THE STUDY OF RHEOLOGICAL PROPERTIES OF BITUMEN BLENDS MODIFIED WITH DISSOLVED PLASTIC WATER SACHET

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ABSTRACT

Rutting, which is permanent deformation or consolidation of asphalt pavement, is one of the flexible pavement failures. Research has shown that one of the ways of resisting this failure is by modifying the rheological properties of bitumen. This modification can be achieved by the addition of dissolved plastic water sachet (DPWS), a well-known waste in Nigeria, to bitumen. This study was conducted to investigate the effect of DPWS on the rheological properties of bitumen and at the same time reduce the environmental hazard associated with PWS disposal with consequential pavement material improvement. Bituminous blends containing DPWS at various percentages 0, 1, 3, 5, 7, 9, 11, 13, 15 and 17% by weight of conventional bitumen were used for the study. Tests on rheological properties such as dynamic viscosity, phase angle, peak shear stress and peak shear strain were carried out on unmodified and DPWS modified hot and warm bitumen blends to determine the corresponding complex shear modulus and complex shear modulus elastic portion. Results obtained from the tests were compared between control sample (0% DPWS) and DPWS modified bitumen samples. The test results showed that the dynamic viscosity increased upon addition of the DPWS at 135°C and at 165°C, it initially increased upon addition of DPWS up to 7% before it became constant till 17% DPWS addition; and the phase angle decreased upon addition of DPWS at both 135°C and 165°C for hot mix bituminous samples. Likewise, for the warm bituminous samples, the absolute viscosity increased and phase angle decreased upon addition of DPWS at both 135°C and 165°C. The best complex shear modulus elastic portion results occurred upon 9% and 17% DPWS addition for hot mix bituminous samples and upon 5% and 17% DPWS addition for warm mix bituminous samples when subjected to temperatures of 135°C and 165°C respectively. These percentages are the best to resist rutting on our traffic roads from this study.

Keywords: Complex Shear Modulus, Dissolved Plastic Water Sachet, Dynamic Viscosity, Bitumen Blends, Phase Angle, Rheological Properties, Rutting.

INTRODUCTION

One of the problem facing developing countries like Nigeria is environmental pollution and increase in waste water sachet has contributed to this menace. Water sachet modifier (WSM) obtained from waste water sachet is gradually becoming important in asphalt modification in order to reduce the effect of this waste on environmental pollution and so also flexible pavement properties improvement. Plastic water sachet (PWS) is a low-density polyethylene (LDPE) material that has extremely low rate of degradation (Ademiluyi *et al*., 2007). The rheological properties of water sachet modified bitumen are influenced by blending conditions and water sachet contents which could be in liquid or solid form.

Bitumen is a dark black thermoplastic and visco-elastic material with a boiling point of 977°F obtained during distillation of crude oil (Roseveld *et al*., 1997; Guma *et al*., 2012; Dahunsi *et al*., 2013). This consists of high molecular asphaltene-resins composite diffused in an oily medium of lower molecular naphthenic aromatics and saturated compounds. This mixture is known as micelles. Chemically, it is made up of 95% hydrocarbon, 3% sulphur, 1% oxygen and 1% nitrogen (Chetan and Sowmya, 2015; Remisova *et al*., 2016; Bolarinwa *et al*., 2018). It is used for pavement engineering due to its adhesive and waterproof properties (Roseveld *et al*., 1997). Loeber *et al*., (1998); Mashaan and Karim, (2012) reported that the strong temperature associated with bitumen binder depends on rheological properties assembled by the relationship of the individual components which are asphaltene, resins, aromatics and saturates. An increase in one of these components would change the morphology and rheological behaviour of bitumen. So, bitumen with high asphaltene/resins ratio was more rigid and elastic than bitumen with high resins/asphaltene ratio because the former has lower phase angle and higher complex shear modulus compared with the latter with a higher viscous behaviour.

Rheology is the study of deformation and flow of materials under the influence of external stresses. The deformation and flow of bitumen depends upon the load applied, rate of loading and temperature. Bitumen exists in different forms depending on the subjected temperature or rate of loading. For example, bitumen becomes a viscous material at elevated temperatures, it becomes a highly elastic material at decreased temperatures and becomes an elastic solid and a viscous fluid at intermediate temperatures (Van der Poel, 1954). The elevated temperatures are correlated with slow rates of loading while the decreased temperatures are correlated with higher rates of loading. This study helps to characterize the dynamic mechanical behavior of binders (Fernandes *et al*., 2008).

Presently, the rheological properties of bitumen, presented in terms of complex shear modulus (stiffness) and phase angle, are usually determined using a dynamic shear rheometer. The data could be presented in isochronal plot, isothermal plot, black diagram, cole-cole diagram or master curves. Isochronal plot represents the behaviour of the system at a constant time of loading, isothermal plot represents the behaviour of a system at a constant temperature, black diagram allows all the dynamic shear data to be presented in one plot without manipulating them with the time-temperature superposition principle, cole-cole diagram presents the visco-elastic balance of the bitumen without incorporating time of loadings and/or temperatures as one of the axes and master curves represent the binder behaviour at a given temperature over a wide range of time of loadings (Yusoff *et al*., 2011). In the same vein, isochrones are curves of complex modulus as a function of temperature at constant time of loading, isotherms are curves of complex modulus as a function of time of loading at constant temperature, black diagram is a plot of complex moduli against phase angles and cole-cole diagram is a plot of loss moduli against storage moduli (Airey, 1997).

