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Rheological Properties of Plastic Modified Bitumen for Sub-Tropical Areas of Ethiopia

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Abstract The principal problems in any asphalt pavement performance are the sensitivity of bitumen towards temperature, loading time and climate in asphalt mixture. In Ethiopia, asphalt binders have been selected based on penetration grade at 25°C for the construction of all road pavements. Daily traffic growth, performance of dense graded asphalt (DGA), maintenance and rehabilitation expenditure demand better, life-long, and high efficient alternative asphalt mastics and mixtures for minimizing pavement distress. The objective of this research is to evaluate the performance of plastic modified bitumen for sub-tropical areas of Ethiopia. The effect of temperature on strain (deformation) were investigated on the rheology of two commonly used bitumens (40/50 and 85/100) in Ethiopia. In addition, the rheological properties of 40/50, 85/100, polyvinyl chloride (PVC) modified 40/50, low density polyethylene (LDPE) modified 40/50, PVC modified 85/100 and LDPE modified 85/100 binders were investigated by penetration grade and SuperPave grading systems. The PVC and LDPE polymers were mixed with the two bitumens from 0-7% and 0-9% (only odd numbers), respectively. The samples were subjected to a series of consistency, rotational viscometer and performance grading tests at different temperatures. Those tests showed that 3% PVC and 5% LDPE modified binders had better penetration, softening point, ductility, viscosity and performance grade results for both 40/50 and 85/100 bitumen grades compared with the other percentages of the two modifiers. Thus, 40/50, 85/100, 40/50+3% PVC, 40/50+5% LDPE, 85/100+3% PVC, 85/100+5% LDPE were subject to additional Superpave rheology test like rolling thin film oven, amplitude sweep, multiple stress creep recovery, and Fourier transform infra-red tests. As observed from the Superpave test results, the PVC and LDPE modified binders had lower % heat loss, higher linear viscoelastic region (LVER), lower unrecoverable creep compliance and higher percent recovery than the unmodified bitumens in both 40/50 and 85/100 grades. In conclusion, the bitumen with penetration grade 40/50 and 85/100 were improved to 30/40 and 60/70 by both selected modifiers respectively. Those neat bitumens were also improved from PG64-Z(40/50) to PG82-Z (by both modifiers), and from PG52-Z (85/100) to PG76-Z(by 3% PVC) and PG82-Z(5% LDPE) by Superpave grading.

Keywords: *bitumen rheology, LDPE and PVC Plastics, modified bitumen*

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1. Introduction

In highways structural design, specifically upper structures of the pavement, bitumen and aggregate are the main parts which needs more scientific studies. The rheology of bitumen and the natural properties of aggregate determine the quality and life span of a road pavement. The rheological behavior of bitumen is a very complex phenomena which varies from purely viscous to elastic depending on the rate of loading time and temperature. As a mastic material, bitumen plays a basic role in determining many aspects of flexible pavement performance. Flexible asphalt mixture, which its flexibility depends on the bitumen properties, needs to be flexible enough to prevent pavement cracking at low services temperatures and stiff enough to prevent rutting at high service temperatures. These functional properties are required to enable pavements to accommodate increasing traffic loading rates in varying climatic environments [1].

The major pavement distresses like rutting, fatigue, and thermal cracking are the major problems of pavement. Due to this, researchers have searching new or modified pavement materials to prevent such problems. Polymer modifiers can improved the rheological properties of bitumen. Asphalt polymer modifiers may be divided into four major types. These are natural rubber, synthetic latex, block copolymers and plastics (like low density polyethylene (LDPE), high density polyethylene (HDPE), poly vinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) and others) [2].

The variation of temperature and load rate determines the properties of flexible pavement. Repeated traffic loads and environmental factors are the major deteriorating factors in asphalt pavements. At high temperature, the stiffness of hot mix asphalt (HMA) may decreased by using modifiers which helps in lay down and compaction during construction. Likewise, rutting may be reduced, at high service temperature, by using some modifiers which increases the stiffness of HMA. Thermal cracking also controlled by plastic modifiers through reducing its stiffness and increasing its relaxation properties. As a result, it is possible to increase pavement service life, reduce life cycle and maintenance costs [6,8].

Processed plastic wastes were used as a modifier in a heated bitumen in different percentages ranging from 0-12% by weight of bitumen to obtain the modified bitumen in asphalt mixture. The result of the addition of processed plastics in asphalt mixture showed that 8% by weight of bitumen improved stability, fatigue life and adverse water logging conditions of the asphalt concrete mixture. Besides, 0.4% bitumen by weight of the asphalt mix was saved due 8.0% processed plastic by weight of bitumen for the preparation of modified bitumen that would contribute in reducing the overall cost of asphalt mixture [3]. Therefore, the life span of the wearing course is also expected to increase using the modified bitumen in comparison to the use of unmodified bitumen.

Re-cycled Polyethylene Terephthalate (PET) also reduced permanent deformation of the asphalt wearing surface. The aim of this study was to evaluate and determine the maximum percentage of PET and the rut resistance of PET as polymer additives to asphalt mixture. At 7.5% plastic content (which was the maximum percentage of plastic) the optimum bitumen content of the unmodified mixture were improved from 5.3 to 5.2%. This research concluded that PET modified bitumen provide better resistance against rutting due to the binding property of PET in the modified mixture compared to conventional mix [4].

As waste PET is powdered and mixed with bitumen at a temperature of 150°C, the softening point of PET modified bitumen is higher compared to the conventional binders. Due to this PET modified binder has higher resistance to permanent deformation and rutting [5].

Some researchers also compared properties of bituminous mixes containing plastic/polymer (waste PP) (8 and 15% by weight of bitumen) with conventional bituminous mixes. Their result shows that marshal stability of modified mixes was 1.21 and 1.18 times higher than conventional mixes for modifier proportions 8 and 15% respectively. ITS and rutting resistance were also improved in modified mixes. Indirect Tensile Strength (ITS) for conventional mix was 6.42 kg/cm^2 while these where 10.7 and 8.2 kg/cm^2 for modified mixes 8 and 15% respectively, rutting for conventional mix was 7 mm while these where 2.7 and 3.7 mm for modified mixes 8 and 15%, respectively. Thus waste PP modified bituminous mixes are expected to be more durable and have an improved performance in field conditions [6].

Recycled Plastics also used for coating mix aggregate and replace a portion of the mineral aggregates (by volume) of an equal size (2.36–5.0 mm) producing new mix named Plastiphalt [7,8]

2. Materials and Methodology

2.1. Materials

2.1.1. Bitumen

Bitumen with penetration grades 40/50 and 85/100 were used for the preparation of modified samples which obtained from Tayres Hydrocarbon International P. L. Co. ETHIOPIA. The physical properties of the original bitumens (both 40/50 and 85/100) are given in Table 1 based on penetration grade, viscosity grade and performance grade (PG).

Table 1. Physical Properties of used bitumen

Physical Property	Result obtained		Standard
	40/50	85/100	
Penetration at 25°C (77°F), 0.1mm, 100g, 5sec.	46.3	96	ASTM D5
Ductility at 25°C (77°F) 5cm/min, (cm)	126.7	150+	ASTM D113
Specific Gravity at 25°C	1.034	1.018	ASTM D70
Softening Point (°C) (ring & ball method)	52.75	45.85	ASTM D36
Viscosity, 135°C (275°F), min, cSt, using Rotational Viscometer	218.2	213	ASTM D4402
Performance Grade (PG), using DSR	64-Y	52-Y	AASHTO T315
Rolling Thin Film Oven (RTFO), 163°C (325°F)	34.93	34.88	ASTM D2872

2.1.2. Plastics

Low density polyethylene (LDPE) and polyvinyl chloride (PVC) were selected for the modification of both 40/50 and 85/100 bitumen grades. Those products were found at defense plastic industry in Addis Ababa, Ethiopia. The physical properties of those plastics are given in Table 2.

Table 2. Properties of LDPE and PVC [9]

Properties	Results		ASTM Standards
	LDPE	PVC	
Density	0.9185 gm/cm^3	1.38 gm/cm^3	D1505, D792
Tensile strength	10.11 N/mm^2	2.6 N/mm^2	D638
Flexural modulus	0.203 GPa	2.9 GPa	D790
Melting point	113.2°C	212°C	D3418
Chemical unit	$(\text{-CH}_2\text{-CH}_2\text{-})_n$	$(C_2H_3Cl)_n$	

2.2. Study Design

This research is designed based on experimental research method. Experimental research is focused on the description and analysis of what will be or what will occur, under a carefully controlled condition, quality and quantity. It also takes place in the laboratory which aims at finding of the relationships between two factors under a controlled situation [10]. This study was based on laboratory tests as the main procedure to achieve its study goal. An experiment is conducted to collect the primary data and examine the effect of a plastics on the bitumens which is the rheological properties of LDPE and PVC modified bitumen. The control variable for this study were the rheological properties of unmodified binder used in

ASTM and AASHTO design manuals which is the secondary research data. The bitumen (both 40/50 and 85/100) had modify using different percentage of LDPE and PVC separately. The LDPE and PVC plastics were typically added at a percentage of 1, 3, 5, 7, 9, and 1, 3, 5, and 7 for both 40/50 and 85/100 bitumen grades by weight of bitumen, respectively and separately.

