Influence of Polymer Type and Structure on Polymer Modified Asphalt Concrete Mix

Ibnelwaleed A. Hussein[1*], Hamad I. Al-Abdul Wahhab[2] and Mohammad H. Iqbal[1]

1. Department of Chemical Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

2. Department of Civil Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

Two low-density polyethylene (LDPE) resins and two ethyl vinyl acetate (EVA) polymers were used to modify asphalt binder, and then mixed with asphalt concrete according to Marshall Method of mix design (ASTM D 1559). Effect of weight average molecular weight (M_w) of LDPE and vinyl acetate (VA) content of EVA was studied by performing Marshall Stability, moisture susceptibility (AASHTO T 283-89), resilient modulus (M_R) and permanent deformation (rutting) tests. EVA with low VA content showed lower stability loss in Marshall Stability test and improved resistance in moisture susceptibility test in comparison to hot mix asphalt concrete mix (HMA) and other polymer modified asphalt concrete mixes (PMAMs). Higher M_R and better rutting resistance were observed for PMAMs than that of HMA. This elastic behaviour of modified asphalt correlates very well with the M_R and rutting resistance properties of PMAM.

On a utilisé deux résines de polyéthylène (LDPE) de faible masse volumique et deux polymères d'acétate d'éthyl vinyl (EVA) afin de modifier le liant asphaltique, puis de le mélanger avec du béton asphalte selon la méthode de Marshall de conception des mélanges (ASTM D 1559). On a étudié l'effet du poids moléculaire (M_w) moyen du LDPE et de la teneur en acétate de vinyle (VA) de l'EVA au moyen de divers tests : stabilité de Marshall, susceptibilité à l'humidité (AASHTO T 283-89), module d'élasticité (M_R) et déformation permanente (orniérage). L'EVA de faible teneur en VA montre une perte de stabilité moindre dans le test de stabilité de Marshall et une meilleure résistance dans le test de susceptibilité à l'humidité, comparativement au mélange béton asphalte mélangé à chaud (HMA) et d'autres mélanges de béton asphalte modifié par des polymères (PMAM). On observe un meilleur M_R et une meilleure résistance à l'orniérage pour les PMAM que pour les HMA. Le comportement élastique de l'asphalte modifié montre une très bonne corrélation avec les propriétés de M_R et de résistance à l'orniérage des PMAM.

Keywords: asphalt concrete mix, Marshall Stability, moisture susceptibility, resilient modulus, permanent deformation

INTRODUCTION

Although 4–6 wt.% of asphalt binder is used with hot mixed asphalt concrete mix (HMA), it improves pavement performance significantly (Al-Dubabe et al., 1998). The most commonly observed types of distress in asphalt concrete pavements are rutting, fatigue cracking, low temperature cracking, aging, ravelling and stripping.

Many investigations were performed on polymer modified asphalt (PMA), where asphalt binder is modified by different types of polymers. Goodrich (1988) related asphalt binder and PMA performance to the performance of asphalt concrete mix. It was observed that the performance of PMA such as temperature susceptibility, force ductility, and low temperature ductility didn't correlate with the performance of the mixes with modified binders. It was concluded that tests that involve very high strains didn't correlate conventional asphalt binder tests to the performance of HMA. In another study, Anderson et al. (1999) studied the relationship between low-temperature binder stiffness and HMA stiffness and poor correlation was reported. However, many researchers (Panda and Mazumder, 2002; Chen et al., 2004; Airey et al., 2004; Hansen and Anderton, 1993; Parker and Brown, 1992; Perdomo et al., 1992; Zoorob and Suparma, 2000; Zhou et al., 1997; Amirkhanian and Williams, 1993; Iqbal et al., in press) investigated the properties of HMA and PMAM, and improvement in performance among asphalt concrete mixes was compared. Moreover, some researchers studied modelling of HMA behaviour like viscoelastic properties, permeability, etc. (Berthelot et al., 2003; Krishnan and Rao, 2001).

