1.92	2.15	3.84	9.03	Average	3.75	4.15	9.55	18.82

Results and Discussion

Marshall Test results for HDPP fibre reinforced asphalt

Findings from the results of Marshall Test parameters for the asphalt mixes are shown in Figures 1 to 6.

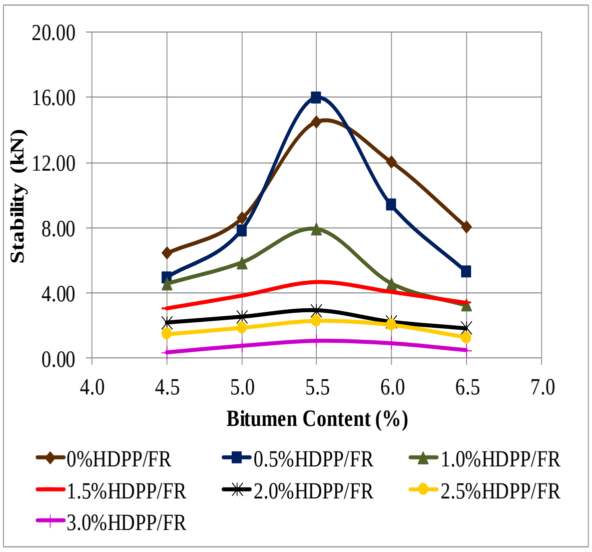

Figure 1. Relationship between stability & BC

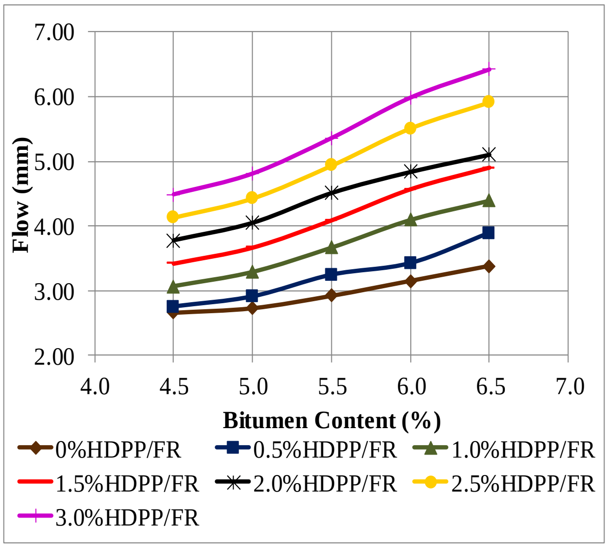

Figure 2. Relationship between flow & BC

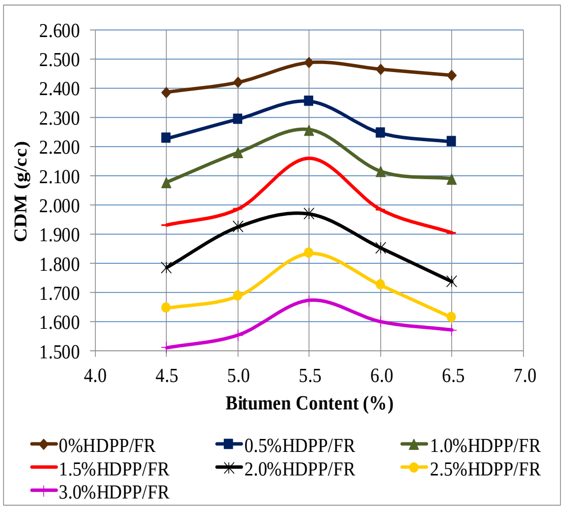

Figure 3. Relationship between BSG & BC

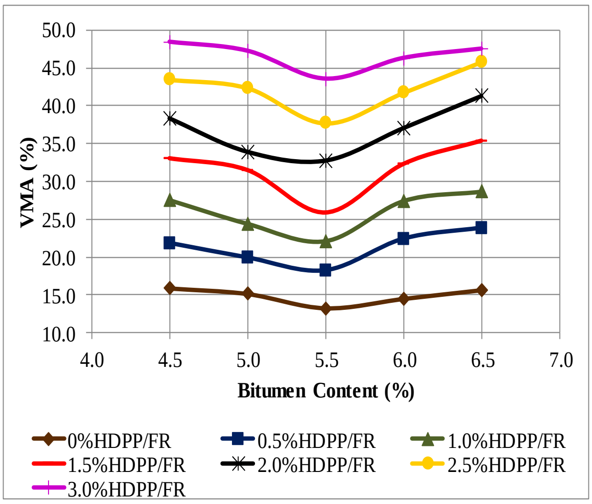

Figure 4. Relationship between VMA & BC

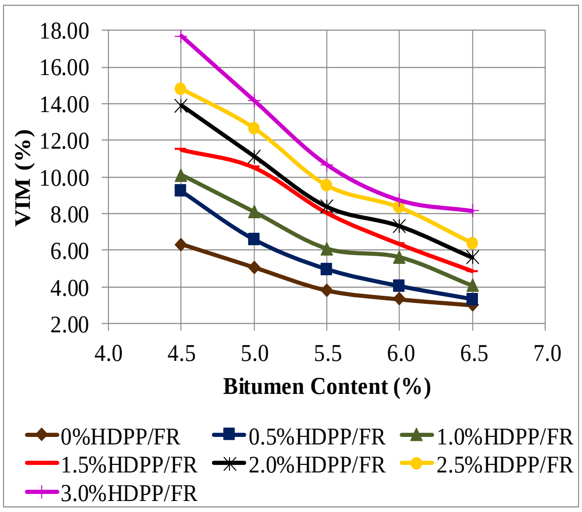

Figure 5. Relationship between VIM & BC

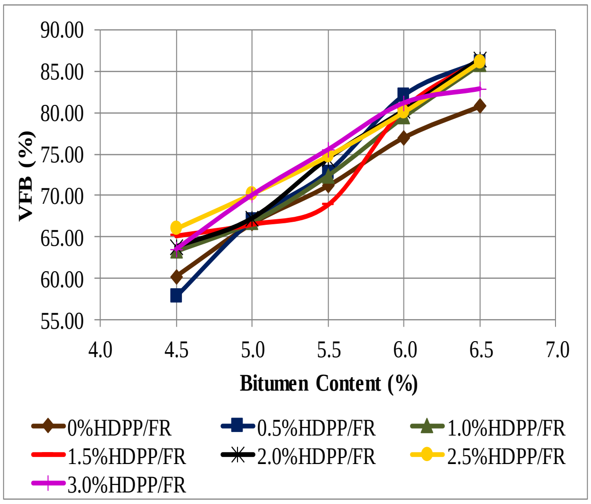

Figure 6. Relationship between VFB & BC

The various trends emanating Marshall Test are summarized:

a) The stability increased from 0 to 0.5% HDPP contents, the optimum being 15.97 kN at 0.5% HDPP. The value accounts for 9.99% increase in strength and is responsible for compensating in tensile strain suffered by asphalt specimen when loaded. Increasing HDPP content beyond the optimum threshold drastically increased the void and deformation and reduces the overall strength of the mix. The findings agreed with [16] and [17] who observed increase in strength and higher fracture energy of PP fibre reinforced mix.