The modification of the binder have to be evaluated to check whether it is better than the original binder or not through many laboratories. The effect of plastic modifiers (LDPE and PVC) on the mastic properties of the bitumen were evaluated using the penetration grade and Superpave asphalt binder tests and specifications. Asphalt binder physical and rheological property tests were employed to evaluate its physical and rheological properties. The asphalt consistency tests (like penetration, softening point and ductility tests), durability test (rolling thin film oven test- RTFO), specific gravity, Superpave asphalt binder tests (like RTFO, DSR) and Fourier Transform Infra-red (FT-IR) test were used to evaluate the mastic ability of the modified binder samples.

2.3. Preparation of Modified Binder Samples

LDPE and PVC plastics were chose for the modification of the bitumen. The LDPE plastic added to 40/50 and 85/100 bitumen grades separately at a percentage of 1, 3, 5, 7, and 9 by weight of bitumen, respectively. The same is true for PVC plastic which added at a percentage of 1, 3, 5, and 7 for both bitumen grades by weight of bitumen, respectively. Mechanical mixer was used to prepare the mastic samples at a mixing temperature range of 165-175°C.

Blending time, blending temperature and shear rate are the major factors that affects a proper blending. To blend a polymer, it has to disperse in a bitumen. This can be achieved through using high shear blender [11]. If a thermoplastic polymer and bitumen are mixed, it would be heterogeneous, homogenous or micro-heterogeneous. If it is heterogeneous, the components of the mix separate and has none of the characteristics of a bitumen. In the case of homogeneous mix, the polymer dissolves by the oils of the bitumen which in turns destroy any molecular interaction and increases only viscosity. The modification of the bitumen properties with respect to the original is very slight. But micro-heterogeneous mixture, it is made up of two distinct finely interlocked phases. This gives a compatible and modified bitumen properties [12].

2.3.1. Blending of LDPE with Bitumen

The LDPE plastic polymer that found from the industries for the modification of bitumen was a granular sample. The desired amount of asphalt mastic and the desired percentage of LDPE was weighted. First, the asphalt binder was heated at a temperature of 165-175°C and then some amount of bitumen was added to another container for mixing with the LDPE which controlled the gradually added LDPE from changing to a gel. While at the mixing of the granular LDPE with that little amount of bitumen, the rest of bitumen added in to the mix at controlled temperature range. The mixing continued for 15-20 minutes with a mechanical mixer which rotates 2500 rev/minute while controlling the temperature. The LDPE modified bitumen was a clear mastic and had a uniform consistency.

2.3.2. Blending of PVC with Bitumen

The asphalt mastic was heated to a temperature of 165-175°C in different containers for different percentages of PVC plastic. Then, the PVC powder was gradually added with manual gentle mixing while controlling the mixing temperature. After gently mixing, the blend was mixed by the mechanical mixer at 2500 rpm for 15-20 minutes within a specified temperature. Like the LDPE modifier, PVC modifier was also clear mastic and had a uniform consistency. Finally, both plastic polymers are adopted as a potential asphalt mastic modifiers and all the tests were employed on those samples for asphalt mixture.

3. Result and Discussion

3.1. Penetration and Softening Point Tests

The consistency of bitumen measured by penetration, softening point, ductility and viscosity tests. As shown in Table 3 the original bitumens penetration grade are highly modified by the LDPE and PVC modifiers. The penetration values of the original bitumens (40/50, 85/100) decreased as the percentage of both LDPE and PVC increased. For example, 7% PVC decreased the penetration values of 40/50 and 85/100 bitumen grade from 46.3 to 28.5 and 96.0 to 54.7 mm, respectively. The penetration grade of those bitumens changed from 40/50 to 20/30 and from 85/100 to 50/60 due to the PVC modifier at 7%. And, 9% LDPE also reduced the penetration values of 40/50 and 85/100 bitumen grade from 46.3 to 30.8 and 98.0 to 59.8 mm, respectively. The penetration grade of those bitumens changed from 40/50 to 30/40 and from 85/100 to 50/60 due to the LDPE modifier at 9%. Higher penetration value indicates that the bitumen is soft and vice versa. Both modifiers improved the penetration values of original bitumens and created new modified bitumens. This means the modified bitumen samples withstands higher loads.

The softening point values have also shown [Table 3] that the modified bitumen samples possessed a great improvement on the consistency properties of the binders. As the temperature increased the hardness of the modified binder increased than that of the original bitumen. The softening value of 40/50 penetration grade of bitumen increased from 52.8 to 71.9 and 52.8 to 69.8°C at 7% PVC and 9% LDPE, respectively. The softening value of 85/100 penetration grade of bitumen also increased from 45.9 to 67.2 and 45.9 to 66.6°C at 7% PVC and 9% LDPE as shown in Table 3, respectively. Higher softening point is preferred in warm climate whereas lower softening point is preferred in cold climate. A bitumen with higher softening point means that it has better binding property and withstands higher temperature effect.

But according to ASTM 36 the upper limit of the softening point value for road pavements are 63°C. Thus, 40/50+5% PVC, +7% PVC, +7% LDPE and +9% LDPE modified binders were out of the softening point range of the asphalt mastics. 85/100+7% PVC and +9% LDPE were also above the range of the softening point limit that ASTM limits for asphalt mastic.

3.2. Penetration Index (PI)

The penetration index is determined from the bitumen's softening point (ring and ball test) and penetration values of the samples. Most of the binders which are used for roads have the penetration index between [-1, +1] [13]. As observed in Table 3, 40/50+7% PVC, 40/50+7% LDPE, 40/50+9% LDPE, 85/100+5% PVC, 85/100+7% PVC, 85/100+7% LDPE and 85/100+9% LDPE modified bitumen samples (there PI value written by bold) were out of a range [-1, +1]. The PI values of those samples indicated that they are not used for road pavement construction.

Table 3. Penetration, softening point, and PI values for all unmodified and modified binders

Binder Type	Penetration (25°C, 0.1 mm)	Softening Point (°C)	PI
40/50	46.33	52.75	-0.72
40/50+1% PVC	41.33	55	-0.47
40/50+3% PVC	38.00	59.8	0.34
40/50+5% PVC	32.50	65.1	0.97
40/50+7% PVC	28.50	71.9	**1.79**
40/50+1% LDPE	43.67	53.9	-0.59
40/50+3% LDPE	40.00	56	-0.32
40/50+5% LDPE	37.67	62.65	0.86
40/50+7% LDPE	33.83	65.85	**1.19**
40/50+9% LDPE`	30.83	69.8	**1.63**
85/100	96.00	45.85	-0.66
85/100+1% PVC	81.00	49.1	-0.21
85/100+3% PVC	71.33	53.85	0.64
85/100+5% PVC	64.67	59	**1.51**
85/100+7% PVC	54.67	67.15	**2.59**
85/100+1% LDPE	89.00	48.65	-0.06
85/100+3% LDPE	79.83	50.85	0.21
85/100+5% LDPE	72.33	55.2	0.99
85/100+7% LDPE	67.83	61	**2.05**
85/100+9% LDPE	59.83	66.55	**2.74**

Since the better result of the PI for roads is between [-1, +1], samples which had PI value less than -1 and greater than +1 were rejected for further study in this study.

3.3. Ductility Test

The effect of both modifiers made the original bitumen hard and reduces its elasticity as the percentage of modifier (LDPE and PVC) increased as shown in Table 4 (a) and (b). 40/50+5% PVC, +7% PVC, +7% LDPE and +9% LDPE were below the ductility range of the asphalt mastics which is 99 cm according to ASTM. 85/100+7% PVC and+9% LDPE were also blow the ductility range. But the others fulfilled the requirement of the ductility limit and possessed better elasticity in the proper ductile region.

Table 4 (a). Ductility values of unmodified and PVC modified 40/50 and 85/100 bitumen

Binder type	Ductility (cm)
40/50	126.7
40/50+1% PVC	117.9
40/50+3% PVC	105.4
40/50+5% PVC	89.8
40/50+7% PVC	68.8
85/100	150+
85/100+1% PVC	141.2
85/100+3% PVC	122.0
85/100+5% PVC	100.5
85/100+7% PVC	79.2

Table 4 (b). Ductility values of LDPE modified 40/50 and 85/100 bitumen

Binder type	Ductility (cm)
40/50+1% LDPE	121.0
40/50+3% LDPE	112.2
40/50+5% LDPE	100.9
40/50+7% LDPE	90.9
40/50+9% LDPE	76.3
85/100+1% LDPE	145.8
85/100+3% LDPE	137.1
85/100+5% LDPE	121.9
85/100+7% LDPE	106.4
85/100+9% LDPE	91.9

3.4. Relation between Penetration, Softening Point and Ductility

The relationship between penetration, ductility and softening point is highly relevant to analyze the consistency and hardness of asphalt mastic. As the penetration and ductility values decreased the softening points increased as shown in Figure 1 (a) and (b). That means the results obtained from penetration and ductility is supported by the results obtained from the softening point. As the percentage of PVC and LDPE modifier increased (in both 40/50 and 85/100) the penetration and ductility values decreased while the softening points increased [Figure 1(a) and (b)]. This showed that the bitumen grade has improved from the present grade to the other better grade. Linear model is employed on the test data analysis. The values of R^2 is even greater than 0.95 in most cases that indicates the linear model represented the three consistency tests relationship.