Murphy et al. (2001) modified asphalt binder using recycled polymers like polyethylenes, polypropylenes, polyetherpoly-urethane and rubber. The performance was evaluated by measuring viscosity, penetration, softening point, aging and rheology. Moreover, mix tests like indirect tensile stiffness and

* *Author to whom correspondence may be addressed.*
E-mail address: ihussein@kfupm.edu.sa

rutting resistance were performed. In that study, rutting performance was appeared to reflect the binders melt rheology. Therefore, there are different reports about the correlation between the properties of PMA and their mixes.

In a recent publication (Hussein et al., 2005), our group studied the influence of the weight average molecular weight (M_W) of low-density polyethylene (LDPE) and vinyl acetate (VA) content of ethyl vinyl acetate (EVA) on the properties of PMA. It was found that EVA with low VA content (19.5 wt.%) showed the best storage stability and reduced temperature susceptibility as well. Moreover, EVA modified asphalt extended the window of the performance grading (PG) and improved viscoelastic behaviour of base asphalt binder. In addition, the influence of the M_W of LDPE on the properties of PMA was studied.

In this study, the effect of polymer type and structure on polymer modified asphalt concrete mix (PMAM) was investigated. Effect of polymer structure was observed by studying influence of molecular weight of low-density polyethylene (LDPE) and the VA content of EVA on the properties of PMAM. On the other hand, properties of LDPE PMAM and EVA PMAM were compared to observe the effect of polymer type. These observations were based on Marshall Stability test, moisture susceptibility (stripping) test, resilient modulus and permanent deformation measurements. Moreover, correlation between PMA and PMAM was investigated.

EXPERIMENTAL

Material

Two LDPEs of different M_w and two EVA polymers of different VA contents were used to modify asphalt binder. This modification was done with 4% polymer as this concentration satisfied the required PG (76-10) in the Arabian Gulf region (Hussein et al., 2005). The PG was evaluated according to Strategic Highway Research Program (SHRP) specification. Table 1 shows the properties of the polymers used in this study as well as the PG for PMAs, where asphalt binder was mixed with 4% of each polymer. The polymer resins were supplied by ExxonMobil, Belgium. Supplier data are presented in Table 1. Moreover, M_w and molecular weight distribution (MWD) are reported, which were measured by gel permeation chromatography (WATER GPC2000). Details of this measurement are described elsewhere (Hussein et al., 2005).

Asphalt binder of PG 64-22 was used in this study. The asphalt binder was obtained from Saudi Aramco Riyadh Refinery. Low M_w LDPE was labelled as LDPE1 and the high M_W LDPE as LDPE2. On the other hand, EVA with 19 wt.% VA content was represented by EVA1 and the 27.5 wt.% VA content of EVA by EVA2. The two EVA resins had the same melt flow index (MFI). Aggregates, used to prepare mix samples, were obtained from local sources (details are given in Table 2). Comparison of the two LDPEs will reveal the influence of M_w. Similarly, the effect of VA content will be obtained by comparing the two EVA resins. Moreover, LDPE1 and EVA1 mixes have similar MFI, which might provide insight on whether LDPE or EVA (similar MFI, see Table 1) provide better PMAMs.

Polymer and PMA Sample Preparation

25 mm diameter and 2 mm thick flat discs of as received polymer were prepared in a carver press for rheological tests. A mould temperature of ~20°C above the melting point of each polymer was selected. Polymer resins were charged between two platen of the carver press and pressure between the platens was raised gradually up to 7 metric tons and kept for 5 min. Water flow was allowed to cool the platens to room temperature, and disc shaped polymer samples were collected.

PMA samples were prepared by blending pre-weighed polymer with asphalt binder at 160°C in a high shear blender (~2500 rpm) at optimum blending time (OBT), which was 30, 20, 15 and 20 min for LDPE1, LDPE2, EVA1 and EVA2, respectively. Determination of OBT was mentioned elsewhere (Hussein et al., 2005). In addition, asphalt binder was treated under similar conditions up to 50 min to give similar processing conditions. After blending, samples were collected in a rubber mould and used to perform frequency sweep tests in an ARES rheometer. A temperature of 50°C and a strain of 20% (in linear viscoelastic region) were used in frequency sweep tests. The purpose of frequency sweep test is to compare frequency response of polymer modified asphalt binder with that of modified asphalt mix.

