An Experimental Study on Bitumen Properties Modified with Polypropylene Polymer from Waste Disposable Cups for Flexible Pavement Applications

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Abstract:

Waste disposal, especially plastic waste, is of great concern worldwide due to its non-biodegradable nature. Because these wastes remain on earth for thousands of years without any degradation or decomposition, they pose health, environmental, and social concerns and occupy valuable space. Also, the significantly higher axle load and traffic volume beyond design limits result in serious pavement deterioration problems. Consequently, incorporating these waste plastics into road construction may present environmental and engineering benefits. Thus, this investigation assesses the impact of including waste plastic cups as bitumen modifiers. Firstly, FTIR analysis was carried out in the laboratory on the waste modifier material showed it mainly comprised of polypropylene. Secondly, a study conducted on the physical features of bitumen with and without the modifier discovered that the modifier decreased the penetration, specific gravity, and ductility by 69.90%, 3.40%, and 42.60%, respectively, whereas it increased the softening point by 48.0%. Therefore, a substantial enhancement in temperature vulnerability and stability of the bitumen can be achieved by incorporating the modifier. Thirdly, the FTIR analysis conducted on the pure and modified bitumen showed the presence of extra new peaks in the structure of the modified bitumen. Thus, the features of this modified bitumen with increasing modifier content resulted from the chemical change in its structure. Finally, the One-way analysis of variance (ANOVA) conducted at various bitumen contents revealed less than a 5% significant level, indicating that the modifier had a substantial impact on pure bitumen. The findings from this study present an vital reference for the improvement in hot mix asphalt properties as well as solid waste management and utilization.

Keywords: *Plastic wastes, Polypropylene, FTIR, Bitumen, and ANOVA*

I. INTRODUCTION

Flexible pavement construction involves the use of bitumen and mineral aggregates. Bitumen, a product of crude oil distillation, plays a vital role in binding aggregates together by coating them. Road surfaces with penetration grade bitumen (pure/unmodified bitumen) have been observed to bleed in harsh environments, develop cracks in cold conditions, and are prone to serious damage due to higher axle load. A common method to improve the quality of bitumen is modifying its rheological properties by blending it with organic synthetic polymers like rubber and plastics [1]. Bitumen is a viscoelastic, thermoplastic, and rheological material. Temperature, load, and the rate at which the load is applied all affect its deformation properties. At low temperatures, it exhibits elastic behaviour while at high temperatures it exhibits viscous behaviour. Thus, the features of hot mix asphalt significantly rely on the type and nature of the bitumen which is the binder in the mixture. Bitumen consistency is its capacity to hold and sustain its main bonding technique when subjected to temperature and load application, as it is a thermo-visco-elastic material. Bitumen consistency is generally a function of its penetration and viscosity [2]. Other properties of bitumen besides its consistency such as its softening point and ductility are also paramount in assessing its field performance [3].

It is worth mentioning that due to climate changes, higher axle wheel forces, higher volume of traffic, as well as poor construction practices, the conventional bituminous binders can no longer offer the required consistency to provide the required mechanical properties of the flexible pavements necessary to withstand vertical plastic deformations and longitudinal depression along the wheel path also known as rutting; as well as thermal susceptibility. To curb this problem, polymer modification of bitumen, which incorporates polymers into bitumen by mechanical mixing or chemical reaction, is now very common [4-6]. These polymers are readily available as waste materials. In 2001 alone, approximately 30,000,000 tons of polypropylene (PP) product was consumed worldwide [7] and the products generated monumental waste after their useful service life.

Researchers and road practitioners have been searching for ways to modify bitumen using polymers in the last four decades. This has increased the volume of research articles published since 1970s. The polymers that have been used to modify bitumen include (for example. polyethylene (PE), polypropylene (PP), ethylene-vinyl acetate (EVA), ethylene–butyl acrylate (EBA)) and thermoplastic elastomers (for example. styrene–butadiene–styrene (SBS), styrene–isoprene–styrene (SIS), and styrene-ethylene/butylene–styrene (SEBS) [4, 8-13]. According to reports, these polymers give bitumen greater qualities, including increased stiffness at high temperatures, increased resistance to cracking at low temperatures, improved resistance to moisture, and longer fatigue life [10, 14-18]. Moreover, Polacco et al. [4] opined that the addition of polymer of about 2–6% by weight can strongly enrich the binder properties and permit the building of safer roads and the reduction of maintenance costs. Ahmadinia et al. [19] stated that the important features of binders modified with polymers are that they improve adhesion and degree of cohesion, creating an aggregate coating material that is expected to increase the degree of the aggregate surface roughness and produce a superior asphalt mixture. Also, modified bitumen improves permanent and recovered strains compared to the unmodified binder. The reason for this aforementioned improvement could be because the polymer-rich domains act as a reinforcement.