A research into the evaluation of PWS as a viable bitumen modifier in fluidal form for pavement works alongside the metrics for its dissolved form will contribute to additional waste recycling strategy by finding useful application of PWS in dissolved form and as a part of solution to the global nauseating environmental problem of a non-degradable waste disposal. A knowledge of the optimized proportioning of the modifier and production metrics shall indicate the quantitative and semi-economic advantage of pavement works at reduced temperature and energy demand.

This paper looked into the rheological properties of hot and warm bitumen blends modified with PWS in dissolved (liquid) form using the black diagram method of representation. This is a better way of determining the behaviour and suitability of PWS modified bitumen in resisting rutting on asphalt roads and other construction works when compared to the isothermal and isochronal plots commonly used.

MATERIALS AND METHODS

Sample preparations

The bitumen used for the entire tests was a 60/70 penetration grade bitumen, obtained from Messrs Reynolds Construction Company Ltd, Oyo state, Nigeria. Table 1 shows the specification of the normal bitumen before it was modified. The waste PWS used was collected in sacks (batches) from hostels, residents, restaurants and canteens within Adeleke University, Ede, Osun State. These were sun-dried and shredded to size of 2 mm manually with the aid of scissors before undergoing pyrolysis. 200 g of bitumen was heated in oven until it turns to fluid condition and known amount pyrolysed plastic waste was slowly added, while the speed of mixer was maintained at 1200-1500 rpm and the temperature was kept between 135°C and 165°C. The concentrations of sachet water bags waste used were 0, 1, 3, 5, 7, 9, 11, 13, 15 and 17% by weight of the bitumen. Mixing was continued for 1 hour to produce homogenous hot mix bituminous mixtures. Rheological tests were then conducted on the prepared samples.

For modified warm bitumen blend, laboratory blender capable of maintaining constant temperature and uniform blending speed for long duration was used. 3% sasobit (by weight of bitumen), at constant rate was added to one part of each of the samples of hot bitumen blends to produce modified warm bitumen blend. A 3-percent-addition of **Sasobit** yields the best results when aiming at a maximum temperature reduction of 30°C for production of warm mix asphalt. (www.sasobit.com). When mixing temperature of 135-165˚C was attained then Sasobit was slowly added in bitumen. Then mixing was continued for 2hrs at 4000 rpm so as to achieve a homogeneous blend of warm modified bitumen. Rheological tests were also conducted on the prepared samples.

Table 1: Waste water sachet and bitumen properties

PROPERTY	DETAILS		
	PLASTIC BEFORE SHREDDING	PLASTIC AFTER SHREDDING	BITUMEN
Type	Plastic water sachet	Pelletized plastic water sachet	VG-30
Colour	White	White	Black
Material	Low density Polyethylene (LDPE)	Low density Polyethylene (LDPE)	
Size (mm)		2.00	
Density (g/cm^3)	0.92	0.92	0.98
Melting point (°C)	105	105	-
Penetration	-	-	60-70 dmm
Temperature	-	-	25°C

Laboratory tests

The tests carried out on the prepared PWS modified bitumen samples are rheological property tests where dynamic viscosity, phase angle, peak shear stress and peak shear strain were measured using the Brookfield programmable rheometer model DV-III according to American Society for Testing and Materials Method .

Dynamic viscosity for bitumen

Dynamic viscosity is a measure of the resistance to flow of a liquid under an applied force. It is a property that characterizes the flow behaviour of certain bituminous material. The dynamic viscosity is measured in units of Poise. According to Aflaki *et al.* (2009), modified asphalt binders are usually more viscous than unmodified ones. It was measured using Brookfield programmable rheometer at temperatures 135ºC and 165ºC, spindle No. 27, and a rotating speed of about 200 rpm.

Phase angle of bitumen

This property is a lag between the applied shear stress and the resulting shear strain. It provides a relative indication of the viscous and elastic behaviour of the asphalt binder. The larger the phase angle, the more viscous the material. A phase angle of 90º means the asphalt binder is purely viscous and purely elastic asphalt binder occurs at a phase angle of 0º. A viscoelastic asphalt binder has a phase angle near 45º, which normally occurs at intermediate temperatures. It was measured by the Brookfield programmable rheometer.

Complex shear modulus

This property is a ratio of the applied shear stress to the resulting shear strain. It can be considered the sample's total resistance to deformation when repeatedly sheared. It was measured using the Brookfield programmable rheometer. Its values can range from 0.5 – 6.0 kPa.