In general, as observed from the three test results, the PVC and LDPE modifiers changed the grade of the original binder to the other new grades. Both PVC (>=3%) and LDPE (>=5%) shows a significant change of grade from 40/50 to 30/40, 85/100 to 60/70 and more as shown in penetration values. But PI, ductility values and softening points results have shown that 40/50 +5% PVC, 40/50 +7% PVC, 40/50 +7% LDPE, 40/50 +9% LDPE, 85/100 +5% PVC, 85/100 +7% PVC, 85/100 +7%LDPE and 85/100+9%LDPE were out the range of the minimum required ductility range and the maximum expected softening point value. This means that as the amount of modifier increased, the modified bitumen become harder. This is undesirable, since it indicates the increasing of energy consumption levels during the mixing and compacting processes of construction. Whereas 40/50 + 3% PVC, 40/50+5% LDPE, 85/100+3% PVC and 85/100 + 5% LDPE passed all the consistency tests requirement. Thus those samples have selected for further study on their rheology and in the asphalt mixture performance properties evaluation.

The penetration, softening point and ductility values have revealed that the PVC modifier had a great improvement than the LDPE on both grade of bitumens.

3.5. Rolling Thin Film Oven Test

This test were employed to evaluate the short term aging of the pure and modified bitumen samples. The asphalt binders that are subjected to RTFO test for the determination of % loss on heat were 40/50, 40/50+3%

PVC, 40/50+5% LDPE, 85/100, 85/100+3% PVC, 85/100+5% LDPE as presented in Table 5. Those samples had a better improvement on the consistency and rheological properties of the two grade of bitumens.

Aging of the binder in rolling thin film oven (RTFO) simulates during mix production and construction by exposing the films of binders to heat and air and approximates the exposure of asphalt to these elements during hot mixing and handling. As observed in Table 5 RTFO residue increased and % loss on heat reduced at the specified modified samples than the unmodified bitumens.

The test data showed that the addition of 3% PVC and 5% LDPE modifiers on the pure 40/50 bitumen reduces the amount of % loss of mass from 0.2 to 0.086 and 0.143% on heat, respectively. Similar situation also observed for modified and unmodified 85/100 grade bitumens. This means that the plastic modifiers reduced the short aging effect of the asphalt mastic during mixing and compaction.

Ageing the selected samples also used for DSR tests.

Table 5. RTFO residue and % Loss on heat

Binder Types	Bitumen (gm)	RTFO Residue (gm)	Loss on Heat (%)
40/50	35	34.93	0.200
40/50 +3%PVC	35	34.97	0.086
40/50 +5%LDPE	35	34.95	0.143
85/100	35	34.88	0.343
85/100 +3%PVC	35	34.92	0.229
85/100 +5%LDPE	35	34.9	0.286

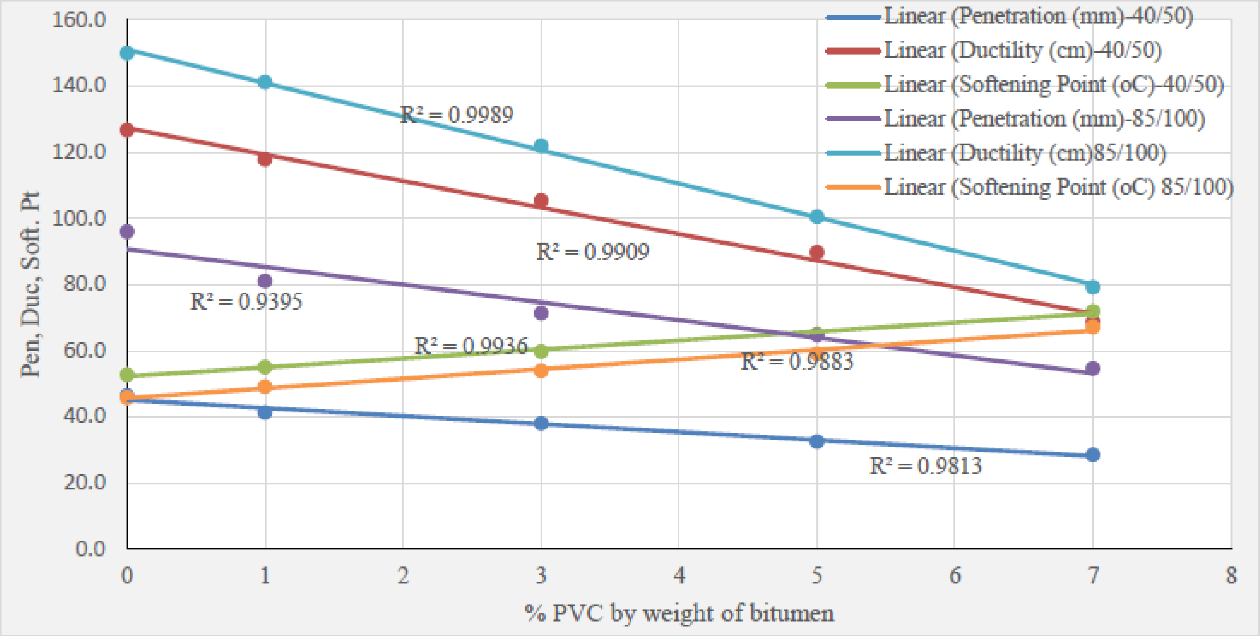

Figure 1(a) Relationship of penetration, ductility and softening points of PVC modified 40/50 and 85/100 binders

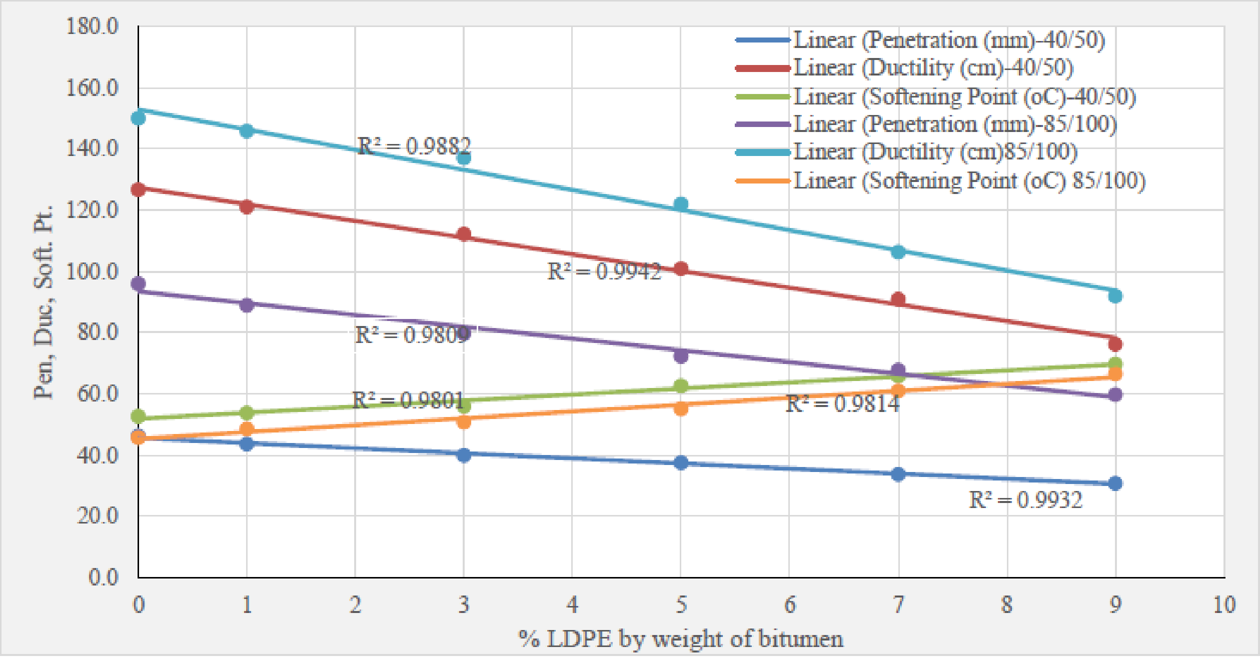

Figure 1(b). Relationship of penetration, ductility and softening points of LDPE modified 40/50 and 85/100 binders

3.6. Dynamic Shear Rheometer Test

3.6.1. Performance Grade Test

Bitumen is a viscoelastic material which behaves partly like an elastic solid and partly a viscous liquid [1]. The dynamic shear rheometer (DSR) test is used to characterize the visco elastic nature of the binder from 4 -88°C temperature ranges [14]. In this study, the DSR tests were conducted at a high temperatures starting from 52-88°C for the determination of performance grading of all samples.

To determine the performance grading of asphalt binder, the basic rheological parameters (complex shear modulus (G^*), phase angle (δ) and the rutting parameter (G^*/sin(δ)) were determined for the pure and RTFO aged samples by DSR over a specified temperatures. The performance level of the unaged and RTFO aged samples were determined based on their complex shear modulus (G^*) and phase angle (δ) values at high temperature. According to Superpave design limit, the minimum value of G^*/sin(δ) is 1kPa for unaged and 2.2kPa for RTFO aged samples as explained in AASHTO M320.

The shear modulus (G^*/sin(δ)) versus temperature graphs obtained for samples modified by PVC and LDPE are seen in Figure 2 (a) and (b), respectively. When the pure 40/50 and 85/100 bitumen were modified using PVC and LDPE modifiers with different percentage, the complex shear modulus values continuously increased for unaged and RTFO aged samples. The increase in complex shear modulus values indicates that the bitumen gained additional shear strength with addition of PVC and LDPE. The lower the complex shear modulus (G*) value of the bitumen means the lower the stiffness value and easily deformed without developing large stresses. The phase angle is also an indicator of viscous deformation of bitumen relative to elastic deformation. As it can see from Table 6, the phase angle values of the modified binder decreased compared to the pure bitumen. This indicates that when phase angle decreased, the viscous deformation decreased and the elasticity of the bitumen getting increased. As the values of complex shear modulus (G*) increased and the values of the phase angle (δ) decreased, the value of rutting (wheel tracking) parameter, G*/sin(δ), increased. The higher this value is, the greater the resistance of the modified binder to rutting (wheel tracking) at high temperature.

