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Evaluation of Rheology and Moisture Susceptibility of Asphalt Mixtures Modified with Low Density Polyethylene

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Abstract: This study evaluated rheological properties of low density polyethylene (LDPE) modified asphalts using conventional methods (penetration, softening point and rotational viscosity) and dynamic mechanical analysis (DMA). In addition, Marshall Properties and moisture damage of mixtures from these asphalts and four aggregates were studied using ASTM D1559 and ASTM D4867. LDPE modification improved asphalt temperature susceptibility. Practical LDPE dosages obtained were 2.5% and 3.0% (w/w) for 60/70 and 80/100 asphalts, respectively. LDPE addition slowed down approach of asphalt to a pure viscous liquid while increasing complex modulus at high temperature. The modified asphalts exhibited pseudo-plasticity and LDPE reduced shear susceptibilities of 60/70 and 80/100 asphalts by 16% and 34%, respectively. Modified mixtures exhibited stability increase to a maximum followed by a decrease possibly because of stretching of asphalt by LDPE. The total voids in mix remained within 3-5% for LDPE dosages between 0 and 3%. Limestone mixtures resisted moisture damage, while pumice behavior was asphalt specific. Neat granite and quartzite mixtures did not resist moisture damage though LDPE made them resistant.

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***Key words**: Aggregate; Asphalt; Moisture; Polyethylene; Rheology.*

Introduction

Asphalt pavements are normally subjected to high stresses under harsh environmental conditions. To guarantee proper performance of structural asphalt bound layers, some of the crucial asphalt properties include high stiffness at moderate or elevated temperatures to avoid deformation, and high resistance to moisture damage at the asphalt-aggregate interface. To achieve these properties, plastics (plastomers) are added to asphalt so as to improve temperature susceptibility, shear susceptibility, viscoelastic response, volumetric properties and resistance to moisture damage [1-7]. Plastomers commonly used to achieve this include polyethylene (PE), polypropylene (PP), ethyl vinyl acetate (EVA), polyvinyl chloride (PVC), polyolefins, etc [8]. These polymers should be compatible with asphalt, must resist degradation at high mixing temperatures, should be capable of being processed by mixing/laying equipment, should maintain their properties after blending with asphalt during storage and are required to be cost-effective [9]. To achieve the goal of asphalt modification, polymers should create a secondary network within asphalt by molecular interactions or by reacting chemically with the asphalt.

This work centered on utilization of low density polyethylene (LDPE) which is non-polar in nature and immiscible with asphalt. Its use is usually limited to the production of impermeable membranes in which case, higher quantities (6-30% w/w) are added with respect to those used in asphalt paving mixtures [10]. LDPE is a plastomer available as plastic bags which after domestic use causes disposal and environmental problems. Particles of plastic bags are less tightly packed and less crystalline because of side branches, and hence their density is low. A major challenge with asphalt modified with plastomers is control of storage stability. A solution to this challenge involves adding comonomer components with active polar groups which chemically react with asphalt during blending and hence prevents separation of the asphalt and the plastomer [10].

Rheological evaluation of asphalt can be made based on properties like Penetration Index (PI) and Viscoelasticity. PI is commonly used as a quantitative measure of temperature susceptibility of asphalt [8]. The lower the PI the higher the temperature susceptibility. Asphalt with PI < - 2 is Newtonian and highly temperature susceptible since it embrittles at low temperatures and is prone to cracking [8]. Asphalt with PI > +2 is less brittle and exhibits elastic properties under high strains [11]. The acceptable range of PI is -1.0 to +1.0 to ensure good performance. Asphalt viscoelastic response can be assessed using dynamic rheological properties which refer to its response to periodically varying stresses and strains. Asphalt exhibits viscoelastic behaviour depending on the temperature and time over which observations are made. Response of asphalt to loading changes from purely elastic obeying Hooke's law to purely viscous or Newtonian as temperature increases. Many asphalts exhibit a small temperature range of viscoelastic behaviour marking transition from elastic to viscous response. The smaller this range is, the more the field deterioration, manifested as thermal cracking and/or deformation. A wide variety of experimental equipment for measuring the dynamic properties of asphalt has been developed [9]. Polymers may modify asphalt rheology and hence improve performance with respect to PI and Viscoelasticity. In this research, PI was determined based on the conventional asphalt properties like penetration and softening point. Viscoelastic response was determined based on complex modulus and phase angle, which were measured using Dynamic Mechanical Analysis (DMA) employing shear rheometry.

Polymer treatment of HMA to abate moisture-induced damage is

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a promising strategy and has been encouraged by many agencies. Polymers utilize the desirable properties of different functionalities in the same molecule and offer improved water resistance capability. Influence of both elastomers and plastomers on moisture damage has been largely studied although systematic characterization has not been achieved. Limited research work has centered on the use of LDPE in controlling moisture attach especially in acidic asphalts that are known to be prone to this damage. Attempts have been made to mix plastomers (e.g. Elvaloy) with phosphoric acid before blending with asphalt to improve both polymer dispersion and performance [12]. Most research has focused on low acid asphalts from crude sources with acid numbers less than 0.5 mg/g.