Lewandowski [5] found out that the cohesive force between asphalt and aggregate could be improved by using SBS. Also, [19] discovered that polymer-modified bituminous mixtures appear to possess the highest potential to increase the durability and service life of the pavement. Torghroli et al. Reference [20] researched the recycling of solid industrial wastes (SIW) such as rubber tires and plastics has shown to be a very promising way to improve the engineering properties of asphalt paving materials, in addition to providing a solution to the world's environmental problems. This study aims to experimentally study the effect of modifying bitumen with polypropylene polymer obtained from disposable waste cups for application in flexible road pavements. Therefore, using polypropylene (PP) waste in asphalt mixes is an effective strategy to improve pavement performance, reduce maintenance costs, and reduce the problem of disposal of unwanted polypropylene (PP) wastes, which are environmental and health concerns.

2. MATERIALS AND METHOD

2.1 Materials

The following are the materials used in this investigation;

i. Waste plastic cups

ii. Bitumen

The bitumen used for this research is the 80/100 penetration grade bitumen obtained from MOTHER CAT Construction Company Ltd, Zaria, Kaduna State, Nigeria while the waste plastic cups used as modifier was sourced from waste bins, refuse dumps, and wherever they were kept after usage within Samaru, Zaria.

2.2 Methods

Physical properties tests on bitumen as well as the chemical composition of the disposable cups were conducted to ascertain their suitability for use in bituminous mixtures. These tests were conducted according to standard code specifications (ASTM and BS). All tests were carried out in the Department of Civil Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria, Kaduna State except the FTIR that was conducted in the Department of Chemistry, Faculty of Physical Science, Ahmadu Bello University, Zaria, Kaduna State. The following section presents the test conducted on unmodified and modified bitumen and code of specification.

2.2.1 Tests on the modifier (waste disposable cups)

Fourier Transform Infra-Red Spectrum (FTIR) analysis [21]. The Fourier Transform Infra-Red spectrum (FTIR) analysis was conducted according to [22]. The Infrared spectrum analysis was used to determine the structure and confirm the presence of polypropylene molecules in the waste disposal cups. The vibrational energy levels of the sample molecules transit from the ground state to the excited state when they are subjected to infrared radiation because the molecules selectively absorb radiation of particular wavelengths. The measure or degree at which the bonds between the molecules absorb infra-red energy at a particular wavelength is described by the graph of Transmittance against wavelength. The transmittance describes the amount of infrared radiation absorbed, while the wavelength describes the frequency of the wavelength at which the molecules absorb the infra-red energy. An Agilent Cary 630 FTIR Spectrometer was used to carry out the evaluation. The facility has a wavelength ranging between 4000– 650 cm-1. Table 1 shows a standard Infrared Spectroscopy Absorption used to compare FTIR results.

2.2.2 Tests on pure bitumen and modified bitumen

Consistency tests conducted on the pure and the modified bitumen are as follows:

i. Penetration test [23];
ii. Softening point [24];
iii. Ductility test [25];
iv. Specific gravity test [26]
v. Flash and fire point test [27, 28] and;
vi. Solubility test [29]
vii. Fourier Transform Infra-Red spectrum (FTIR) analysis [30]

3. RESULTS AND DISCUSSION

3.1 The Fourier Transform Infrared (FTIR)

A correlation of the standard chart of Infrared Spectroscopy Absorption Table (ISAT) in Table 1 and the FTIR test results of the modifier, as shown in Figure 1, was used to determine the presence of polypropylene in the modifier.

The polypropylene compound comprises functional groups and bonds such as the C-C bond, C-H (methylidyn) bond, CH2 (methylene) bond and the CH3 (methyl) bonds both from the alkane and the alkene family as observed in the diagram. The sharp transmittance peaks as observed in the FTIR spectrum with the wave numbers 2840 cm-1, 2870cm-1, 2918 cm-1 and 2952cm-1 is associated with C-H bending which is also present in the CH2 bond asymmetric stretching, while the transmittance peaks associated with 2851.4cm-1, 864.7cm-1, 898.3 cm-1 and 745.5 cm-1 are properties of C-H stretching and bending.

Table 1: Infrared Spectrum Absorption

S.No.	Frequency range (cm^{-1})	Bond type	Bond name (Family name)	Molecular Motion
1`	2840 - 3000	C – H	methylidyn (Alkanes)	Stretching
2	860 -900	C – H	Methylidyn (Alkane/Aromatic)	Bending
3	1290-1430	C – H	Methylidyn (Alkenes)	Bending in plane
4	1585 - 1600	C – C	Aromatic	Stretching
5	1450 - 1600	C = C	Aromatic	Stretching
6	900 - 860	C - H	Methylidyn	Bending
7	900 - 675	C - H	Aromatic	Out of plane bending
8	1450-1465	CH_2, CH_3	Methyl, Methylene	Bending
9	808	C - C	Alkane	Rocking
10	2922.2	CH_2	Methylene (Alkane)	Assymetric stretching
7	1375.4	CH_3	Methyl (alkanes)	Symmetric bending
8	701 - 600	S – C	From Thiophene group	Stretching