Rutting resistance factor

This property is a ratio of the complex shear modulus to the sine function of the phase angle. It is the most important property in determining the resistance of bituminous samples to rutting. The higher its value, the more resistance to rutting. In order to resist rutting, an asphalt binder should be stiff (that is, not deform too much) and elastic (that is, able to return to its original shape after load deformation). Intuitively, the higher the complex shear modulus value, the stiffer the asphalt binder is, and the lower the phase angle value, the greater the rutting resistance factor is. Its minimum specification to resist rutting is 1.0 kPa (Fazaeli et al, 2013).

RESULTS AND DISCUSSION

Hot DPWS modified bitumen blend

The results of absolute viscosity($\boldsymbol{\mu}$), phase angle($\boldsymbol{\delta}$), peak shear stress($\boldsymbol{\tau_p}$), peak shear strain($\boldsymbol{\varepsilon_p}$), complex shear modulus(**G***) and rutting resistance factor(**G*/sin δ**) of the hot DPWS modified bitumen blends are presented in Table 2 and Figures 1 to 3 with the black diagrams at 135°C and 165°C depicted in Figure 4 respectively.

Table 2: Rheological properties results of hot DPWS modified bitumen blend

% DPWS	μ (P)		δ (°)		τ_p (kPa)		ε_p		G* (kPa)		G*/sin δ (kPa)	
	135°C	165°C	135°C	165°C	135°C	165°C	135°C	165°C	135°C	165°C	135°C	165°C
0	4.26	1.38	75.03	58.27	104.60	85.78	65.82	40.90	1.589	2.097	1.645	2.466
1	4.89	1.50	72.59	55.53	120.60	90.14	79.15	43.24	1.524	2.085	1.597	2.529
3	5.31	1.61	70.63	53.79	245.70	95.20	84.32	46.45	2.914	2.050	3.089	2.541
5	5.70	1.71	68.24	51.29	256.90	98.36	89.42	50.10	2.873	1.963	3.093	2.516
7	6.31	1.78	63.77	50.34	310.05	103.22	90.63	55.42	3.421	1.863	3.814	2.420
9	6.93	1.80	58.13	46.39	332.91	128.37	96.39	58.37	3.454	2.199	4.067	3.037
11	7.25	1.80	55.94	44.06	376.12	162.48	114.94	62.02	3.272	2.620	3.950	3.767
13	8.96	1.80	54.26	41.13	380.15	190.59	141.03	67.55	2.696	2.821	3.322	4.289
15	15.30	1.80	52.81	39.33	411.82	218.32	192.60	78.80	2.138	2.771	2.684	4.372
17	20.64	1.80	50.31	37.51	428.83	239.23	198.74	84.00	2.158	2.848	2.804	4.677

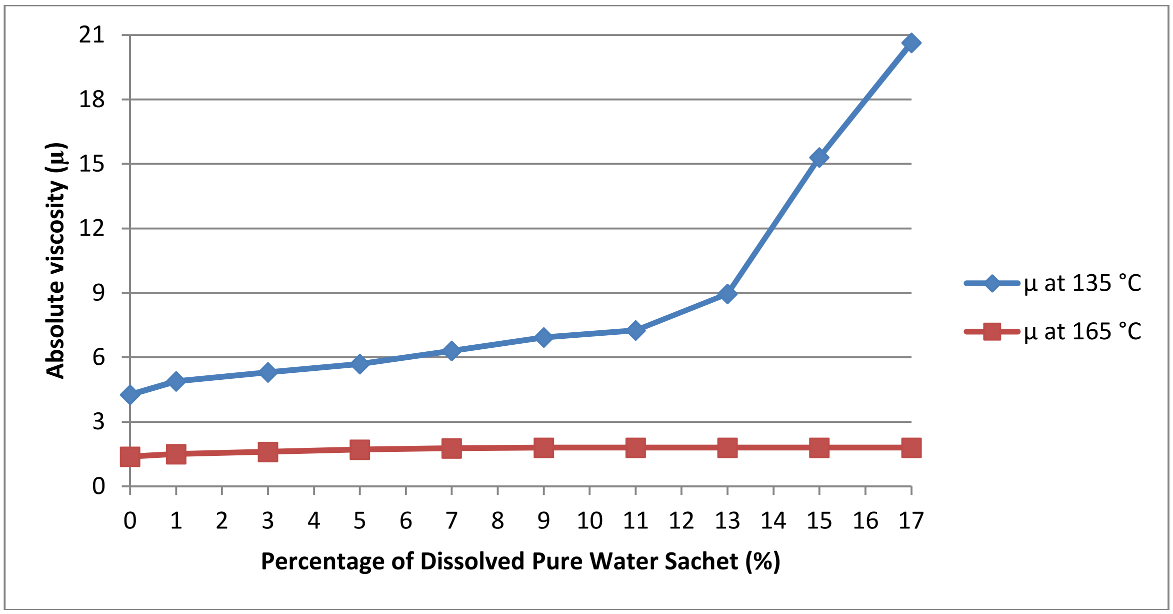

Figure 1: Absolute viscosity of hot DPWS modified bitumen blend

From Figure 1, it will be seen that the absolute viscosity for hot mix PWS modified bitumen increased with increasing percentage of dissolved plastic water sachet at 135 °C. This is because the force needed by the bitumen to overcome its own internal molecular friction increased as the percentage of DPWS added to the bitumen increased. A similar trend was reported by Akinleye et al, 2020. On the other hand, at 165°C, the absolute viscosity first increased consequently from 0 – 9% but remained constant from 9 - 17%. In this case, the force to overcome the internal molecular friction has reached its peak at a percentage of 9%.