In this paper, focus was placed on LDPE modification of asphalts with high acidity with hope that this might contribute to homogeneous dispersion of polymer in the asphalt. The objectives of this investigation were: (i) to evaluate consistency and rheological properties of LDPE modified asphalts, (ii) to ascertain whether LDPE may be beneficial in improving Marshall Properties and moisture susceptibility of these asphalts. The dosage of LDPE used to evaluate Marshall properties and moisture susceptibility was determined by controlling temperature susceptibility based on the requirement of PI to be within the acceptable range of -1.0 to +1.0, and the PI being the maximum possible to minimize temperature susceptibility.

Experimental

Materials

Asphalts

Two asphalts of penetration grades 60/70 and 80/100 were used. The asphalts were sampled from drum deliveries by Energo contractors in Uganda, working on an overlay project of the East African regional highway corridor with high truck tire pressures (95% confidence interval of 0.82 - 0.96 MPa) serving northern Uganda and southern Sudan [13]. Information from the contractors indicated that the asphalts were sourced from Laguna, Venezuelan crude and some of their test properties are given in Table 1. These asphalts were highly acidic as indicated by their high acid numbers of 3.59 and 3.22 mg/g for 60/70 and 80/100 asphalts, determined in accordance with ASTM D 664-95.

Low Density Polyethylene (LDPE)

Plastic bags were furnished by BMK Plastics Company in Kampala who provided information reported in Table 2. These data indicate that the material is an LDPE. The plastic bags were shredded using a pair of scissors to about 5mm by 5mm for ease of heating before mixing with asphalt. The LDPE modified asphalt was prepared at 150°C using a shear mixer with the stirrer set at 2000 rpm. LDPE contents used ranged from 0.5% to 4.0% by weight of blend in steps of 0.5%. Typically, 500 g of asphalt was preheated for 3 hours at 150°C to fluid condition in a 1500 mL spherical flask. Upon reaching 145°C a pre-weighed amount of polymer melted to 135°C using a convection oven was carefully added to the asphalt. Mixing proceeded at 150°C for 15 minutes. After mixing, the polymer/asphalt mixture was divided into small cans, sealed in aluminum foil and carefully kept in an oxygen-free environment at room temperature for 2 hours. No phase separation was observed after the above storage. The base (unmodified) asphalt was also subjected to similar temperature treatment as the blends in order to make an accurate evaluation of the LDPE effects.

Table 1. Properties of Original Base Asphalts.

Property	Asphalt	
	60/70	80/100
Penetration, 25°C, 100g/5s, (dmm)[a]	63.0	86.7
Softening Point, (°C)[b]	50.8	46.8
Specific Gravity (g/cm^3)[c]	1.021	1.015
Ductility, 25°C, (cm)[d]	108	122
Brookfield Viscosity, 135°C, (mPa.s)[e]	564	482
Complex Modulus at 10°C (MPa)	11.8	5.8
Phase Angle at 10°C (degrees)	41	46
Acid Number (mg/g)[f]	3.59	3.22

[a] ASTM D5; [b] ASTM D36; [c] ASTM D2041 [d] ASTM D113; [e]ASTM D4402; [f] ASTM D664-95

Table 2. Mechanical and Physical Properties of LDPE Used.

Property	Value	Standard
Density (g/cm^3)	0.920	ASTM D792
Tensile Strength (N/mm^2)	14.6	ASTM D638
Water Absorption, 24 hrs (%)	Trace	ASTM D570
Tensile Elongation at Yield (%)	560	ASTM D638
Coeff. of Linear Expansion (/°F)	3.4×10^{-5}	ASTM D696
Melting Point (°C)	106	ASTM D3418
Operating Temperature (°C)	68 Max	-

Aggregates

Four aggregates obtained from different parts of Uganda were used with the two LDPE modified asphalts to study Marshall properties and moisture susceptibility. Properties of the aggregates are listed in Table 3. The aggregate grading proposed for this study conformed to Ugandan dense graded mix specifications as shown in Fig. 1.

Methods

Rheometry and Viscosity Tests

In this work, viscoelastic properties of the modified asphalts were determined using dynamic mechanical analysis (DMA) in accordance with AASHTO TP5-97. Measurements were made using a controlled dynamic shear rheometer (Rheometrics-RDA II) instrument with a sinusoidal strain set at a frequency of 10 rad/s (1.6 Hz) and temperature sweeps from 30 to 100°C typical of Ugandan traffic speeds and tropical pavement temperatures, respectively. Parallel plates (diameters 8 mm and 1.5 mm gap) were used. In each test, about 0.2 g of the test sample was applied to the bottom plate covering the entire surface and then mounted into the rheometer. When material had reached the softening point, the top plate was carefully placed onto the sample, followed by neat trimming of the protruding parts of the sandwiched asphalt. After adjusting the final gap to 1.5 mm, the sinusoidal strain was applied by an actuator. Viscoelastic parameters (complex modulus, G* and phase angle, δ), were obtained by a computer directly connected to the rheometer.