Mix Design

The mix design was done according to Marshall Method (ASTM D 1559) of mixed design. Wearing course was used as mix code. The details of the mix design for base asphalt mix are given in Table 2 and similar design was used for PMAM. The standard cylindrical shaped Marshall specimen of 100 mm × 62.5 mm was prepared for HMA and PMAM. The prepared specimens were used for the following tests.

Marshall Stability Test

Stability is an important property of the bitumen mixture in the wearing course design. It shows the ability to resist shoving and rutting under traffic (Hınıslıoğlu and Ağar, 2004). Marshall Stability test of HMA and PMAM was performed in a Marshall testing machine at a constant rate of 51 mm/min. Six specimens were immersed into a water bath at 60°C. After 40 min (initial condition), 3 specimens were tested and the average compressive load required to break the sample was determined and corrected by multiplying with a stability correction factor to get the initial stability. The remaining 3 specimens were kept for 24 h and the required compressive load was measured in the same way to get the final stability.

Table 1. Characterization of polymers

Polymer	Density (g/cm^3)	Melting point (°C)	MFI (g/10 min)	M_W (kg/mol)	MWD	PG (asphalt binder + 4% of corresponding polymer)
LDPE1	0.913	100	155	71.92	9.75	76–16
LDPE2	0.913	100	70	102.93	12.4	76–10
EVA1 (19 wt.% VA)	0.938	81	150	45.63	4.71	82–10
EVA2 (27.5 wt.% VA)	0.950	68	150	40.48	5.4	76–22

Moisture Susceptibility Test (Lottman Test, AASHTO T-283-89)

Moisture susceptibility was evaluated by determining the changes in the mechanical properties of the specimens after conditioning. This test reveals the resistance of compacted bituminous mixture to moisture induced damage. It is done by measuring the change of diametral tensile strength resulting from the effects of saturation and accelerated water conditioning of compacted asphalt mixtures in the laboratory. The results may be used to simulate the long-term stripping susceptibility of the asphalt mixtures. Samples were conditioned in water for 2 h at room temperature. The load was applied on the specimen at a constant deformation rate of 51 mm/min and the load at failure was measured at dry condition. This load is called indirect tensile strength (ITS). For the wet condition, specimens were subjected to vacuum up to a saturation level of 60%, in water at 60°C for 24 h, then at room temperature for 2 h, and finally ITS was measured. The ratio between the value of the wet ITS and the dry ITS was calculated and expressed in percent form, which is known as tensile strength ratio (TSR).

Resilient Modulus, M_R (ASTM D 4123)

Diameter resilient modulus is the measure of pavement response in terms of dynamic stresses and corresponding strains. A static load of about 10 lb was applied to hold the specimen in place. A dynamic load in the elastic range was applied with a frequency of 1 Hz (ASTM D 4123), and the resulting horizontal deformation was obtained at 50°C. Our interest was to evaluate M_R at high temperature (76°C) since PG in the Gulf region is 76-10, but the maximum attainable temperature in the existing experimental set-up is 50°C.

Permanent Deformation (Rutting)

Permanent deformation measurements were performed on HMA and PMAM at 50°C. The controlled stress loading at 150 initial μ-strain level, which showed elastic region, was used at 1 Hz. The deformation was measured by linear variable differential transducer and data were stored in a data logger. The data were collected at every 5 s for the first 100 load repetitions; every 10 s for the next 100 repetitions; then every 15 s for the following 100 repetitions, and finally every 30 s up to the sample failure.

RESULTS AND DISCUSSIONS

Melt Rheology

Rheology is the science of deformation and flow of materials. Melt rheology means measurement of rheological properties (viscosity and elasticity) of PMA in the melt state. For PMAM the measurement of stress-strain relationship is considered solid-state rheology. Viscoelastic properties of PMA were measured in the melt state. In Figure 1, storage modulus, G′, of PMA is shown for the 4 wt.% polymer concentration. Moreover, base asphalt binder was shown for comparison purposes. Addition of polymers increased G′ value of base asphalt binder. The highest increase was obtained for EVA1 modified asphalt. At low frequency (ω), both LDPEs and EVA2 PMAs showed similar values of G′. At high ω, G' value for EVA2 modified asphalt was the lowest among other PMAs. In the following sections, we will examine whether the melt rheology of PMA is correlated with the properties of their PMAM.