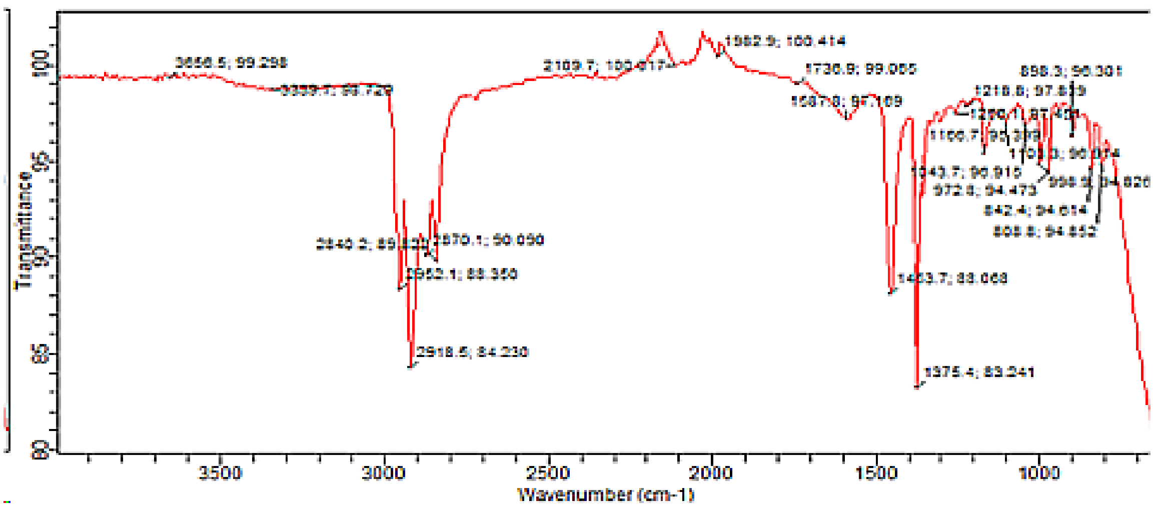

Figure 1: FTIR Spectrum of Waste plastic cups

The 808 cm-1 wave number is an indication of the presence of C-C stretching. The sharp transmittance peaks characterized by the 1375.4 cm-1 and 1457 cm-1 wave number as observed in Figure 1 is a strong indication of the presence of the C-H group present in the CH3 and CH2 bond from an alkane group. All the functional groups that are present in a polypropylene compound have been called out and indicated by strong transmittance peaks as shown in the FTIR spectrum. It can therefore be concluded that the modifier material was predominantly made from polypropylene. Other wave numbers that are present in the result but were not called out may have occurred as a result of hardeners and dyes used in the manufacture of the modifier material which constitutes a little percent of the modifier as observed by the shortness of their transmission peaks, therefore, ignored.

3.2 Physical properties tests on the Unmodified Bitumen

The results of the physical properties test conducted on the unmodified bitumen are shown in Table 2.

These results were within the specified limits of the [31], for 80/100 penetration grade bitumen. This implies that the bitumen sample is of penetration grade 80/100 and therefore suitable for use in HMA production.

3.3 Impact of the modifier on penetration

The variation of penetration with modifier content is represented in Figure 2 below. It was observed from Figure 2 that the penetration value of the unmodified bitumen (control) which is at 0% modifier content was 96.5 tenths of a millimeter (0.1mm) which decreases by 4% with an addition of 2% modifier content by weight of bitumen.

Table 2: Consistency and other tests conducted on uncontaminated bitumen

S/N	Test conducted	Unit	Result	Specification	Remark
1	Penetration	0.1mm	84	80 – 100	OK
2	Softening point	ºC	49	48 – 56	OK
3	Ductility @ 25 ºC	Cm	77.7	100 (Minimum)	OK
4	Specific gravity	NIL	1.043	1.01-1.06	OK
5	Flash-point	ºC	251	250 (Minimum)	OK
6	Fire-point	ºC	218	NIL	
7	Solubility in C_2S	%	100	99 min	OK
8	Viscosity @ 60 ºC	Secs	1522	NIL	

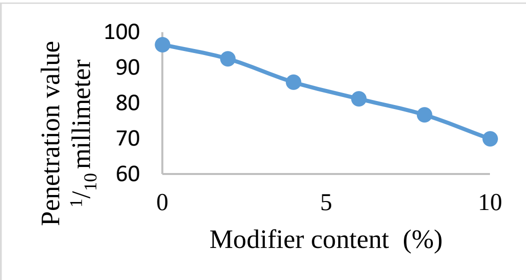

Figure 2: Variation of penetration with modifier content

This decreasing trend was observed with a further increase in the percentage of the modifier, with the highest percentage decrease of 69.9 % with respect to the control at 10% modifier content. Casey et al. [32]. stated that an increase in polymer contents in bitumen decreases penetration value. Since the penetration value of modified bitumen resulted in a harder and more consistent bitumen, the rutting resistance features of the blend can be enhanced. However, the flexibility of the bitumen can be affected

3.4 Effects of the modifier on the ductility

The variation of ductility with modifier content is shown in Figure 3. The effect of the modifier on the ductility of bitumen depicts a reducing fashion with higher content of the modifier. The downward movement could be assigned to the fact that the bitumen becomes dense or rigid as the percentage modifier content increases, which is an indication of the reduction in temperature susceptibility and improvement in rutting resistance of the bitumen. Akbari et al., [33] and [34] postulated that by increasing polymer contents in bitumen, the modified bitumen may lose its ductility very quickly.