Table 3. Physical and Mineralogical Properties of the Aggregates.

	Granite	Quartzite	Limestone	Pumice	Specification
ACV	7.5	14.6	7.4	19.6	21 Max
AIV	14.4	22.0	23.4	38.9	25 Max
Flakiness Index	18	21	22	23	25 Max
Specific Gravity (g/cm^3)	2.778	2.676	2.598	2.469	-
Water Absorption (%)	0.77	1.16	3.04	2.15	-
Rock Type	Igneous	Metamorphic	Sedimentary	Volcanic Ash	-
Quartz	35	89	4	nd (not determined)	-
Orthoclase	46	2	-	nd	-
Plagioclase	7	-	-	nd	-
Augite	-	-	-	nd	-
Hornblende	-	2	-	nd	-
Calcite	-	-	85	nd	-
Others	12	7	11	nd	-

Table 4. Marshall Properties of Asphalt Mixtures.

Asphalt	Property	Aggregate			
		Granite	Quartzite	Limestone	Pumice
60/70	OBC, %	4.86	4.80	5.40	5.50
	Stability, kN	8.10	19.4	20.4	19.7
	AV, %	3.50	3.66	4.39	4.50
	VFA, %	78.00	76.60	69.91	66.77
	VMA, %	15.91	15.64	14.59	13.54
80/100	OBC, %	5.00	4.78	5.60	5.30
	Stability, kN	8.05	17.3	19.5	19.9
	AV, %	3.82	3.94	4.24	5.13
	VFA, %	76.24	75.00	71.02	61.57
	VMA, %	16.08	15.76	14.63	13.35

Being a principal asphalt rheological property, viscosity of modified asphalts was measured using a rotational (Brookfield) viscometer fitted with a thermosel. 30 g of modified asphalt was heated in an oven to sufficient fluidity at 130^{o}C. The sample was weighed in a sample chamber, placed in the thermosel and left for the temperature to settle at 135^{o}C. The spindle was then lowered into the chamber and when the temperature was stable, the viscometer was turned on at a set speed. Viscosity (in Pa.s) was obtained from the digital display of the viscometer. The flow behavior was investigated using five speeds of the viscometer i.e. 15.0, 17.5, 20.0, 22.5 and 25.0 rpm (corresponding to shear rates of 900, 1050, 1200, 1350 and 1500 s^{-1}).

Mix Preparation

Marshall Mix design (ASTM D1559) was conducted to determine the optimum binder content (OBC) and other fundamental properties for each binder/aggretate combination and the results are given in Table 4. The properties included air voids (AV), voids filled with asphalt (VFA), voids in mineral aggregates (VMA) and Marshall Stability. At the OBC and each dosage of LDPE, three (3) replicate Marshall Specimens (100mm diameter and 63mm height) were prepared using 75 blows for all aggregates and binders compacted at 140^{o}C. These were, as much as practically possible, kept identical with respect to air voids content, aggregate gradation, level of compaction, asphalt content, 24 hour storage, and others. They were used to assess the impact of LDPE asphalt modification on mixture Marshall Properties.

Moisture Sensitivity

Moisture susceptibility of the specimen mixtures at the practical LDPE contents for the asphalts was evaluated in terms of Retained Stability (RS) and indirect Tensile Strength Ratio (TSR). RS and TSR are ratios of mean stability and indirect tensile strength, respectively, after and before water conditioning. Prior to moisture sensitivity evaluation, air voids were calculated and checked to ensure saturation during conditioning. 12 replicate specimens for

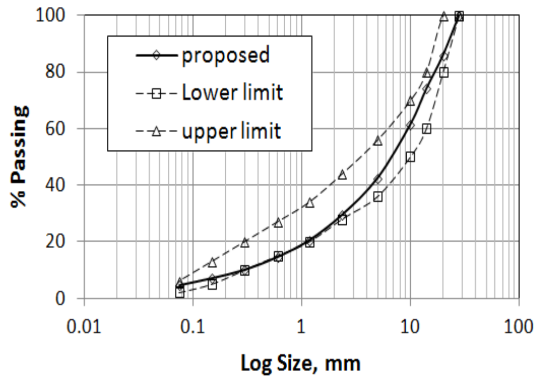

Fig. 1. Grain Size Distribution of Asphalt Mixtures.