Marshall Stability Test

The results of Marshall Stability are presented in Table 3. Three samples were used to obtain the average stability and the

Table 2. Mix design

	Job mix formula (JMF)	Specification limits
1. Optimum asphalt binder content, % (PG 64–22)	5.3	5.3 +/– 0.3
2. Aggregate grading: % Passing		
1″	100	100
3/4″	87	80–95
# 4	55	48–62
# 10	38	32–45
# 40	21	16–26
# 80	13	8–18
# 200	6	4–8
3. Marshall test results (75 blows, compaction temperature 150°C)		
Stability (kN)	18.04	8.00 Min.
% Air voids. Total mix	4.4	4.0–6.0
Flow (mm)	3.2	2.0–4.0
% Voids filled w/asphalt	74	70–80
Stability loss (%)	16.2	20 Max.
Void in mineral aggregates (VMA)	16.04	–

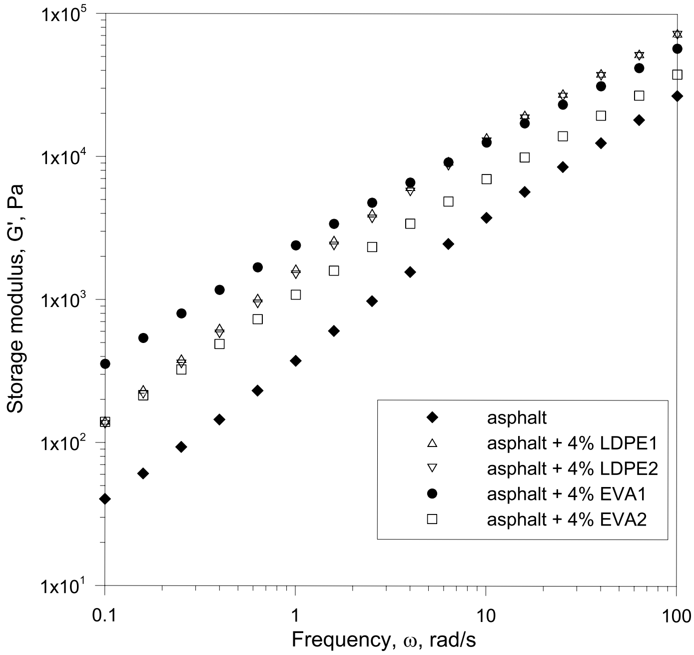

Figure 1. G′(ω) of asphalt binder and PMAs (T_{test} = 50°C)