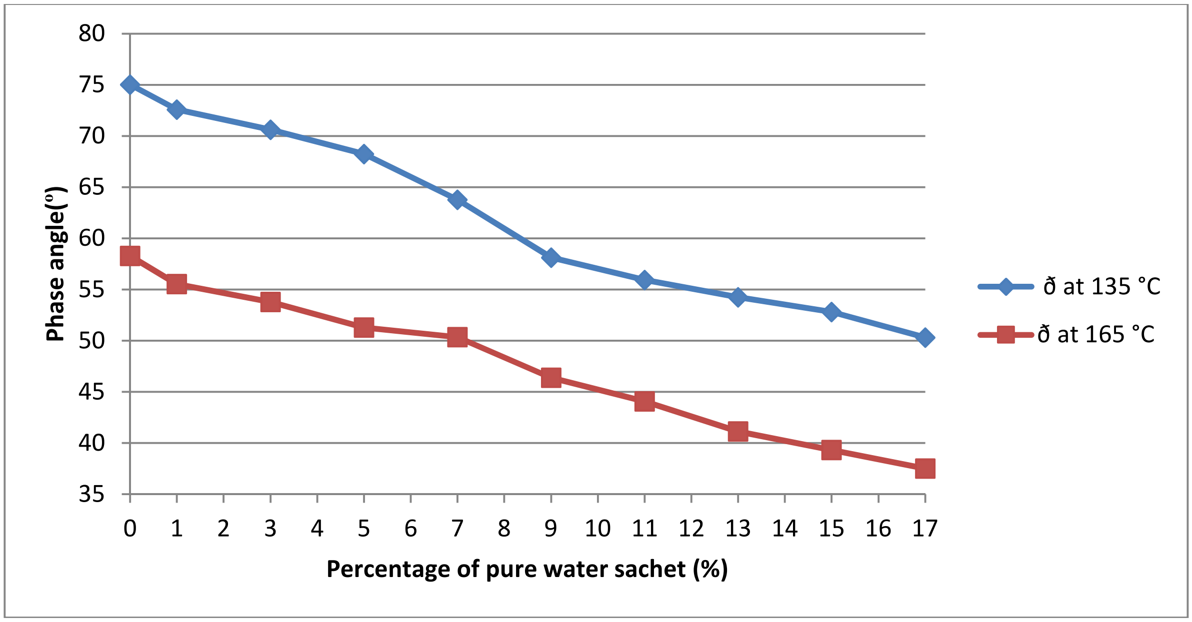

Figure 2: Phase angle of hot DPWS modified bitumen blend

For the phase angle depicted in Figure 2, its value decreased with increasing percentage of plastic water sachet for hot DPWS modified bitumen blend at 135°C and 165°C. At temperatures of 135°C and 165°C, the unmodified bitumen has phase angles of 75° and 58° respectively. Upon addition of DPWS, the modified bitumen was viscous bitumen throughout at 135°C. The modified bitumen became viscous upon addition of 1 - 7%, the viscous bitumen then changed to visco-elastic bitumen when 9% and 11% DPWS were added and became elastic bitumen upon addition of 13 – 17% DPWS at 165°C.