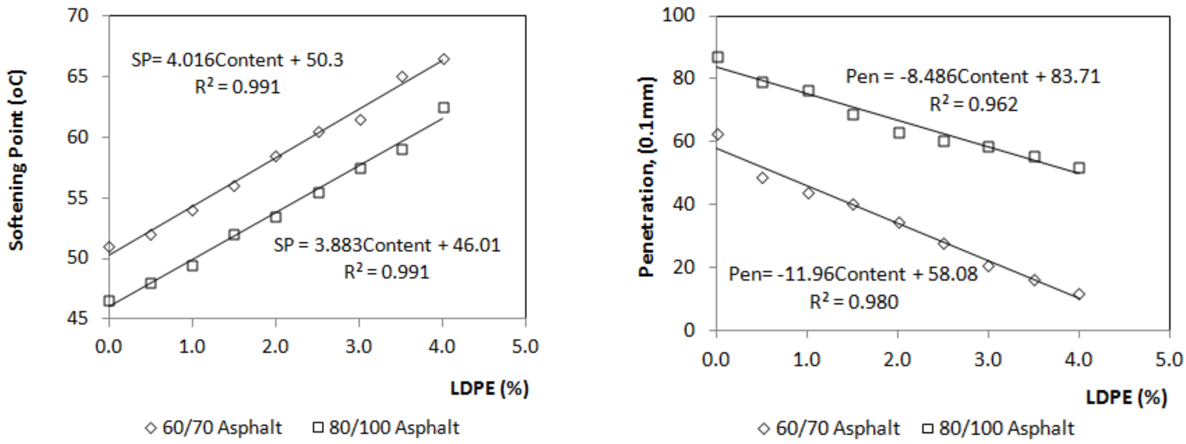

Fig. 2. Consistency Results for the LDPE Modified Asphalts.

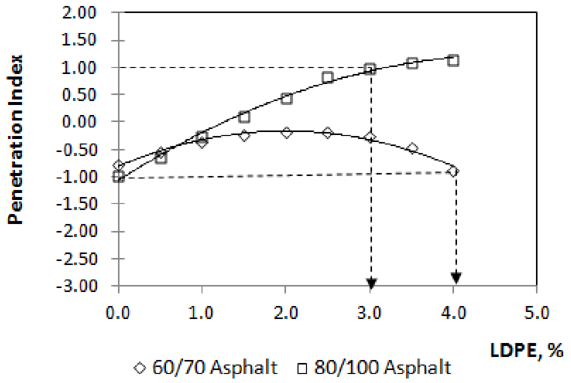

Fig. 3. Variation of Temperature Susceptibility for LDPE Modified Asphalts.

each binder/aggregate combination were used. RS and TSR were each determined using 6 specimens randomly apportioned into two groups from the 12 specimens. In accordance with ASTM D4867, the conditioned specimens were partially saturated for 5 minutes using a vacuum chamber at 67 kPa. Afterwards, specimens were soaked in a water bath for 24 hours at 60°C followed by 1 hour soaking at 25±1°C before testing. On the contrary, the unconditioned specimens were kept in the laboratory at room temperature for 24 hours. Marshall Stability and Indirect Tensile strengths were each separately determined at 25°C on 3 conditioned and 3 unconditioned specimens for each binder/aggregate combination. A UTM 25 hydraulic testing machine (Australian model) was used.

Results and Discussion

Consistency and Rheological Properties

Temperature Susceptibility

Fig. 2 shows variation of softening point and penetration with increasing concentration of LDPE with linear fits put to the data using MS Excel. The results show that LDPE modification of asphalt increases deformation resistance since stiffness raises with reduction in penetration and increase in softening point. Asphalt 60/70 exhibited higher sensitivity to LDPE since its slope was higher than that of 80/100 in both situations. The relationship between Penetration Index (PI) and LDPE concentration was examined. For each LDPE dosage, penetration and softening point were determined from the linear fits of Fig. 2 and the Pfeiffer and van Doormaal method used to determine PI. The results of PI for the modified asphalts are shown in Fig. 3. The PI of asphalt 80/100 increased from -0.9 to +1.5 indicating reduction in temperature susceptibility with LDPE dosage. The PI for the 60/70 asphalt ascends from -1.0 to about -0.16 at LDPE of 2.5% then drops back to -1.0. In other words, its temperature susceptibility reduces with polymer modification up to 2.5% LDPE beyond which, temperature susceptibility starts increasing. Extrapolation of the curve for the 80/100 asphalt suggests that this behaviour observed with the 60/70 asphalt (reversal of temperature susceptibility) might also be observed at high LDPE concentrations. Horizontal (dotted) lines corresponding to PI extremes of -1.0 to +1.0 were extended up to the curves and the corresponding LDPE dosages obtained. Based on the criteria explained earlier (at end of section 1) for determination of practical LDPE concentrations, dosages of 2.5% and 3.0% by weight of 60/70 and 80/100 asphalts, respectively, are appropriate and were used to evaluate Marshall Properties and moisture susceptibility.

Viscoelasticity for Modified Binders

In this part of the study, the modified asphalts at LDPE contents of 1.0%, 2.0% and 3.0% were used to ascertain rheological behaviour. Viscoelastic behavior of the modified asphalts from intermediate to high service temperatures (30 – 100°C) was assessed using dynamic mechanical analysis. Phase angle and complex modulus – as functions of temperature – were determined at 1.59 Hz over a temperature range of 30 – 100°C. The results are given in Fig. 4. The phase angle generally increases rapidly to a maximum at a temperature of 70°C after which, it becomes more or less constant. Besides the influence of temperature, addition of LDPE leads to reduction in the maximum phase angle. Increased differences (more separation of curves) in phase angles of asphalts with different LDPE concentrations tend to become prominent as temperature increases from 40°C to 100°C. This means that LDPE may slow down the approach of asphalt to a pure viscous liquid. In other words, the dissipation of stored energy per cycle of deformation reduces with increase in LDPE dosage. This is desirable as it is an