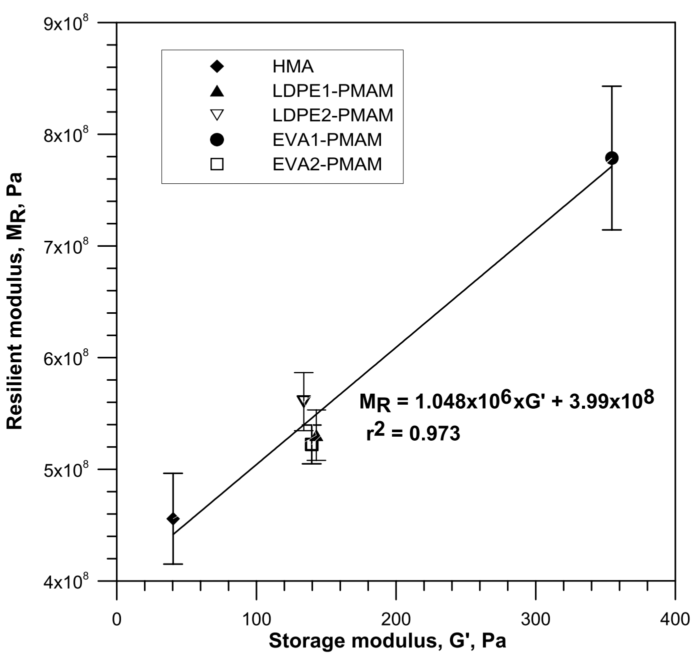

Figure 2. Resilient modulus for HMA and PMAMs at 50°C

corresponding standard deviations were reported. It can be observed that the initial stability for HMA was higher than PMAM. All PMAMs showed similar initial stability. The percent stability loss was the highest for HMA and the least for EVA1-PMAM. No significant difference in percent stability loss was observed between LDPE1 and LDPE2. Therefore, increasing M_w from 72 to 102 kg/mol had no effect on the stability of LDPE modified asphalt concrete mixes. EVA1 mix showed remarkable retained stability in comparison with EVA2. The reason is likely the presence of lower amount of VA in EVA1. EVA with high VA content has a rigid long molecule that is not compatible with asphalt's constituents as discussed in a previous publication (Hussein et al., 2005). Comparison between polymer types

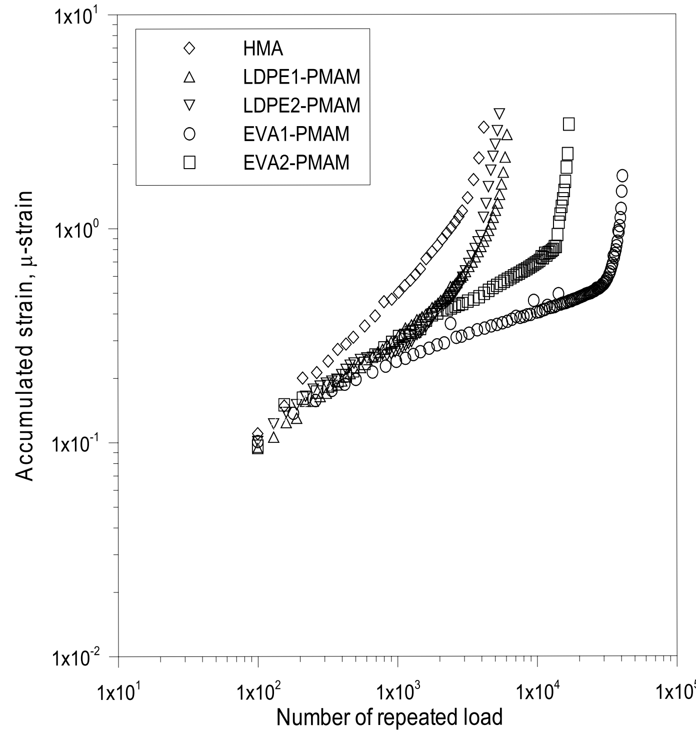

Figure 3. Rutting curve at 150 µ-strain at 50°C

(LDPE1 and EVA1) of similar MFI suggests that EVA1 is more stable than LDPE1.

Moisture Susceptibility Test

The initial and final ITS values were presented in Table 4. The average ITS value for three specimens is shown along with the standard deviation. The TSRs were lower for PMAMs in comparison to HMA except EVA1 mix, which indicates that PMAMs retained less strength due to water saturation in comparison to HMA. LDPE may have physical bond only with asphalt phase. No network behaviour or cross-linking (chemical bond) is expected from such a stable polymer made by free radical polymerization (Hussein et al., 2000). The physical bonding between PMA and aggregates is expected to be weakened; resulting in loss in ITS. Moreover, these results show that LDPE1 (low M_w) PMAM is more water sensitive than that of LDPE2 (high M_w) PMAM. The previous rheological results suggest that LDPE2 forms better homogeneous mixture with asphalt binder than that of LDPE1. EVA1 showed excellent network behaviour in PMAM and retained ITS was the best. Values of TSR for EVA2 PMAM are comparable to LDPE PMAMs. Earlier results (Hussein et al., 2005) showed better storage stability for EVA1 modified asphalt over that of EVA2 modified asphalt. Also, the resistance to moisture induced damage of EVA1 is better than LDPE1.