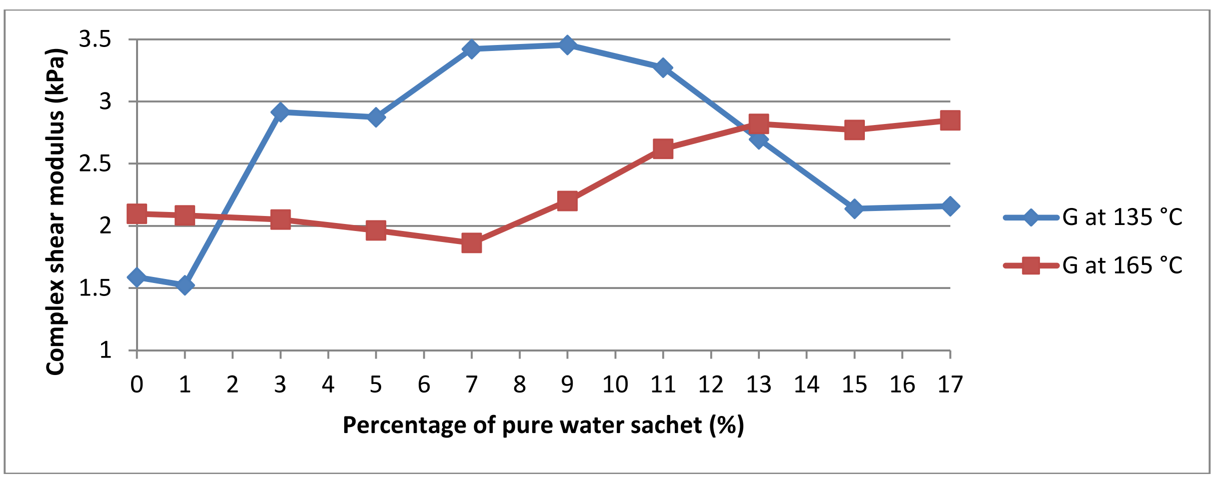

Figure 3: Complex shear modulus of hot DPWS modified bitumen

Figure 3 shows that the complex shear modulus at both 135°C and 165°C followed irregular trends. At 135 °C, the value of complex shear modulus for the unmodified bitumen was 1.589 kPa which later decreased when 1% DPWS was added but increased upon subsequent addition of PWS from 3% to 17%. The lowest and highest values occurred at 1% and 9% respectively. On the other hand, at 165°C, the value of 2.097 kPa for unmodified bitumen decreased upon 1 – 7% DPWS addition but increased when 9 – 17% DPWS was added. The lowest and highest complex shear modulus occurred when 7% DPWS and 13% DPWS were added respectively.

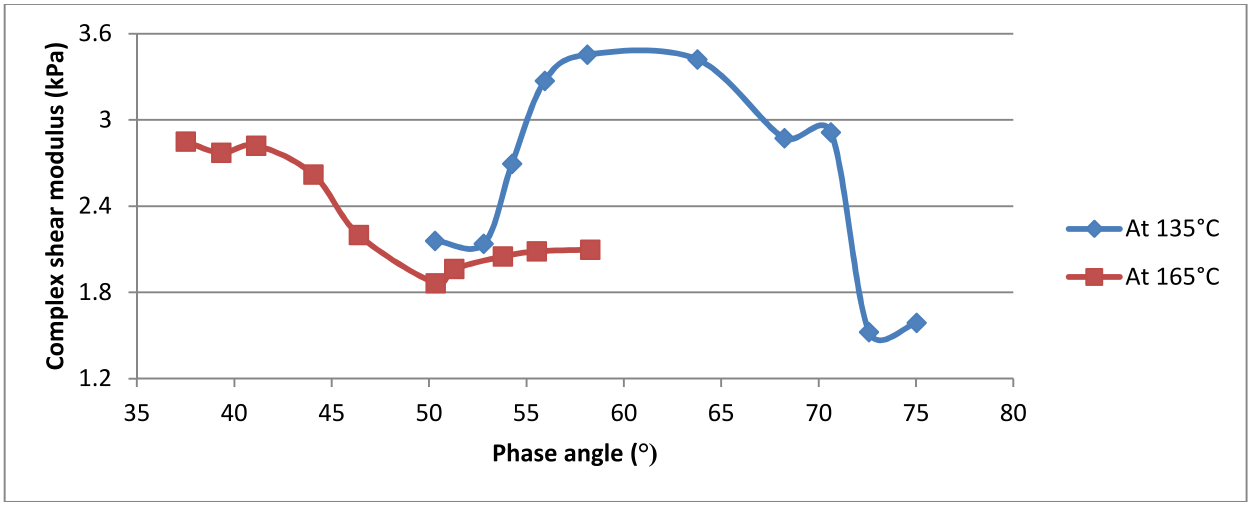

Figure 4: Black diagram of hot DPWS modified bitumen blend

Figure 4 shows that at 135°C, the softest hot DPWS modified bitumen occurred when 1% DPWS was added and the hardest occurred when the percentage of DPWS added was 9%. This means 9% is the best % DPWS addition to reduce rutting. Meanwhile, at 165°C, the softest and hardest hot DPWS modified bitumen occurred upon 7 % and 13 % DPWS addition respectively in Figure 5. From Table 2, it will be seen that all the values of G/sin δ for DPWS unmodified and modified bitumen are greater than the minimum specification of 1.0 kPa for performance graded unaged asphalt binder at 135°C and 165°C. This means they all passed at these temperatures and the higher the rutting resistance factor values, the higher the resistance to rutting.

Warm mix DPWS modified bitumen blend

The results of rheological properties of the warm DPWS modified bitumen blends are presented in Table 3 and Figures 5 to 8. The corresponding black diagrams are depicted in Figures 9 and 10 respectively.