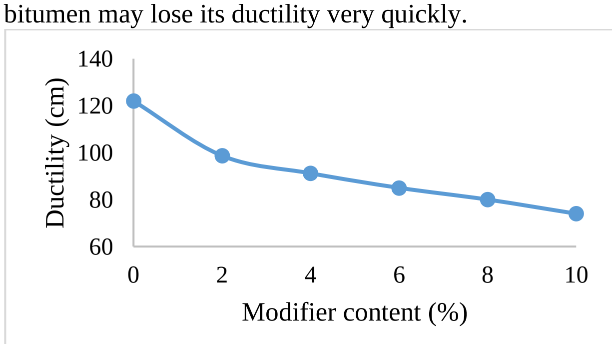

Figure 3: Variation of ductility with modifier content

A sharp drop was detected between the pure bitumen and the modified bitumen at 2% modifier content, but between 4% to 10% replacement, a steady drop was observed. The trend observed could be due to the absorption of the low molecular weight oils present in the bitumen when polymers are added to it in molten stage as revealed by [35] . This absorption of oils increases the asphaltene content that is generally present in bitumen and according to [36] , the asphaltene content has a general impact on the consistency of bitumen by making it harder and less ductile.

3.5 Effects of the modifier on the softening point

Softening test results was performed on unmodified and modified bitumen is illustrated in Figure 4.

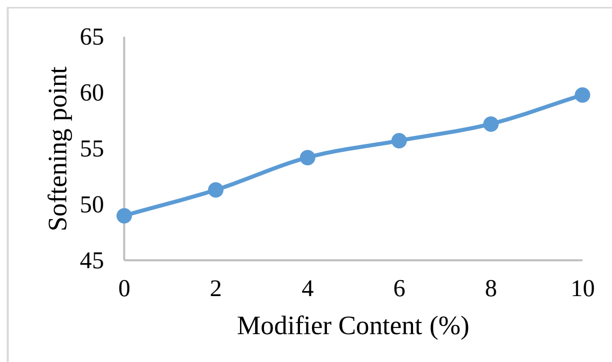

Figure 4: Variation of softening point with modifier content.

From the Figure, it can be observed that as the percent of modifier increases, the softening point also increases. At 10% modifier content, there was 48% increase in softening point in comparison with the unmodified bitumen and this could be as a result of increased viscosity of the bitumen mix. [33, 37, 38] claimed that with the addition of various polymers (PP, PS, PE and PET) to bitumen, softening point increase thereby leading to increase in temperature susceptibility and better rut resistance at higher temperatures. Therefore, bitumen modified with polypropylene will resist the flexible pavement against permanent deformation and rutting due to the higher softening point.

3.6 Effects of the modifier on the specific gravity

Results of impact of the modifier on specific gravity at the various modifier contents is illustrated in Figure 5.

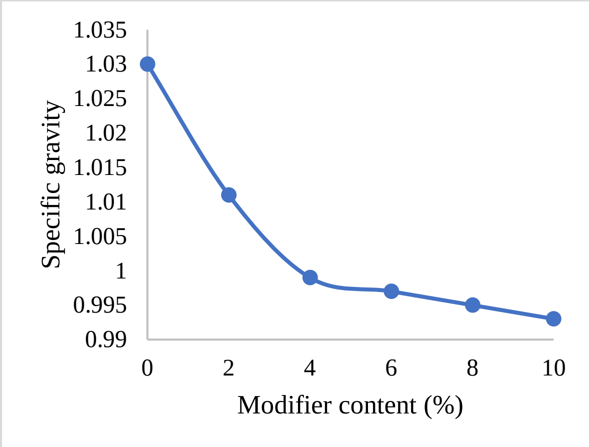

Figure 5: Variation of specific gravity with modifier content

Figure 5 shows that the specific gravity of the modified bitumen decreases with increasing modifier content. The trend exhibited by the specific gravity may also be attributed to oils that are absorbed by the polymer from the bitumen when it is in molten state [35].

3.7 Fourier Transform Infra-Red spectrum (FTIR) Results

3.7.1 FTIR for Unmodified Bitumen

The FTIR results on the unmodified and the modified bitumen are shown in Figures 6-11 for 0-10% modifier contents at 2% intervals.