b) The CDM of the mix increased up to the optimum as bitumen content increased and then, dropped because of increasing bitumen content. CDM decreased as HDPP is increasing because inadequate aggregates surface contact grip offset by HDPP thereby entraining voids with the asphalt mix. HDPP is lower in specific gravity than mineral aggregates;

thus, lower the density of the compacted asphalt mix. The optimum bitumen content is observed to be 5.5%.

c) The design VIM used is 5.0% because of increasing volume of compacted mix as HDPP content increased from 0 to 3.0%. 0 to 0.5% HDPP satisfied the range of 3.0 to 5.0% VIM content recommended by Asphalt Institute (1997) for a stable mix. The optimum bitumen content used is 5.5%. VIM excessively increased thereby entraining more voids as HDPP content increased.

d) The flow results increased as HDPP increased from 0 to 3.0% HDPP content at optimum bitumen content of 5.5%. 0 to 1.0% HDPP fibre contents meet Marshall Criteria for stable mix because of higher and low resistance to deformation.

e) The VMA for all 0 to 3% HDPP fibre concrete meets the minimum of 12.0% VMA recommended by Asphalt Institute (1997) assuaging problem of quick traffic densification that may lead to fatigue failure. The optimum bitumen content is 5.5%.

f) Also, the VFB for 0 to 3.0% HDPP mixes are within range of 65 – 75% recommended by Marshall Criteria for heavy traffic axle loading of 10^6 ESAL. The optimum bitumen content is also 5.5%.

Indirect tensile strength (ITS)

The trends indicated by Indirect Tensile Strength (ITS) at various HDPP contents are as shown in Figure 7.