Table 3: Rheological properties results of warm mix DPWS modified bitumen blend

% DPWS	μ (P)		δ (°)		τ_p (kPa)		ε_p		G* (kPa)		G*/sin δ (kPa)	
	135°C	165°C	135°C	165°C	135°C	165°C	135°C	165°C	135°C	165°C	135°C	165°C
0	5.94	1.65	88.51	89.32	98.24	72.64	54.72	31.52	1.795	2.305	1.796	2.305
1	6.41	1.73	86.73	85.46	112.52	86.74	68.93	37.40	1.632	2.319	1.635	2.326
3	7.05	1.88	84.45	80.27	247.63	103.25	75.31	54.37	3.288	1.899	3.303	1.927
5	7.63	1.97	82.06	77.36	294.71	132.54	82.40	62.25	3.577	2.129	3.612	2.182
7	8.50	2.04	80.31	75.42	324.68	140.45	96.47	70.39	3.366	1.995	3.415	2.061
9	8.90	2.07	76.20	70.31	372.18	158.72	128.35	88.25	2.900	1.799	2.986	1.911
11	16.40	2.10	70.11	64.28	430.27	215.48	170.63	112.64	2.522	1.913	2.682	2.123
13	24.89	2.10	62.05	57.53	450.74	237.41	210.28	130.61	2.144	1.818	2.427	2.155
15	40.54	2.10	53.26	44.51	460.21	287.30	236.38	143.82	1.947	1.998	2.430	2.850
17	86.51	2.10	43.54	32.74	530.54	319.26	293.11	164.22	1.810	1.944	2.628	3.594

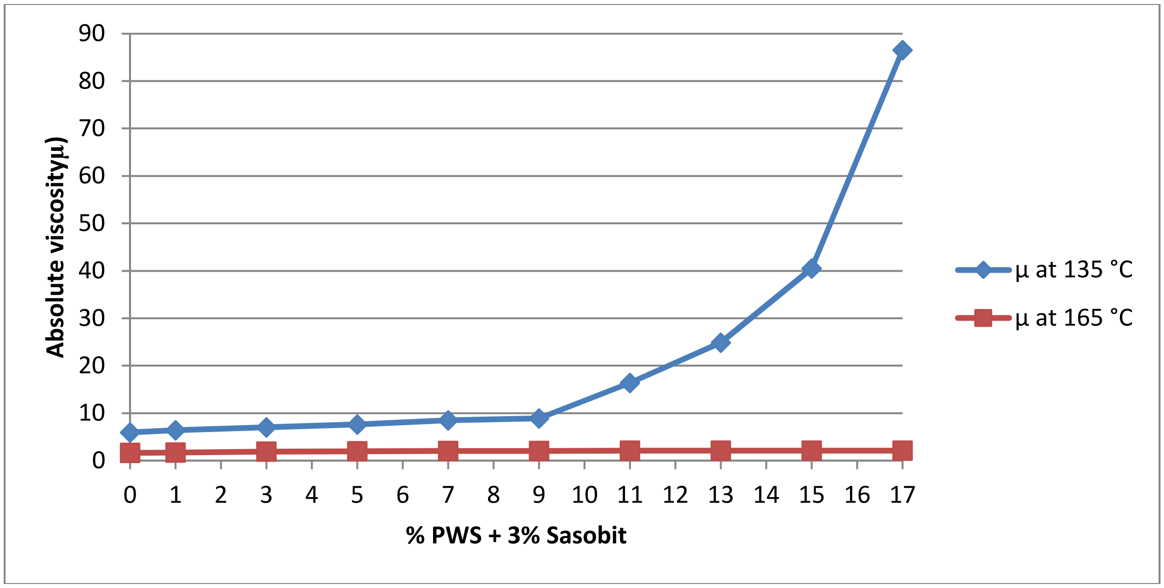

Figure 5: Absolute viscosity of warm mix DPWS modified bitumen

From Figure 5, it is depicted that the absolute viscosity for warm DPWS modified bitumen blends increased with increasing percentage of plastic water sachet at 135°C because the force needed by the bitumen to overcome its own internal molecular friction increased as the percentage of DPWS added to the bitumen increased. This is in line with Akinleye et al, 2020 on preliminary properties of DPB modified bitumen blends. On the other hand, at 165°C, the absolute viscosity of the unmodified bitumen increased upon addition of 1 – 9% DPWS but remained constant when 11 – 17% DPWS were added after it has reached its maximum value of 2.10 Poise.