The Infrared (IR) band of the unmodified bitumen was accounted to fall between 4000cm^{-1} to 650cm^{-1} as depicted in Figure 6. The unmodified bitumen possesses absorption peaks at 2922cm^{-1}, 2851cm^{-1}, 1871cm^{-1}, 1598cm^{-1}, 1457cm^{-1}, 1375cm^{-1} and 1033cm^{-1} respectively. Peaks at 3422cm^{-1}, 865cm^{-1}, 809cm^{-1} and 746cm^{-1} respectively appeared as shoulder. The infrared absorption peaks obtained are analogous to those of [39] and they submitted the absorption bands are related to asphalt binder of grade of PG 64–22 as follows; 2922cm^{-1} (CH_2 CH_3), 2882cm^{-1} (CH_2 CH_3), 1601cm^{-1} (C=C), 1455cm^{-1}, 1376cm^{-1}, 1031cm^{-1} (SO_2), 868cm^{-1}, 813cm^{-1}, 747cm^{-1} and 722cm^{-1} (C=C). Allocating functional groups is determined by Infrared Spectroscopy Absorption.

3.7.2 FTIR of PP-modified Bitumen

Figures 7 to 11 display the principal absorption peaks of the PP-modified bitumen's infrared spectra at 2%, 4%, 6%, 8%, and 10%. Comparing peak position and concentrations of the different peaks showing in the infrared spectra of the unmodified bitumen and PP-modified bitumen (with 2, 4, 6, 8 and 10% PP content) revealed there is an presence of more new peaks having wave length of 2370 cm^{-1} for C – H methylidyn stretching, 2074 – 2109 cm^{-1} for C – H methylidyn stretching and 1166 – 1188 cm^{-1} for C – H wagging rocking in the spectra of PP-modified bitumen specimen. It is evident from this that bitumen and PP have interacted in some way, changing the structure of the modified bitumen. A conspicuous vanishing of peaks with wave number 3421cm^{-1} for NH, OH stretching, which is in line with the submission of [40], who revealed that certain infrared peaks in modified bitumen vanished.. Furthermore, peak transition happened at infrared spectra of PP-modified bitumen, which is in concordance with works of [41], who reported that there could be shifting of some of the peaks in PPA-modified bitumen.

Table 4 shows the modifier has a notable impact on the specific gravity at 2%,4%, 6%, 8%, and 10% modifier compared with the control i.e. (Sig-values <0.05).

Table 5 demonstrates that, in comparison to the control, the modifier has a substantial impact on the penetration property for modifier concentrations of 2%, 4%, 6%, 8%, and 10% (Sig-values <0.05).

Table 6 demonstrates that, in comparison to the control, the modifier has a substantial impact on the ductility property at modifier levels of 2%, 4%, 6%, 8%, and 10% (Sig-values <0.05)

When compared to the control, i.e., (Sig-values <0.05), Table 7 demonstrates that the modifier has a substantial impact on the Softening-point characteristic at 2%, 4%, 6%, 8%, and 10% modifier contents.

3.8.1 Regression Analysis

Table 8 presents the results of the regression analysis that was done to determine a relationship between the attributes of modified bitumen and the modifier content.

Table 8 shows the various regression model of each property describing the connection between the bitumen's characteristics and the contents of the modifier. The models developed showed that the linear regression is best fit model to establish the relationship between the physical characteristics of bitumen; penetration, softening point, ductility property and Specific gravity properties of pure and modifier content with a high degree of correlation (R2). Hence the models generated can be adequately used in the prediction of modifier contents that were not used for this investigation.

4. CONCLUSION

From the investigations conducted, the following conclusions are drawn:

1. Polypropylene (PP) was effectively added into the structure of the pure bitumen. The emergence of extra peaks with wave numbers 2370 cm-1 for C – H methylidyn stretching, 2074 – 2109 cm-1 for C – H methylidyn stretching and 1166 – 1188 cm-1 for C – H wagging rocking respectively and shifting after modification of bitumen using PP confirmed the incorporation.