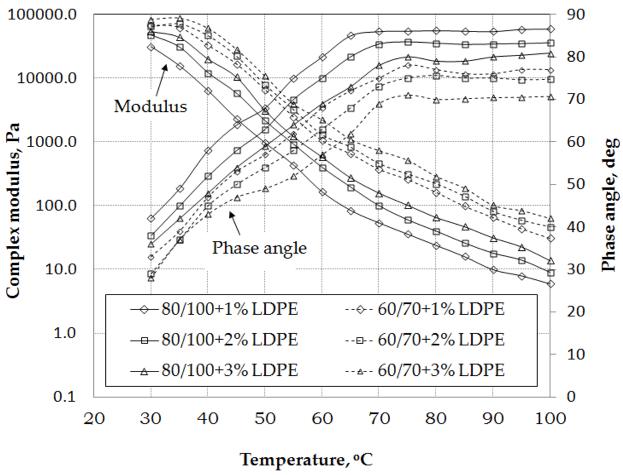

Fig. 4. Viscoelastic Response of the LDPE Modified Asphalts.

Table 5. Temperatures of Blends at Minimum Superpave Rutting Factor.

Asphalt/LDPE Blend	Temperature @ G*/Sinδ = 1 kPa
80/100+1% LDPE	49
80/100+2% LDPE	56
80/100+3% LDPE	58
60/70+1% LDPE	61
60/70+2% LDPE	64
60/70+3% LDPE	67

indication of improvement in viscoelastic response at high temperature, resulting in improved resistance to deformation. The complex modulus generally decreases with increase in temperature and decrease in LDPE concentration. The shapes of plots of complex modulus do not vary with asphalt grade or LDPE concentration. However, as expected the 80/100 asphalt exhibited lower complex moduli compared to the 60/70 asphalt irrespective of the concentration of LDPE. The above observations suggest that LDPE polymers increase complex modulus as well as improving elasticity (increase G* and decrease δ). To draw more definite conclusions, detailed investigations on chemistry of the base asphalts are necessary.

The influence of LDPE on asphalt deformation properties was also investigated. Accordingly, the rheological parameter G*/sinδ selected by Superpave at 10 rad/s was used to express the binder contribution to deformation in the SHRP specifications. High G*/sinδ indicates high resistance to deformation with a limit of 3 kPa set by superpave. This criterion suggests that the binder should have both high complex modulus and elasticity at high pavement temperatures. Since LDPE polymers have been shown to increase G* and decrease δ, G*/sinδ would increase with LDPE asphalt modification. The magnitude of this increase would depend on both asphalt grade and concentration of LDPE. Generally, the stiffer 60/70 asphalts exhibit higher resistance to deformation than the 80/100 grade for all dosages of LDPE. Addition of LDPE with increasing concentration from 1 to 3% improved rutting resistance for both asphalts. At a rutting factor level of 1 kPa (recommended by Superpave), the corresponding temperatures for the different blends are given in Table 5. Generally, the temperatures at G*/sinδ = 1 kPa increased with % LDPE dosage for the two asphalts, indicating improved high temperature performance.

Viscosity and Shear Susceptibility

The viscosity – shear rate comparisons for LDPE modified asphalts are presented in Fig. 5. The asphalts somewhat deviate from Newtonian behaviour and tend to exhibit shear thinning or pseudo-plasticity. From the figure, LDPE modified asphalts have higher viscosities at the same shear rate than the original asphalts. Non-Newtonian behavior is modeled using Eq. (1).

$$\tau = \eta\left(\dot{\gamma}\right)^{c} \tag{1}$$

Hence, $\log\eta = \log\tau - c\log\gamma$

In the equation, c is shear index got from flow data, γ is shear rate, η is viscosity and τ is shear stress. Asphalts are considered dilatant, Newtonian like, or pseudo-plastic when $c > 1.0$, $c = 1.00$, or $c < 1.0$, respectively. Addition of LDPE to asphalts has a significant effect on their shear susceptibility. Since shear susceptibility depends on temperature and asphalt composition, it is not easy to make a broad statement about its effects [8]. The test data (η and γ) for each shear rate were regressed based on Eq. (1) to establish c for the modified asphalts. The values of c were plotted against LDPE dosage as shown in Fig. 6 for the two asphalts. It appears that LDPE modification shifts the asphalts from near-Newtonian flow characteristics ($c = 1.0$) to pseudo-plastic (stress dependent) characteristics ($c < 1.0$). The rates of decrease in shear index, c (reduction in shear susceptibility) were computed as 16% and 34% for 60/70 and 80/100 asphalts, respectively, as the dosage of LDPE increased from 0 to 3%. The reason for this variability for the two asphalts could not be obtained from this study.