As observed from the graphs, the addition of both PVC and LDPE improved the basic rheological properties (G*, δ and G*/sin(δ) as well as the PG values of the pure bitumen. There was even at least one grade improvement on the pure bitumen when added 1% PVC or 1% LDPE. When added 1% virgin PVC to 40/50, the PG was improved from PG 64-Z to PG76-Z. It was improved the pure bitumen by two grades. ‘Z’ represents the low temperature value and have to be determined by bending beam rheometer (BBR) test. But there is no BBR equipment in the country at all. As the percentage of the modifiers by the weight of the bitumen increased the performance grading (PG) values at high temperatures was increased even above the final grade PG88-Z.

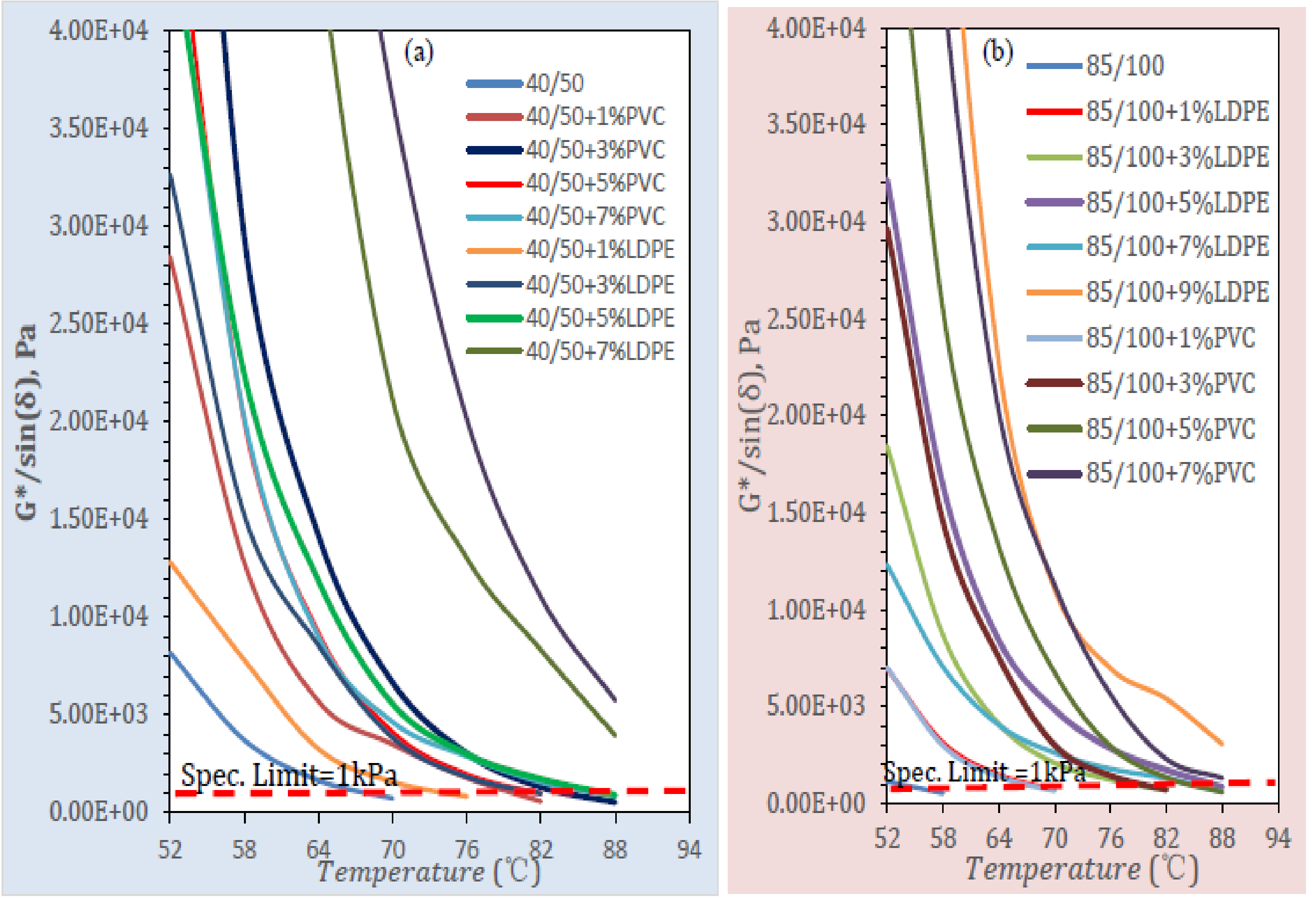

Figure 2. (a) & (b) G^*/sin(δ) Vs Temperature graph for pure and modified bitumen samples

Table 6. Superpave PG of selected samples

Binder Types	Aging Status	Temp. (°C)	G*(Pa)	δ(°)	G*/sin(δ) (Pa)	Superpave Spec. Limit (kPa)	PG
40/50	Unaged	64	1.65E+03	8.69E+01	1.65E+03	≥1	PG64-Z
		70	7.33E+02	8.76E+01	7.34E+02		
	RTFO Aged	70	2.41E+03	8.56E+01	2.42E+03	≥2.2	PG70-Z
		76	1.10E+03	8.69E+01	1.10E+03		
40/50 + 5% LDPE	Unaged	82	1.55E+03	6.43E+01	1.72E+03	≥1	PG82-Z
		88	8.02E+02	6.30E+01	9.00E+02		
	RTFO Aged	82	1.50E+03	4.36E+01	2.18E+03	≥2.2	PG82-Z
		88	9.78E+02	4.21E+01	1.46E+03		
40/50 +3% PVC	Unaged	82	1.30E+03	8.35E+01	1.31E+03	≥1	PG82-Z
		88	5.30E+02	8.64E+01	5.30E+02		
	RTFO Aged	82	3.57E+03	5.73E+01	4.24E+03	≥2.2	
		88	2.06E+03	6.05E+01	2.37E+03	≥2.2	PG88-Z
85/100	Original	52	1.13E+03	8.37E+01	1.14E+03	≥1	PG52-Z
		58	5.38E+02	8.51E+01	5.40E+02		
	RTFO Aged	64	2.80E+03	8.25E+01	2.82E+03	≥2.2	PG64-Z
		70	1.33E+03	8.47E+01	1.34E+03		
85/100 + 5% LDPE	Original	82	1.55E+03	6.36E+01	1.73E+03	≥1	PG82-Z
		88	7.57E+03	6.21E+01	8.57E+03		
	RTFO Aged	82	1.45E+03	4.41E+01	2.08E+03	≥2.2	PG82-Z
		88	9.03E+02	4.23E+01	1.34E+03		
85/100 +3% PVC	Original	76	1.43E+03	8.30E+01	1.44E+03	≥1	PG76-Z
		82	7.23E+03	8.52E+01	7.26E+03		
	RTFO Aged	82	2.75E+03	5.62E+01	3.31E+03	≥2.2	PG82-Z
		88	1.56E+03	5.89E+01	1.82E+03		

3.6.1.1. Effect of Selected PVC and LDPE Modifiers

There was an obvious effect of PVC and LDPE on the asphalt mastic. The addition of the PVC and LDPE modifiers to the asphalt mastic increased its stiffness and decreased the phase angle of the pure bitumens. The value of complex shear modulus (G*) for PVC and LDPE modified bitumen at all percentages were always greater than the value of G* for pure bitumens. The values of phase angle (δ) for PVC and LDPE modified bitumen at all percentages were less than the value of δ for pure bitumen. That means the elastic modulus of both bitumens (40/50 and 85/100) were improved by the effect of both modifiers.

The highest G* value were achieved at highest percentage of PVC (5% and 7%) in both bitumens. But the phase angle was not decreased that much compared to the pure bitumens plus 3% PVC. Both G* and δ had a better value and high rut resistance capability (G*/sin(δ)) at 3% PVC compared to the other percentages in both bitumens. To reduce the viscosity deformation and to improve the elastic modulus, 3% PVC performed and managed better than the others. The values of performance grading (PG) of the 40/50 and 85/100 penetration grade bitumens were improved from PG 64-Z to PG 82-Z and PG 52-Z to PG 76-Z due to 3% PVC modifier respectively as shown in Table 6. This change was a dramatic improvement on the rheological properties of bitumens. This percentage of PVC was better than the other highest percentages according to the short aging and long aging effect of bitumen. The G* values of 5% and 7% PVC modified RTFO aged bitumen couldn't be easily manageable because it was greater than 88°C. So it behaved a purely non-Newtonian fluid characteristics and used for roofing and other purposes not for roads. It is also economically feasible modifying a bitumen by 3% rather than by 5% and 7% PVC modifier by weight of bitumens.