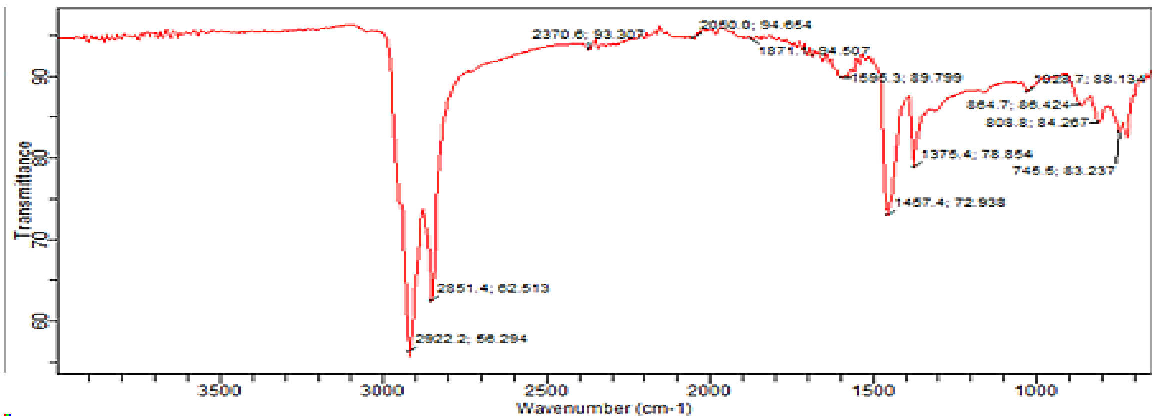

Figure 6: FTIR spectrum of pure bitumen

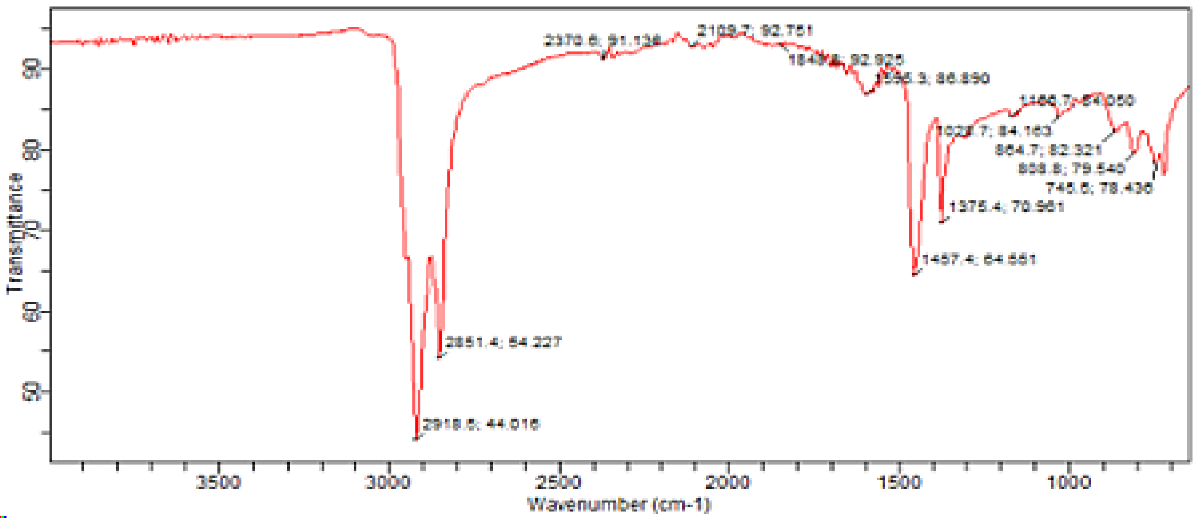

Figure 7: FTIR spectrum of the modified bitumen at 2%PP

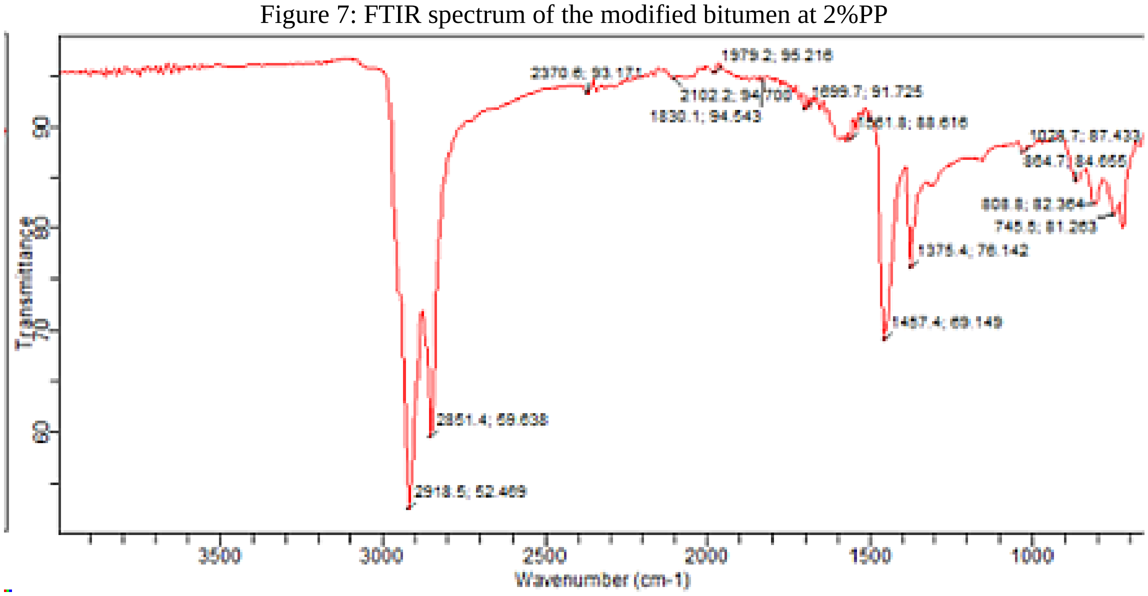

Figure 8: FTIR spectrum of the modified bitumen at 4%PP

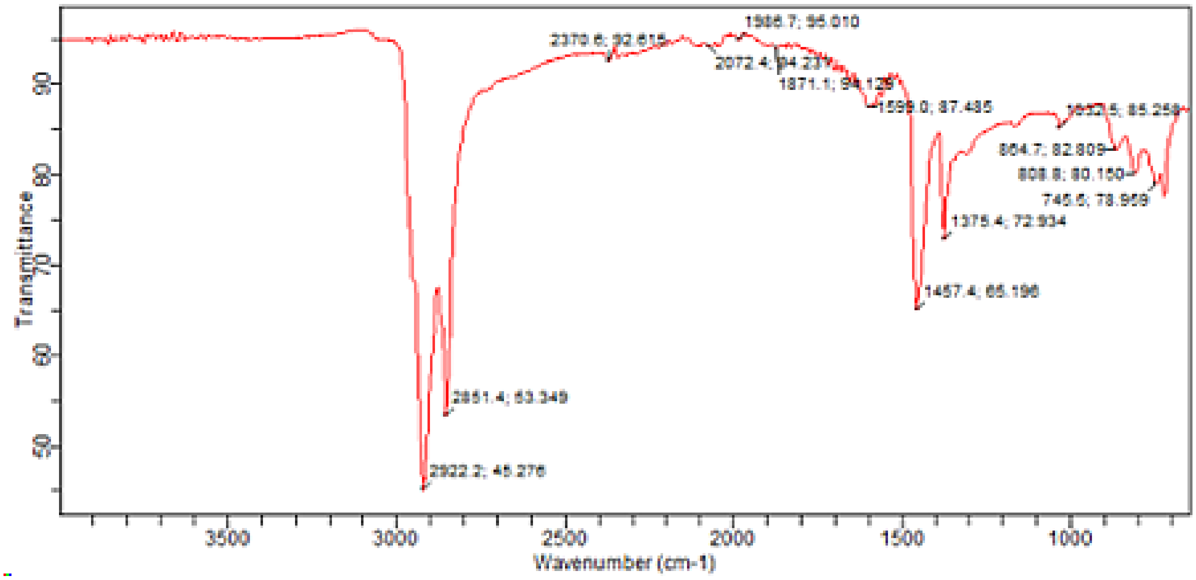

Figure 9: FTIR spectrum of the modified bitumen at 6%PP

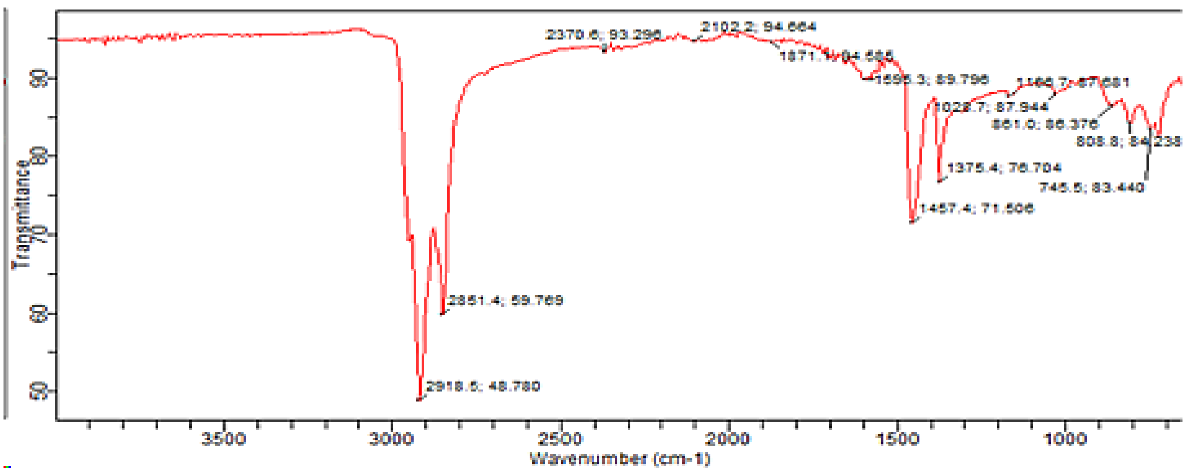

Figure 10: FTIR spectrum of the modified bitumen at 8%PP

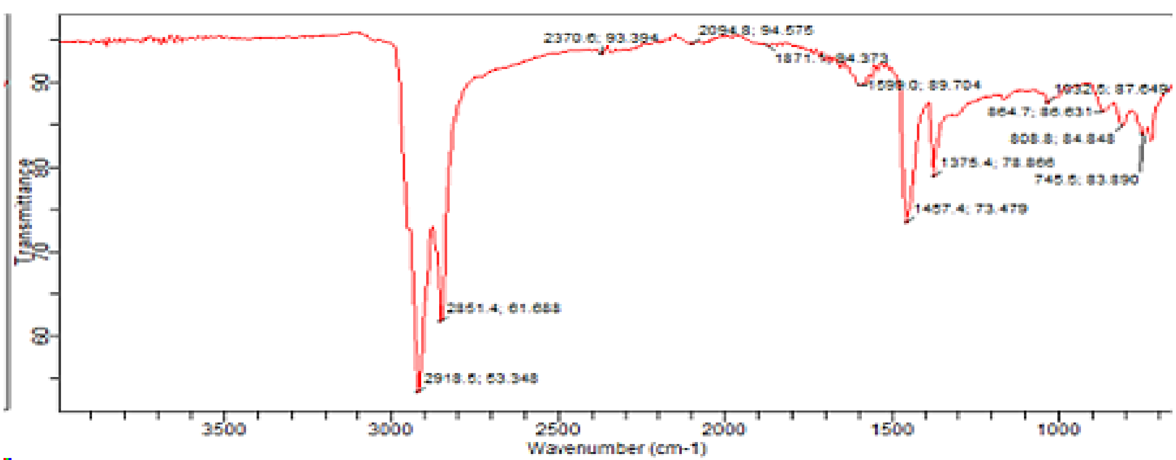

Figure 11: FTIR spectrum of the modified bitumen at 10%PP

3.8 Analysis of Variance (ANOVA)

Outcomes of one-way ANOVA statistical analysis carried on the characteristics of modified bitumen are as presented in Tables 4–7 for specific gravity, penetration, ductility and softening point respectively.

Table 4: ANOVA for Specific gravity Properties at Various Bitumen and Modifier Contents

Bitumen content	Polymer Content (J)	Mean	Mean Difference (I-J)	P-value	Comment
0% (I) CONTROL (1.0333)	2%	1.0110	.02233*	.001	Significant effect
	4%	.9990	.03433*	.000	Significant effect
	6%	.9970	.03633*	.000	Significant effect
	8%	.9950	.03833*	.000	Significant effect
	10%	.9930	.04033*	.000	Significant effect