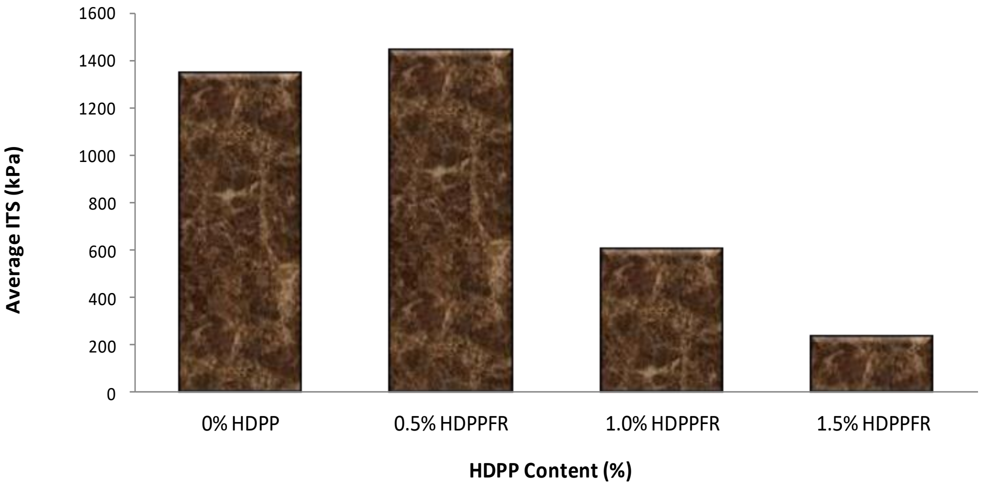

Figure 7. Relationship between Average ITS Values and HDPP content

The ITS results for 0.5, 1.0 and 1.5% HDPP asphalt are respectively 1441.793, 595.746 and 230.9216kPa. Only 0.5% HDPP fibre asphalt meets the recommendations of ASTM D6931-12 and ASTM D4123-05a of minimum ITS value of 1,100kPa. The values of ITS for 1.0 to 1.5% HDPP fibre asphalt were below minimum requirement and could lead to poor rutting resistance especially at higher ambient temperature. At optimum of 0.5% HDPP, ITS increased by 8%.

Permanent deformation (Rutting)

The plots of rutting test conducted for various proportions of HDPP are in Figure 8.

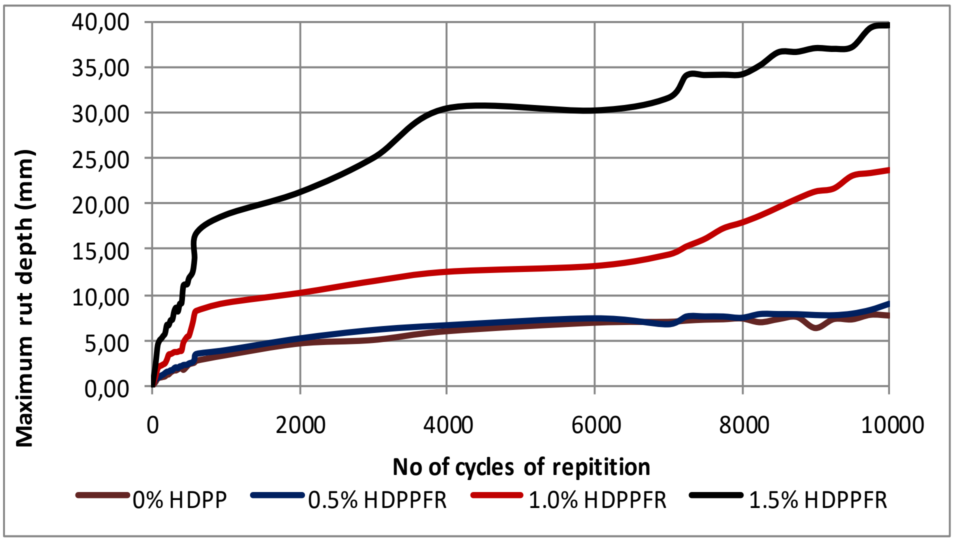

Figure 8. Relationship between Maximum Rut Depth and Load Cycles

Maximum rut of 8 mm was recommended for 8, 000 load cycles of NCHRP Report 508:2003 [15] and 12.5 mm at 10,000 cycles of load repetitions for AASHTO T324 recommendation. Based on these recommendations, only 0.5% HDPP content in Figure 8 meets the recommendations of both NCHRP Report 508:2003 [15] and AASHTO T324 to be adjudged a good mix. The rut depth of 1.0 – 1.5% HDPP contents were increasing because of increasing voids and could cause high oxidation of bitumen, high moisture susceptibility and low deformation resistance failures.

Conclusion

The following conclusions could be made from the research:

- For the Marshall properties, 0.5% HDPP content gave optimally better results than the control (0% HDPP) for the heavy traffic situation simulated. At this optimum, asphalt stability, flow resistance and void requirements are enhanced to withstand the ever-changing traffic and environment situations without failing prematurely.

- Indirect Tensile Strength (ITS) increased by 8% at the optimum HDPP which lies at 0.5%. Also, the rut depths at 8,000 and 10,000 cycles are respectively 7.44 mm and 8.96 mm respectively. These values could improve field performance and the resistance of asphalt mixtures against pavement distresses. Higher HDPP content could lead to increased rutting as a result of increase in voids.

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