The same is true for LDPE modifiers for both bitumens. The proper and highest value of G* was found at 5% LDPE. The special thing in LDPE modifier was, it highly reduced the phase angle by more than a quarter than a PVC modifier. Thus, it enhanced the elastic modulus of asphalt more than a PVC can do at 5% LDPE content especially in 85/100 than 40/50 as shown in Figure 3. Actually, it is obvious that PVC can modify the bitumen better than LDPE at equal quantity because PVC is a plastic polymer with high density, specific gravity, chemical integrity of the bond than the low density polyethylene (LDPE) plastic polymer properties. Figure 3 (a) and (b) presents the graphs G*/sin(δ) values against temperature obtained for those selected unaged and RTFO aged samples from 40/50 and 85/100 penetration grades. Exponential function fits the two relations (G*/sin(δ) and temperature) the best. The coefficient of correlation (R^2) were greater than 0.99 as shown in Figure 3 (a) and (b).

The complex shear modulus (G*) value also increased in RTFO aged binders. The samples for RTFO aged were first selected in consistency and RTFO tests. Those samples were employed for PG determination at a specified temperatures. There G*/sin(δ) results were very high and it shows that it can resist deformation due to rutting (wheel tracking). The PG values of RTFO aged samples were improved due to the addition of the modifiers compared to the pure unaged and modified unaged samples.

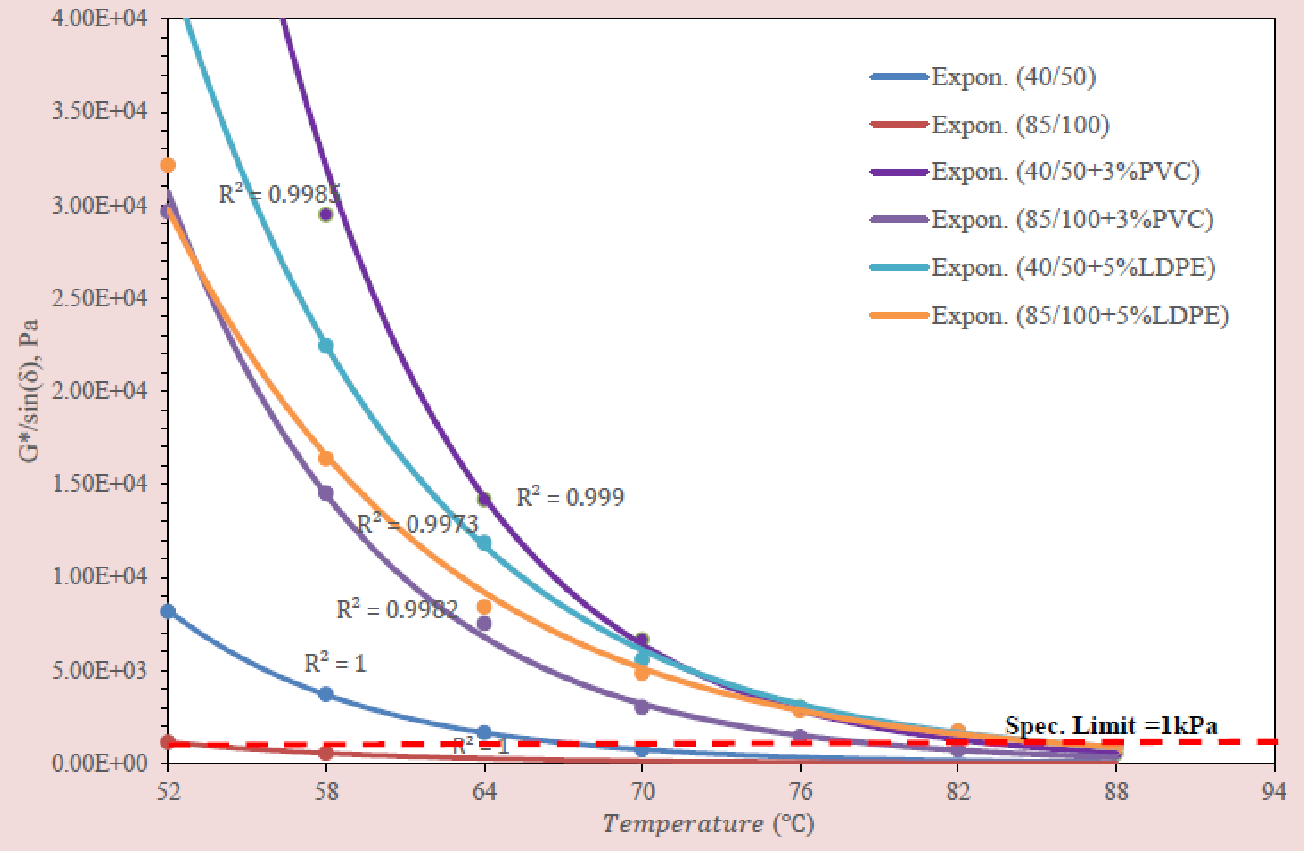

Figure 3. (a). $G^*/\sin(\delta)$ Vs Temperature graph for unaged pure & modified samples

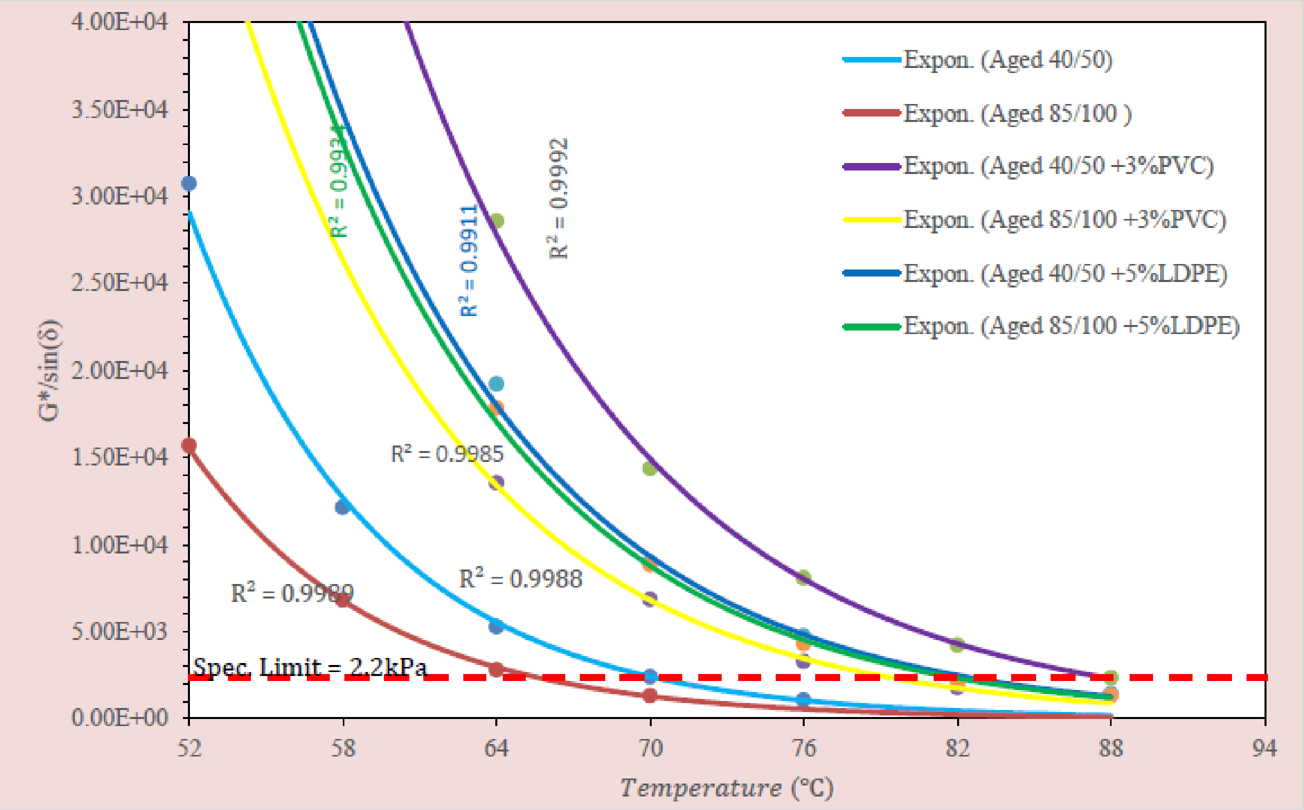

Figure 3. (b) $G^*/\sin(\delta)$ Vs Temperature graph for RTFO aged pure & modified samples

3.6.2. Amplitude Sweep Test

During an amplitude sweep, the amplitude of the deformation (strain) varied while the frequency is kept constant. Amplitude sweep test (AST) mainly used to determine the Linear Viscoelastic Region (LVER) of the asphalt mastic. Linear viscoelastic region used for the determination of the correlation between asphalt binder and asphalt mixture rheology using time temperature superposition, which is valid in the linear region only. For the analysis, the complex modulus (G*) plotted against the strain. The lower deformation value of the moduli (G^*) characterizes the structure of the unmodified or modified bitumen samples at rest in the linear-viscoelastic region.

This test were employed for the selected samples in the previous tests which are 40/50, 40/50+3% PVC, 40/50+5% LDPE, 85/100, 85/100+3% PVC and 85/100 +5% LDPE at a temperature of 20, 38 and 54°C. Those temperatures are taken as a representative temperatures for most of Ethiopia regions. The effect of the plastic modifiers, temperature and aging on the linear viscoelastic region of both bitumens were discussed and determined using this test.