Table 5: ANOVA for Penetration Property at Various Bitumen and Modifier Contents

Bitumen content	Polymer Content (J)	Mean	Mean Difference (I-J)	P-value	Comment
0% (I) CONTROL (96.5000)	2%	92.5000	4.00000*	.001	Significant effect
	4%	85.9000	10.60000*	.000	Significant effect
	6%	81.2000	15.30000*	.000	Significant effect
	8%	76.7000	19.80000*	.000	Significant effect
	10%	69.6000	26.90000*	.000	Significant effect

Table 6: ANOVA for Ductility Property at Various Bitumen and Modifier Contents

Bitumen content	Polymer Content (J)	Mean	Mean Difference (I-J)	P-value	Comment
0% (I) CONTROL (122.0000)	2%	98.7000	23.30000*	.001	Significant effect
	4%	91.2000	30.80000*	.000	Significant effect
	6%	85.0000	37.00000*	.000	Significant effect
	8%	80.0000	42.00000*	.000	Significant effect
	10%	74.0000	48.00000*	.000	Significant effect

Table 7: ANOVA for Softening-point Property at Various Bitumen and Modifier Contents

Bitumen content	Polymer Content (J)	Mean	Mean Difference (I-J)	P-value	Comment
0% (I) CONTROL (2.00000)	2%	.30000	-4.30000*	.001	Significant effect
	4%	.17321	-7.20000*	.000	Significant effect
	6%	.17321	-8.70000*	.000	Significant effect
	8%	.20000	-10.20000*	.000	Significant effect
	10%	.20000	-12.80000*	.000	Significant effect

Table 8: Regression models of bitumen properties

Property	Regression Model	R^2 Value
Penetration	$Y_1 = -266.1X + 97.039$	0.994 (99.4%)
Softening Point	$Y_2 = -0.0536X + 47.743$	0.982 (98.2%)
Ductility	$Y_3 = 0.4196X + 118.8$	0.9678 (96.78%)
Specific Gravity	$Y_4 = 0.0006X + 1.0301$	0.8943 (89.43%)

2. Incorporating PP to pure bitumen has caused a decline in penetration from 96.50 (0.1mm) to 69.90 (0.1mm), ductility from 122 cm to 74.00 cm and specific gravity from 1.03 to 0.993; and an increase in the softening point from 49ºC to 59.80ºC respectively. These changes are reliable indicators that PP is appropriate for extending the service life of bitumen.
3. A one-way ANOVA showed that, for all modifier contents, the modifier had a significant impact on every bitumen property since every Pvalue was less than 0.05 (significant values <0.05), or at the 5% significant level.
4. The regression analysis shows that linear regression is the most suitable fit model to define the connection amid the physical properties of bitumen and modifier content due to the high degree of correlation of 0.8943-0.994.

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