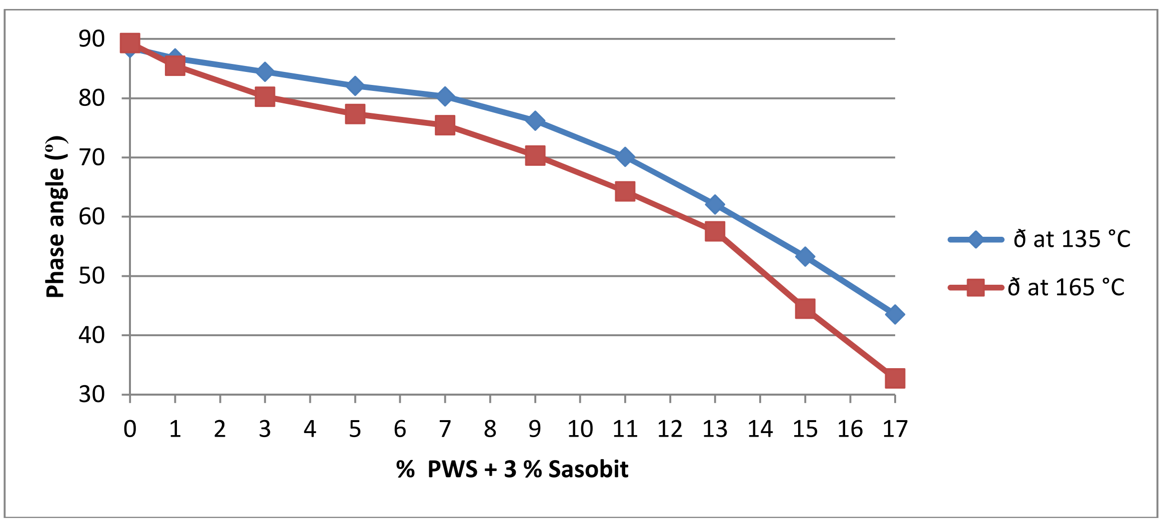

Figure 6: Phase angle of warm mix DPWS modified bitumen

The phase angle of DPWS modified bitumen blends decreased with increasing percentage of plastic water sachet at 135°C and 165°C as depicted in Figure 6. The phase angles of the unmodified bitumen were 88.81° and 89.32° at 135°C and 165°C respectively, meaning the bitumen has nearly complete viscous behaviour because the phase angles are very close to 90° at these temperatures. At 135°C, the behaviour of the modified bitumen changed upon addition of DPWS till it nearly became visco-elastic when 17 % DPWS was added. On the other hand, the nearly complete viscous behaviour changed gradually till it became visco-elastic upon addition of 15% DPWS and tend towards elastic at 17 % DPWS modified bitumen when subjected to a temperature of 165°C.

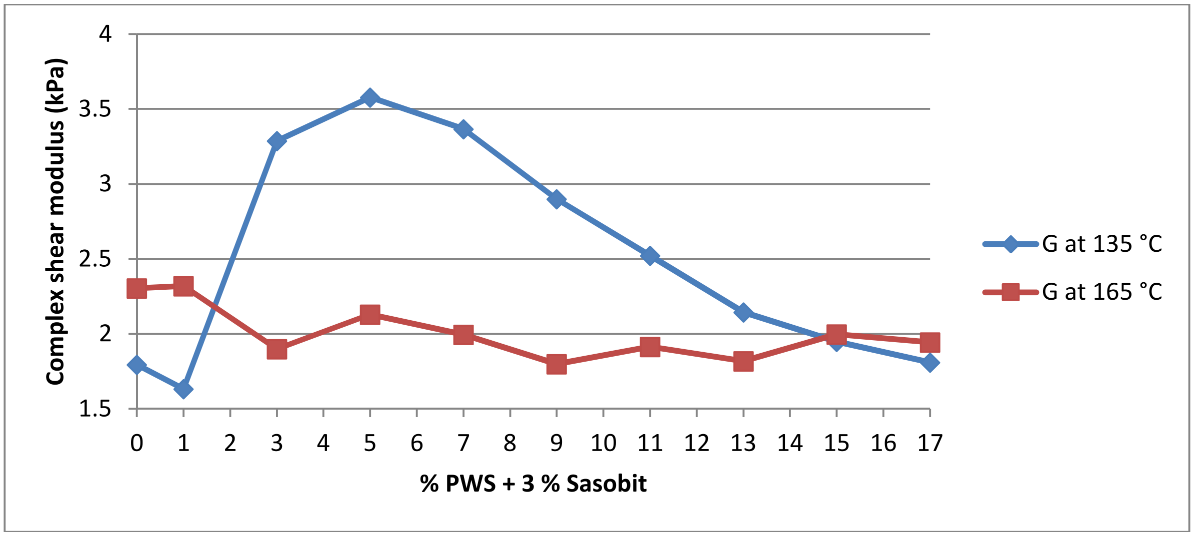

Figure 7: Complex shear modulus of warm mix DPWS modified bitumen

From Figure 7, it will be seen that the complex shear modulus at both 135°C and 165°C followed irregular trends. At 135°C, the value of complex shear modulus for the unmodified bitumen was 1.795kPa which later decreased when 1% DPWS was added but increased upon subsequent addition of DPWS from 3% to 17%. The lowest and highest values occurred at 1% and 5% respectively. Likewise, at 165°C, the value of 2.305kPa for unmodified bitumen increased upon 1% DPWS addition but decreased when 3 – 17% DPWS in 2% increment was added. The lowest and highest complex shear modulus occurred when 9% PWS and 1% PWS were added respectively.