3.6.2.1. Effects of Modifiers and Temperature on Binder LVER

The test results were indicated that the plastic modifiers (both LDPE and PVC) and temperature have affected the asphalt mastic stiffness and strain. As shown in Figure 4(a) and (b), the complex modulus of pure and modified binders have increased as the temperature decreased and vice versa. The G* values of the modified binders were always greater than that of the pure bitumens at all temperatures. But as presented on those Figures (Figure 4), the value of G* decreased as the temperature increased from 20 to 54°C. This means that the asphalt mastic stiffness had affected by temperature.

The linear viscoelastic region of the pure bitumen was less than the linear viscoelastic region of the modified binders as shown in all Figures. This shows that the sample structure of the modified binder is undisturbed on high strain or deformation than the pure bitumens internal structure. The structures of bitumen samples, pure or modified, disturbed at the end of the LVE region. The LVE region of pure bitumen had disturbed before the modified bitumen at all temperatures. This has shown that the modifiers had successfully modify and increased the pure bitumen linearity during deformation.

As observed from both graphs, a long LVE region has scored at a binders modified by 5% LDPE modifier. This means that 5% LDPE was better than the other modifiers according to LVE region.

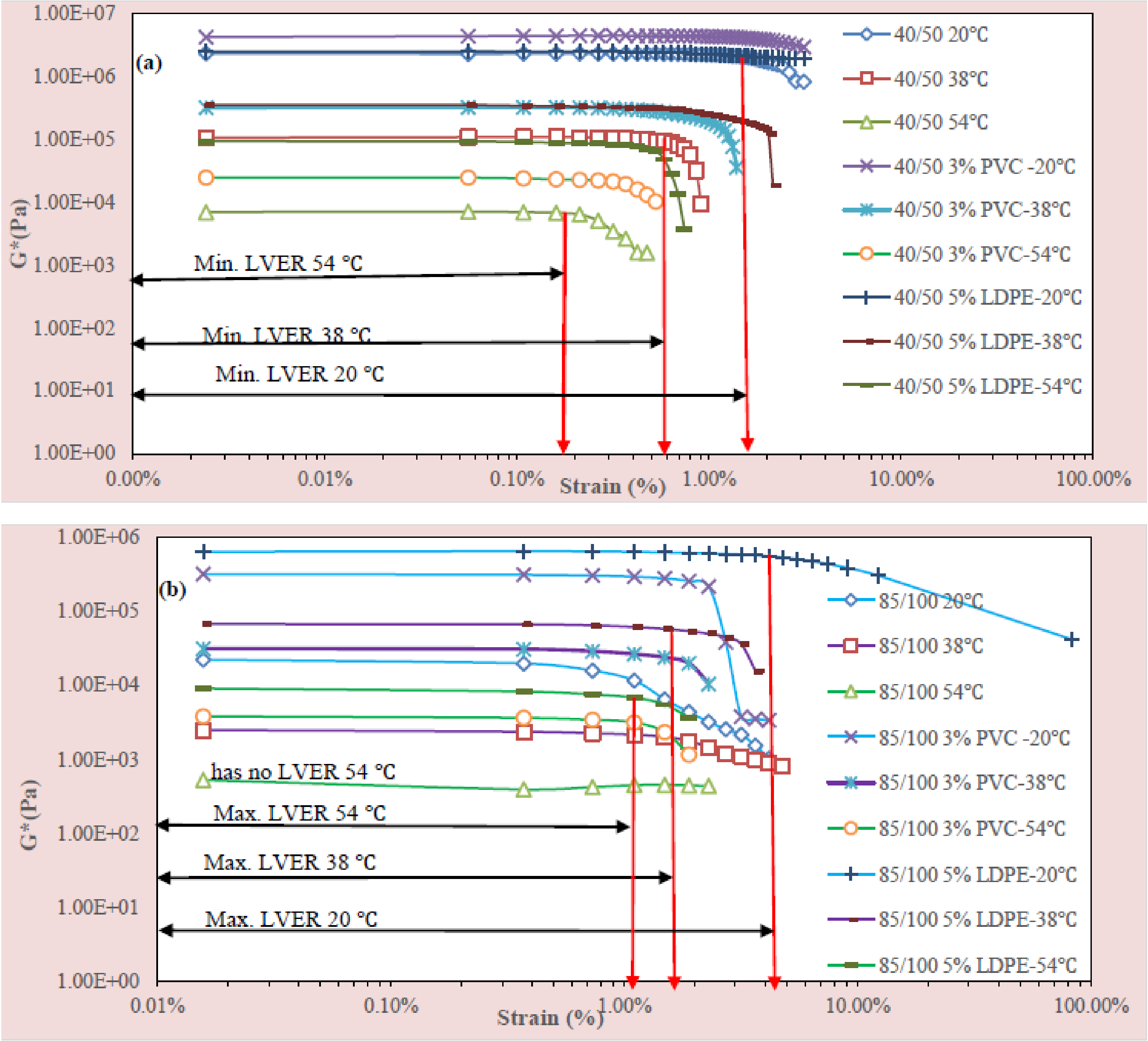

Figure 4. Effects of PVC and LDPE modifiers and temperature on **(a)** 40/50 and **(b)** 85/100 bitumen samples

3.6.2.2. Effect of Aging on Bitumen LVER

It is obvious that the linear viscoelastic region of unaged bitumen was greater than that of aged bitumen at workable temperature. For example, the LVE region of 85/100 and 40/50 unaged bitumen have changed from 0.75 to 0.5% and 0.65 to 0.45% after RTFO aged at 20 and 38°C, respectively.

The linear viscoelastic region of the RTFO aged pure bitumen was less than the RTFO aged modified binders like as a condition of unaged bitumen samples. The samples structure disturbance of RTFO aged pure bitumen was reached before the RTFO aged modified bitumen, which is the end of LVE region, as shown in Figure 5 (a) and (b). Linear viscoelastic region (LVER) of RTFO aged binders were affected not only by modifiers but also by temperature. As the temperature increased, LVER of the RTFO aged pure and modified bitumen decreased. But the temperature didn't alter the grade of the modified bitumen and pure bitumen. The LVER of RTFO aged pure and modified binders decreased uniformly as temperature getting increased as shown Figure 5 (a) and (b).

3.6.3. Multiple Stress Creep Recovery (MSCR) Test

The MSCR test is performed using the Dynamic Shear Rheometer (DSR) apparatus by applying a controlled shear stress of 0.1 kPa and 3.2 kPa using a haversine load for one second followed by a 9 second rest period. During each cycle, the bitumen reaches a peak strain and then recovers before the shear stress is applied again. The multiple stress creep recovery (MSCR) were conducted based on the performance grade of the binder and recommended MSCR testing temperatures. According to AASHTO M320, the recommended testing temperatures of MSCR test bitumen ranges from 46-70°C depending on their performance grade. In this study, the three maximum temperatures were taken, which are 58°C, 64°C and 70°C, for conducting the MSCR test on the selected six asphalt mastic samples (40/50, 40/50+3% PVC, 40/50 +5% LDPE, 85/100, 85/100 +3% PVC and 85/100 + 5% LDPE). The test data's have clearly shown the effect of load on the creep recovery of the mastic samples.

3.6.3.1. Modifiers Effect on Mastic MSCR

Both the PVC and LDPE modifiers were highly decreased the deformation rate of the multiple stress effect as shown in the modifiers effect on creep recovery of those mastics in Figure 6 (a). The deformation of both pure mastics were high compared to the modified bitumen samples at the same temperature (64°C).

The MSCR graphs of 85/100+5% LDPE, 40/50+3% PVC and 40/50+5% LDPE are not clearly shown in Figure 3.6(a). So the magnified graph of those samples were presented in Figure 3.6(b). As the Figure showed, 5% LDPE modified 40/50 and 85/100 had a better result than the other samples on both bitumen grades.