Marshall Properties and Moisture Susceptibility

Marshall Stability

Marshall Stability measures mass viscosity of asphalt/aggregate mixtures and may determine resistance to permanent deformation [8]. For each asphalt/aggregate combination at increasing LDPE, Marshall Stability for the 3 replicate specimens was determined at OBC following the gradation in Fig. 1. Fig. 7 illustrates the effect of LDPE on Marshall Stability of the specimens. Mixtures of modified 60/70 asphalt and quartzite, limestone and pumice exhibited gradual increase in stability to a maximum at 2.5% LDPE beyond which the stability decreased. Granite mixtures exhibited lower stability compared to the other aggregates although with similar trend with maximum stability at 3.0% LDPE. For 80/100 modified asphalt mixtures, Marshall Stabilities similarly increased up to a maximum at 3.0% LDPE followed by a decrease. The stability values for 60/70 asphalt mixtures were generally higher than those of 80/100 asphalt for all aggregate types except Pumice. Addition of LDPE initially increases viscosity and stiffness of the asphalt which raises its rigidity thereby reducing deformation [10]. This increase in viscosity and stiffness goes on up to some dosage of LDPE where stability is observed as maximum. Addition of more LDPE polymer

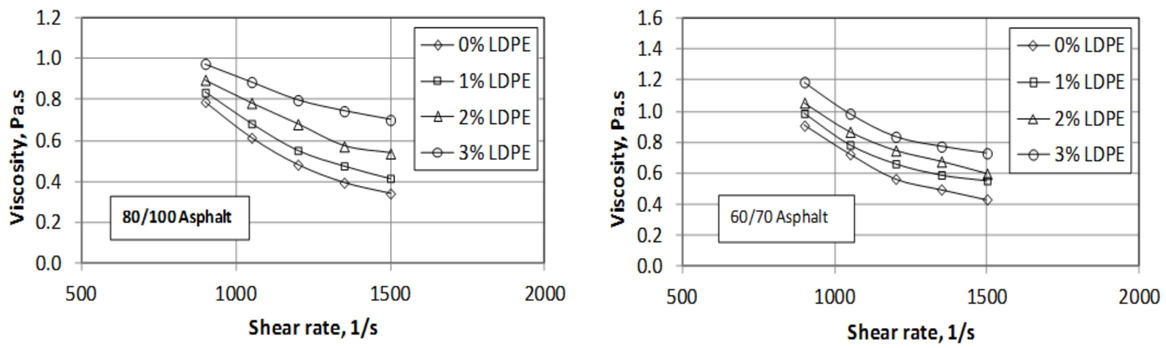

Fig. 5. Relationships between Shear Rate and Viscosity for Modified Asphalt.

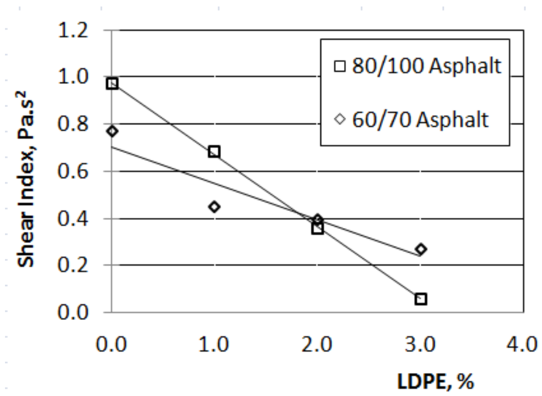

Fig. 6. Effect of LDPE on Shear Susceptibility of Asphalt.

causes coarse dispersions of the polymer leading to stretching or increasing of asphalt volume and perhaps making the mixture exhibit higher voids filled with asphalt [9]. This asphalt with too much polymer is less stiff and therefore causes lowering of Marshall Stability.

Voids in Total Mix

Air voids determine aging of asphalt films and entry of water into the binder/aggregate matrix and hence influence performance. Air voids were calculated from results of Rice specific gravity (ASTM D2041) and bulk specific gravity (ASTM D2726). Fig. 8 shows the influence of LDPE modification on air voids in total mix. The air voids in modified asphalt concrete mixtures generally decreased with LDPE for limestone and pumice for the two asphalts. Granite and quartzite mixtures did not exhibit significant decrease in air voids. At each level of LDPE content, the voids in mix for the 60/70 asphalt mixtures were in most cases lower than for the 80/100 asphalt mixtures. At dosages above 3.0%, the mixtures tend to get out of the air voids range of 3-5% specified by most agencies [8]. As indicated in the previous section, addition of LDPE seems to stretch the asphalt making the mixture exhibit higher voids filled with asphalt, hence reducing the air voids in total mix. Differences observed between aggregates might be ascribed to variations in their asphalt absorption by surface permeable pores.

Moisture Sensitivity Results

Fig. 9 shows the average RS and TSR of the mixtures involving the two asphalts and four aggregates. It appears that moisture damage propensity is sensitive to modification using LDPE. The data indicate that the highest resistance to moisture damage was obtained using limestone and 60/70 asphalt modified with 2.5% LDPE. For ease of analysis, the RS and TSR values at these parameters (limestone and 2.5% LDPE modified 69/70 asphalt) were arbitrarily assigned values of 100 for RS and TSR. The values at other conditions were proportionately normalized relative to these values and all these normalized values are listed in Table 6. RS or TSR value of 70% was taken as the minimum to ensure good performance, since it has been generally considered suitable by many agencies [14-15]. Consequently, the normalized values for RS = 70% and TSR = 70% are 83.0% and 84.6%, respectively, and are included at the bottom of Table 6.