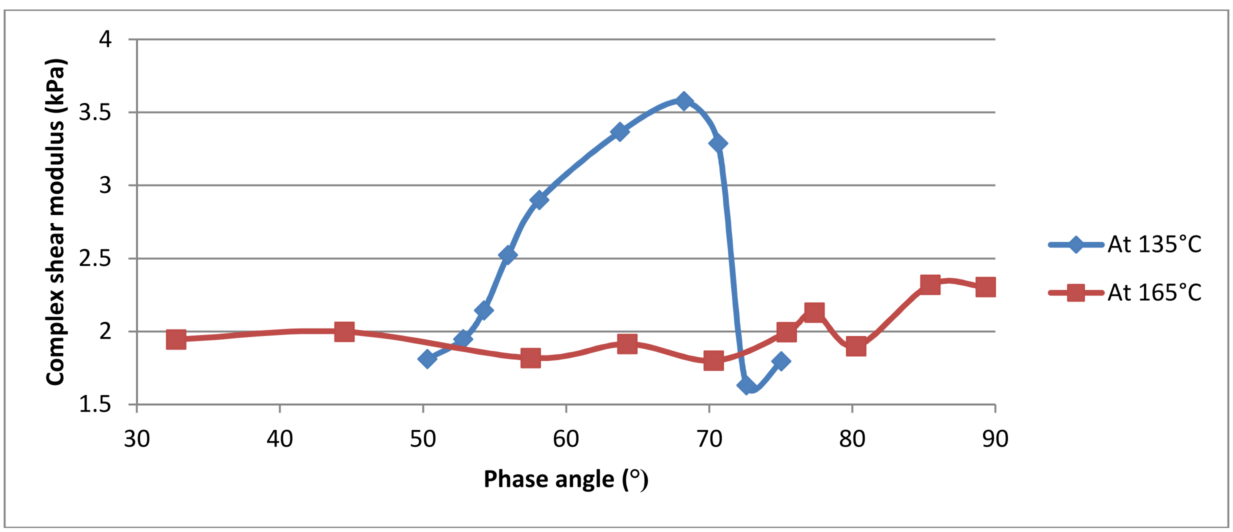

Figure 8: Black diagram of warm mix DPWS modified bitumen blend

It will be seen from Figure 8 that at 135°C, the softest warm DPWS modified bitumen blend occurred when 1% DPWS was added and the hardest one occurred when the percentage of DPWS added was 5%. Meanwhile, at 165°C, the softest and hardest warm mix DPWS modified bitumen occurred upon 9% and 1% DPWS addition respectively. It will be seen that all the values of G/sin δ for DPWS unmodified and modified bitumen are greater than the minimum specification of 1.0 kPa for performance graded unaged asphalt binder at 135°C and 165°C in Table 3 which signifies that they all passed at these temperatures. The best percentages of DPWS to resist rutting in DPWS modified bitumen are 5% and 17% at temperatures of 135°C and 165°C respectively because the complex shear modulus elastic portion (G*/sin δ) were highest at both percentages as shown in Table 3.

CONCLUSION

Experimental study on rheological properties of dissolved plastic water sachet modified bitumen blends were carried out to know the appropriate percentage best to resist rutting at temperatures of 135°C and 165°C. Plastic water sachets were shredded and dissolved by pyrolysis. Rheological properties of modified and unmodified bitumen specimens with various proportions of DPWS modifier were evaluated. The results showed that for hot bitumen blends, addition of DPWS (0 – 17%) increased the absolute viscosity and decreased the phase angle of the bitumen, the shear modulus of unmodified bitumen was higher than that of 1% DPWS modified bitumen but lower than the values for (3 – 17%) DPWS modified bitumen at 135°C. On the other hand, at 165°C, addition of (0 – 17%) DPWS increased the absolute viscosity before it became constant from (9 – 17%) DPWS addition, decreased the phase angle of the bitumen, and the shear modulus of unmodified bitumen was higher than that of (1 - 7%) DPWS modified bitumen but lower than the (9 – 17%) PWS modified bitumen for hot bitumen blend.

Also, for the warm bitumen blend, the absolute viscosity increased and phase angle decreased with increasing percentage of DPWS at both 135°C and 165°C but the complex shear modulus decreased and increased upon 1% DPWS addition at 135°C and 165°C respectively and on the other way, when (3 – 17%) DPWS were added. It is concluded that DPWS can be used to improve bitumen rheological properties and subsequently resist rutting on traffic roads. This can best be achieved upon 9% and 17% DPWS addition at 135°C and 165°C respectively for hot bitumen blend. Likewise, for warm bitumen blend, 5% and 17% DPWS will be the best addition to resist rutting at 135°C and 165°C respectively.

ACKNOWLEDGEMENT

The authors wish to express their profound gratitude to the entire staff of Department of Civil Engineering, Adeleke University, Ede, Nigeria; Department of Chemical and Petroleum Engineering, Afe Babalola University, Ado-Ekiti, Nigeria; and the research department of Tetragrammaton Construction Company Limited, Ibadan for their immense support during materials testing, data collection and processing.

CONFLICT OF INTEREST STATEMENT

On behalf of all authors, I, Akinleye M.T., is hereby confirming that there is no conflict of interest.

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