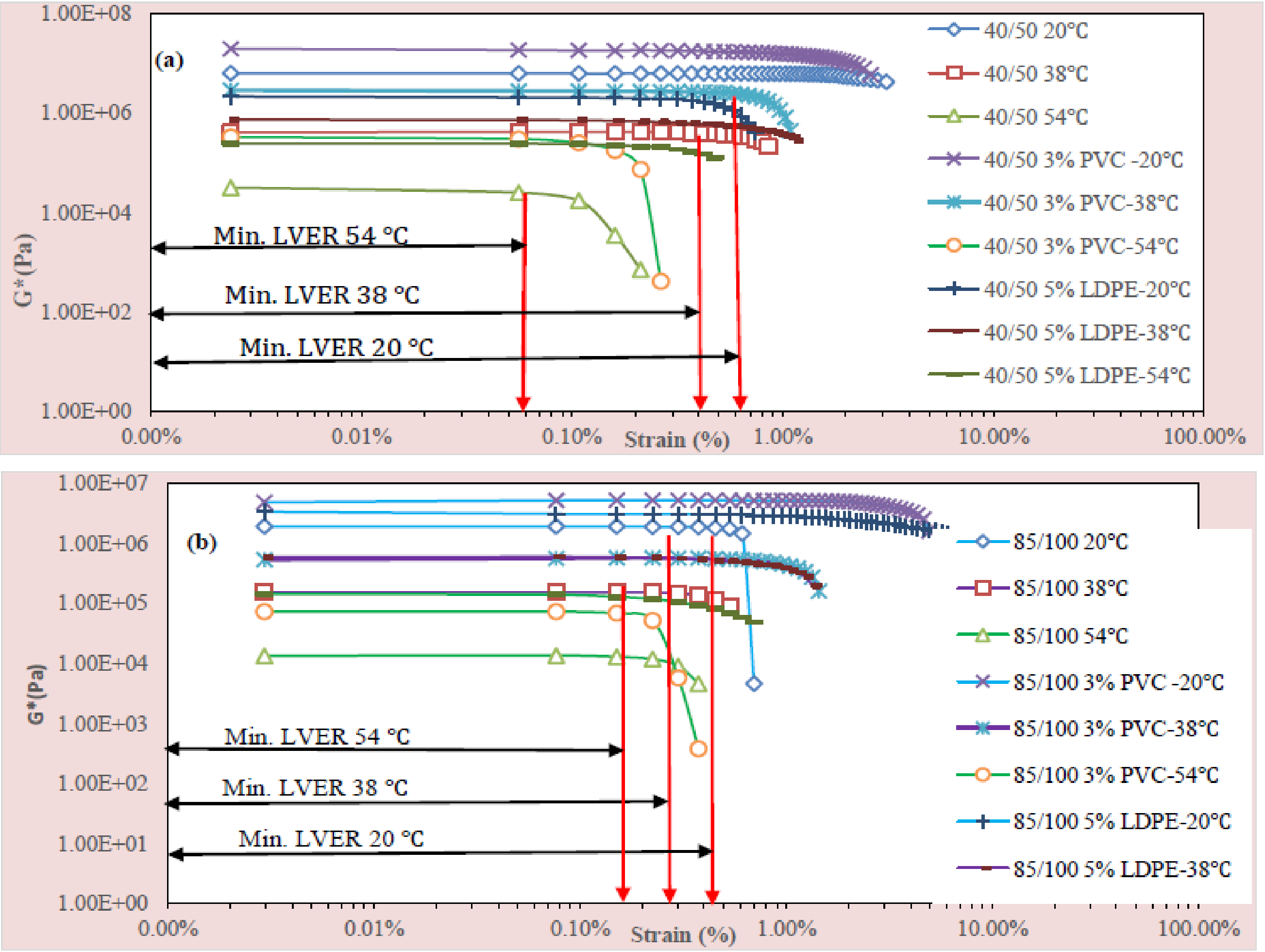

Figure 5. Effects of ageing on LVER of aged PVC and LDPE modified **(a)** 40/50 and **(b)** 85/100 bitumen

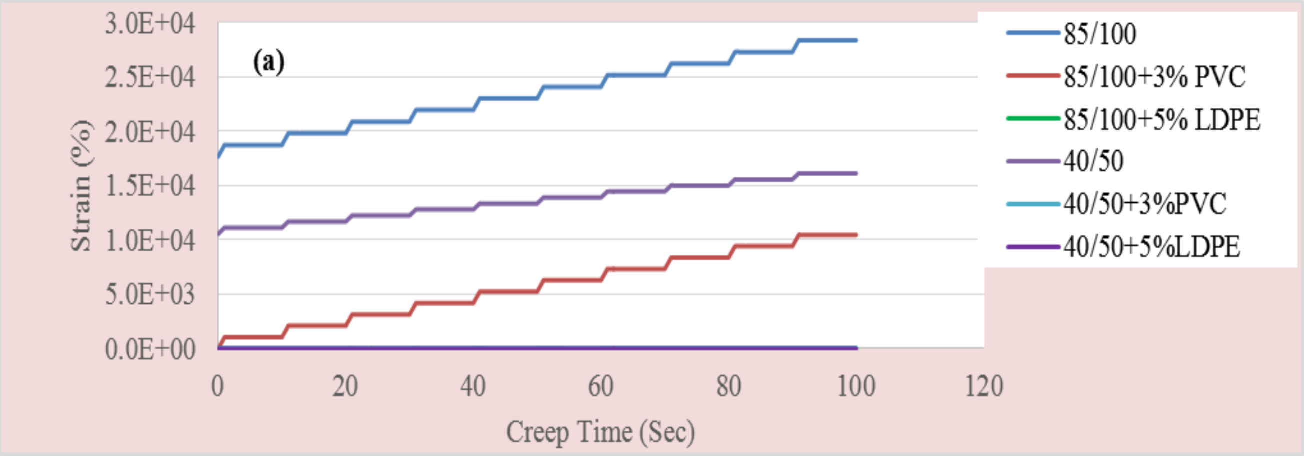

Figure 6. (a) PVC and LDPE modifiers effect on creep recovery of 40/50 and 85/100 mastics after 10 cycles @ 64°C

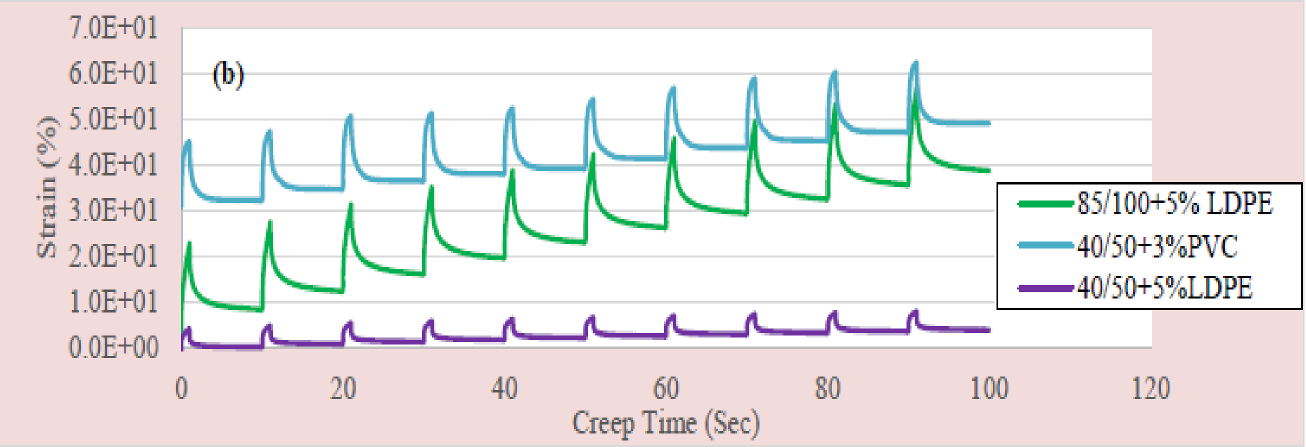

Figure 6. (b) PVC and LDPE modifiers effect on creep recovery of 40/50 and 85/100 mastics after 10 cycles @ 64°C

The modifiers reduced the strain rate of the pure bitumen by four and five times. Thus, it concluded that the PVC and LDPE modifiers at a selected percentage improved the multiple stress and rut susceptibility of the pure bitumens. PVC and LDPE modifiers can be the appropriate modifiers for the rheological properties of the bitumen at the selected percentage of the modifiers.

3.6.3.2. Temperature Effect on Mastic MSCR

In order to test temperature dependency, the three temperatures (58, 64 and 70°C) were taken to check all prepared samples. When the temperature were increased to 64 and 70°C, percent strain also getting increased as shown from Figure 7 on creep recovery graph . When the testing temperature increased from 58-64°C, the strain remained relatively constant and dramatically increased for all bitumen samples. For example, the 85/100+5% LDPE mastic total strain increased by 3.3 as test temperatures increased from 58 to 64°C and 7.6 as test temperature increased from 64 to 70°C. The samples modified by LDPE, at the selected percentage, reduced the strain effect than the samples modified by PVC (at the selected percentage) as shown in Figure 7.

3.6.4. Fourier Transform Infrared (FT-IR) Test

The selected bitumen samples were subjected to FT-IR analysis. These were the six samples of bitumens which are 40/50, 40/50+3% PVC, 40/50+5% LDPE, 85/100 85/100 +3% PVC and 85/100 +5% LDPE. The FT-IR Spectra analysis of these six samples are shown in Figure 8.

The FT-IR spectra peaks of the LDPE and PVC modified 40/50 bitumen samples were higher than the pure 40/50 bitumen at various peak positions and intensities appearing at 470cm^{-1}, 545cm^{-1}, and in the regions 2265-2280cm^{-1} and 3750 –3995cm^{-1}.

On the other hand, peaks appearing at 600 and in the region 3750-4000cm^{-1} is lower than that in the PVC modified 85/100 binder as observed in Figure 8. The result of IR test shows that the free O-H group of polymeric species undergoes in chemical interactions with the asphalt binder. This also implies the O-H group is not in a free state completely.

Another indication of structural changes in bitumen on addition of the plastics into the pure bitumen was disappearance of some peaks and appearance of some new peaks in the modified bitumen samples. Pure bitumen has peak values at 600cm^{-1}, a cluster of peaks in the region 2150-2260cm^{-1} and 3750–4000cm^{-1} which disappear on the LDPE modified 85/100 bitumen as observed in Figure 8 (b).

The modified bitumens had higher intensities than the pure bitumens. The pure and modified 40/50 bitumen had also a higher intensities than that of the pure and modified 85/100 bitumens, respectively. This indicates that the plastic modifiers modified the base bitumens effectively as proved in all FT-IR Figures.