Observing the results in Table 6 in relation to these normalized

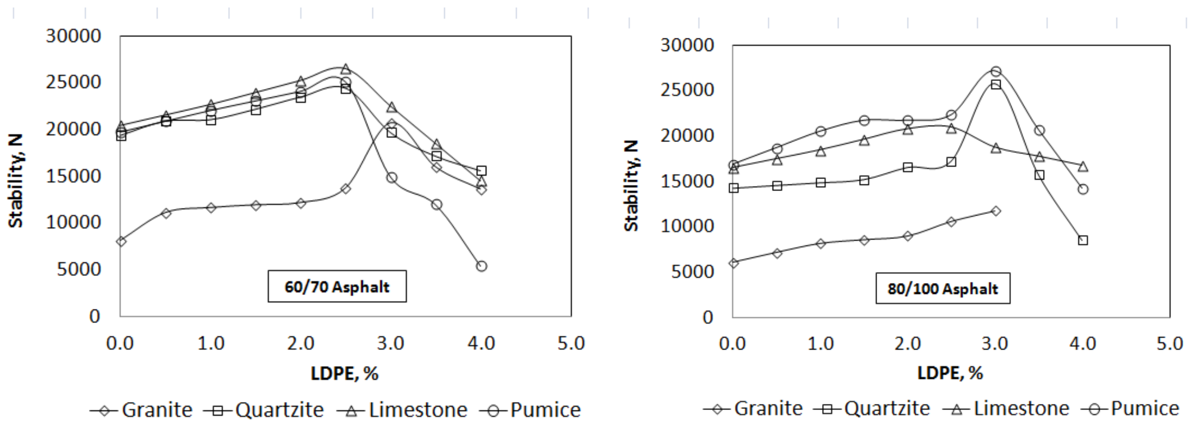

Fig. 7. Marshall Stability of Modified Mixtures from Different Aggregates.

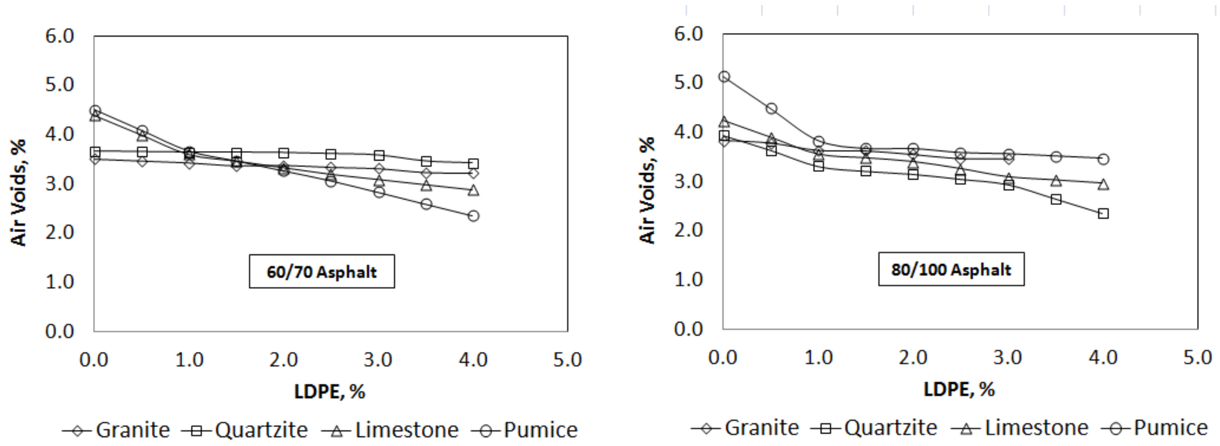

Fig. 8. Air Voids in Modified Mixtures from Different Aggregates.

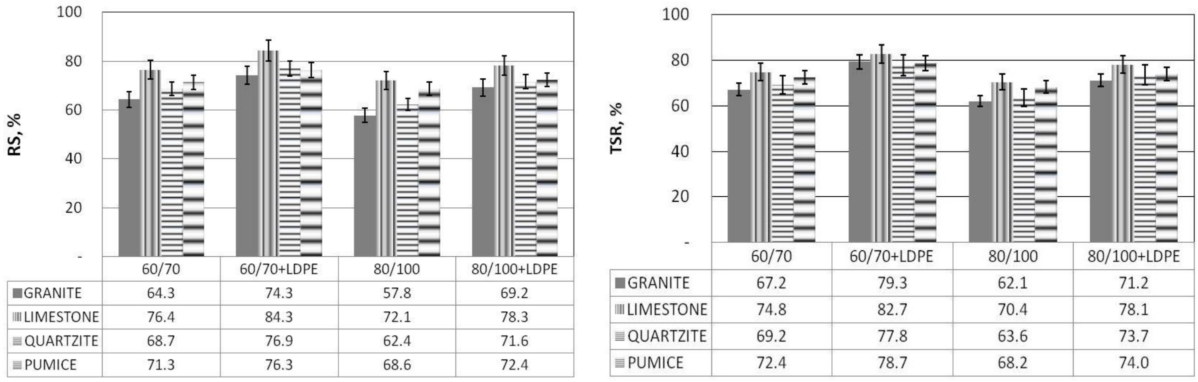

Fig. 9. Influence of LDPE on Water Susceptibility for Different Aggregates.

Table 6. Normalized Results of Moisture Conditioned Mixtures.

	RS, %				TSR, %			
	60/70		80/100		60/70		80/100	
	Plain	2.5% LDPE	Plain	3.0% LDPE	Plain	2.5% LDPE	Plain	3.0% LDPE
Granite	76	88	69	82	81	96	75	86
Limestone	91	100	86	93	90	100	85	94
Quartzite	81	91	74	85	84	94	77	89
Pumice	85	90	81	86	88	95	82	89
Min Values	83.0				84.6			

limiting values, it appears that limestone aggregate exhibited good resistance to moisture damage (normalized RS > 83.0% and TSR > 84.6%) irrespective of the asphalt used or LDPE concentration. The resistance of pumice to moisture damage was asphalt specific since all its mixtures showed good resistance to water damage except those from unmodified 80/100 asphalt. Limestone and pumice aggregates seem to have asphalt absorbing crevices and pores in their surfaces. The results in Tables 3 and 4 showing higher water absorption and OBC values, respectively, corroborate this postulate. It therefore appears that asphalt penetrates these pores promoting better adhesion and mechanical tenacity between asphalt and the aggregate making it difficult for them to separate during water conditioning. Mixtures from granite and quartzite without LDPE modification showed low resistance to moisture damage for both asphalts studied (normalized RS < 83.0% and TSR < 84.6%). Modification with LDPE made these mixtures become resistant to moisture damage. In other words, mixtures from both asphalts and granite or quartzite aggregate (common in central Uganda) exhibiting moisture damage propensity can be improved with LDPE modification. Research has shown that an aggregate with high contents of quartz and orthoclase exhibit surface silanols that render themselves poor adherends to asphalt in presence of water [6]. Resistance to moisture damage for mixtures from such aggregates can only be ascribed to asphalt tenacity which is only mobilized in presence of rough surfaces.

Statistical analysis was done to identify the factors which might contribute significantly to the RS and TSR of the mixtures used in this study. The factors considered were aggregate type (4 levels), asphalt type (2 levels) and LDPE modification (2 levels). ANOVA was applied to the overall data generated from the tests at a 0.05 level of significance. The results of this analysis listed in Table 7 indicate that all the main factors were significant while their two-way interactions were not significant except aggregate/LDPE modification for RS.

Table 7. ANOVA Results Showing p-values for Moisture Damage Results.

Source	RS		TSR	
Single Main Factor				
Aggregate Type (A)	0.001	√	0.007	√
Asphalt Type (B)	0.001	√	0.002	√
LDPE Modification (C)	0.000	√	0.000	√
2-Way Interaction				
(A) x (B)	0.246	x	0.443	x
(A) x (C)	0.034	√	0.124	x
(B) x (C)	0.897	x	0.595	x
R^2 Value	0.986		0.975	

√ indicates that a factor or interaction is significant with respect to major dependent variable; x indicates that a factor or interaction is not significant with respect to major dependent variable.

Conclusions

1. Modification of asphalt with LDPE improved deformation resistance of the asphalts studied since this intervention increased viscosity and stiffness. Practical LDPE dosages of 2.5% and 3.0% are recommended for 60/70 and 80/100 asphalts, respectively, based on temperature susceptibility control.
2. LDPE addition to asphalt slowed down approach of the studied asphalts to a pure viscous liquid while increasing complex modulus at temperatures above 70^{o}C.
3. Modified asphalts deviated from Newtonian flow for all LDPE dosages, typical of pseudo-plasticity. The shear indices or reductions in shear susceptibilities for 60/70 and 80/100 asphalts were 16 and 34%, respectively, as the LDPE dosage increased from 0 to 3%.
4. Addition of LDPE to the asphalts studied increased Marshall Stability and hence resistance to plastic flow up to a maximum followed by a reduction. This might be ascribed to elongation of asphalt by the polymer.
5. Air voids in modified mixtures generally decreased with % LDPE for limestone and pumice and the asphalts studied, while granite and quartzite mixtures did not exhibit significant decrease in % air voids. At LDPE dosages above below3.0%, the mixtures air voids range remained within 3 - 5%.
6. Limestone and pumice aggregates exhibited good resistance to moisture damage. This did hold for limestone irrespective of the asphalt used or LDPE modification while the behavior of pumice was asphalt specific with or without LDPE. Mixtures from granite and quartzite without LDPE modification showed low resistance to moisture damage for both asphalts studied although modification with LDPE rendered them resistant.

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