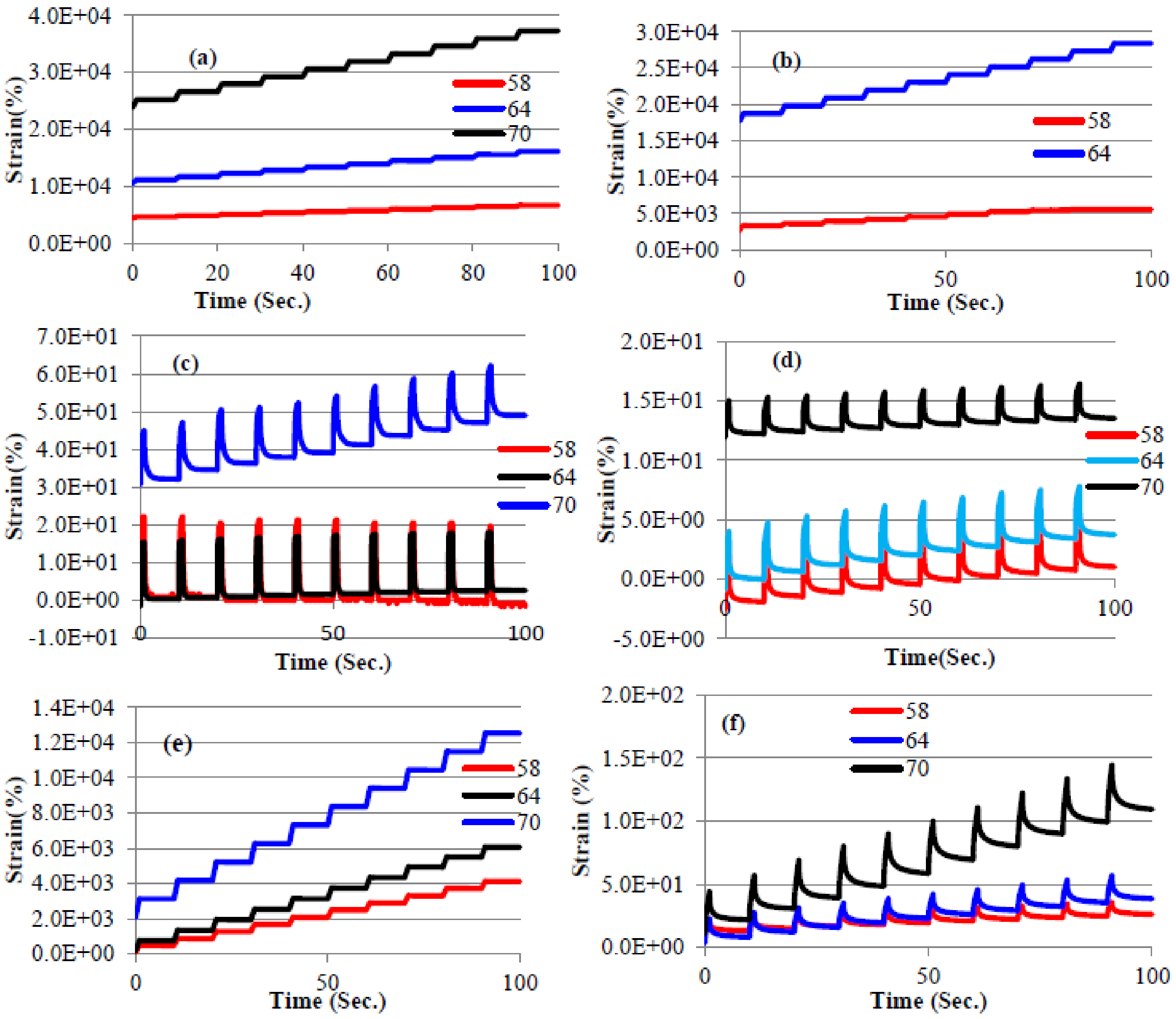

Figure 7. Temperature effect on creep recovery of (a) 40/50, (b) 85/100, (c) 40/50+3% PVC, (d) 40/50 +5% LDPE, (e) 85/100 +3% PVC and (f) 85/100 + 5% LDPE after 10 cycles

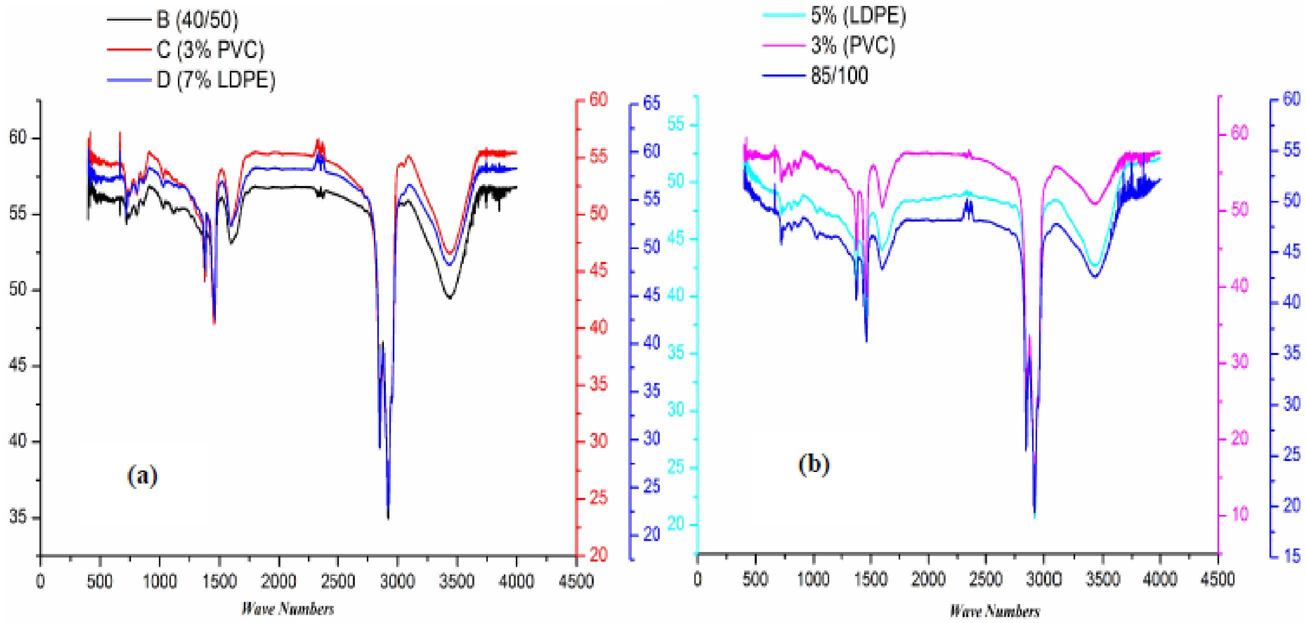

Figure 8. FT-IR Spectra of pure and modified **(a)** 40/50 and **(b)** 85/100 bitumens

4. Conclusions

The following conclusions are given on bitumen rheology depending on consistency, RTFO, DSR, and FT-IR test results. The study evaluated the effects of different percentages of PVC (1-7%) and LDPE (1-9%) plastics by weight of bitumen on the rheological properties of 40/50 and 85/100 binder grades.

According to softening point, penetration index (PI), ductility, and performance grading (PG) test results, 40/50+5% PVC, 40/50+7% PVC, 40/50+7% LDPE, 40/50+9% LDPE, 85/100+5% PVC, 85/100+7% PVC, 85/100+7% LDPE and 85/100+9% LDPE were out of the requirements of penetration grading and Superpave grading systems. But 3% PVC and 5% LDPE by weight of bitumen improved the rheological properties of both 40/50 and 85/100 bitumens in the limit of both grading systems than the other percentages of plastics.

3% PVC by weight of bitumen improved 40/50 and 85/100 penetration grades of bitumen to 30/40 and 60/70, 52.75 and 45.85°C softening points to 59.8 and 53.85°C, 126.7 and 150+ cm ductility length to 105.4 and 122 cm, and PG 64-Z and PG 52-Z performance grades to PG 82-Z and PG 76-Z grades both 40/50 and 85/100 bitumens, respectively.

5% LDPE by weight of bitumen also improved 40/50 and 85/100 penetration grades of bitumen to 30/40 and 60/70, 52.75 and 45.85°C softening points to 62.65 and 55.2°C, 126.7 and 150+ cm ductility length to 100.9 and 121.9cm, and PG 64-Z and PG 52-Z performance grades to PG 82-Z (both) grades both 40/50 and 85/100 bitumens, respectively.

3% PVC and 5% LDPE modifiers by weight of bitumen were reduced the penetration and ductility values, increased the softening point and performance grades of both 40/50 and 85/100 grade of bitumens. Thus, a bitumen with lower penetration, higher softening point and lower ductility means it withstands higher loads, has better binding property and withstands higher temperature, and has good elasticity in the proper ductile region, respectively.

The values found from the rolling thin film oven had also shown that both PVC and LDPE (at 3 and 5%, respectively) modified bitumen had lower percent loss at the selected percentage of PVC and LDPE by weight of bitumen. This shows that the percentage loss during mixing and compacting were lower than the pure bitumens at mixing and compacting temperatures at 3% PVC and 5% LDPE by weight of bitumen.

LVE region values of the PVC and LDPE modified unaged and aged bitumens have shown that their LVER were higher than the pure bitumen at different temperatures. This means that the disturbance of the modified bitumens during deformation or applied load were greater than the pure bitumens. Which implies that a mixture with a modified bitumen can withstand heavy traffic loads with a great linear visco-elastic region. Creep recovery values of the PVC and LDPE modified aged bitumens shows, the modified bitumens were better under multiple creep and had higher percent recovery after load than the pure bitumens at different temperatures. This result concluded that a mixture with a modified bitumens could not easily exposed for rutting and other failures. The FT-IR analysis also proved that both PVC and LDPE modify 40/50 and 85/100 grade of bitumens effectively.

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