Resilient Modulus, M_R

The resilient modulus of HMA and PMAM at 50°C is given in Figure 2. It was observed that M_R for PMAM was higher than that of HMA. These results are in agreement with previous reports (Jew et al., 1986; Metcalf et al., 2000). Both LDPE PMAMs showed almost similar increase in resilient modulus. On the other hand, EVA1 displayed a higher M_R in comparison with EVA2, is a consequence of its high G′ modulus. Moreover, EVA1 showed the highest increase in M_R value among all polymers used in this study. Thus, EVA with low VA content is superior

Table 3. Marshall Stability test

Sample ID	Condition	Sample no.	Stability (kN)	Average stability (kN)	Standard deviation	% decrease in stability
HMA	Initial	1	20.22	19.81	0.35	34
		2	19.64			
		3	19.58			
	Final	1	11.61	13.15	1.39	
		2	14.32			
		3	13.53			
LDPE1-PMAM	Initial	1	16.49	15.33	1	30
		2	14.69			
		3	14.82			
	Final	1	10.06	10.66	0.53	
		2	10.82			
		3	11.10			
LDPE2-PMAM	Initial	1	15.55	14.40	1.52	32
		2	12.68			
		3	14.98			
	Final	1	10.85	9.74	1.21	
		2	9.92			
		3	8.45			
EVA1-PMAM	Initial	1	14.52	14.71	0.21	7
		2	14.67			
		3	14.95			
	Final	1	12.85	12.70	0.63	
		2	12.01			
		3	13.26			
EVA2-PMAM	Initial	1	16.62	15.11	1.43	32
		2	13.76			
		3	14.95			
	Final	1	10.53	10.37	0.17	
		2	10.19			
		3	10.38			

over LDPE (values of G' at a $\omega = 0.1$ rad/s were used in this plot). Data of G' at low ω are usually used to detect morphological differences (Hussein et al., 2003). These results correlate very well with the G′ data of these polymers, where the trend was qualitatively similar. Similar results were reported by the authors for acrylate polymers (Iqbal et al., in press). In this case, value of G' has been taken at 0.016 Hz (0.1 rad/s) rather than 1 Hz to show the robustness of the correlation. Therefore, qualitative screening of polymer for their M_R values could be obtained from simple measurement of G′ of the PMA rather than the PMAM. This means major reductions in testing and savings in resources.

Permanent Deformation (Rutting)

The accumulated strain vs. repeated load at initial tensile strain level of 150 μ-strain and 50°C is displayed in Figure 3. At low repeating loads, there was no significant difference in deformation between HMA and PMAMs. But this difference was distinguishable at higher repetitions, where HMA showed higher permanent deformation rate than PMAMs. Similar findings were reported in previous studies (Srivastava et al., 1992; Baig and Al-Abdul Wahhab, 1998; Iqbal et al., in press). Regardless of the major difference in M_w of the two LDPEs, their rutting resistance is comparable. These results are in agreement with their G′ data, where the two LDPE PMAs showed very similar values (see Figure 1). Although rheological tests were performed at small strain and rutting at large strain, both LDPEs showed comparable performance in each case. Moreover, EVA1 with a higher value of G' (more elastic) than EVA2 demonstrated a higher rutting resistance. Although it is difficult to correlate the linear viscoelastic properties of PMA to the non-linear properties of asphalt concrete mixes, the increase in the elasticity of the PMA is reflected on the rutting properties of PMAMs. The EVA with the highest value of G' showed the best rutting resistance and the LDPEs of similar value of G' displayed similar rutting properties. In another paper the authors (Iqbal et al., in press) obtained similar results for Acrylate polymers. Is this a coincidence? In this study, EVAs were generally better than LDPE in asphalt binder modification. Therefore, it is not just the elasticity that plays a major role in the rutting properties. The polymer structure is another important factor. In general, at such high strains both the elasticity of the PMA and the polymer structure

Table 4. Moisture sensitivity test (Lottman Test)

Sample ID	Condition	Sample no.	ITS (kN)	Average ITS (kN)	Standard deviation	TSR
HMA	Dry	1	10.74	10.77	0.04	62.11
		2	10.77			
		3	10.82			
	Wet	1	6.37	6.69	0.92	
		2	7.73			
		3	5.98			
LDPE1-PMAM	Dry	1	10.48	10.07	0.31	35.75
		2	10.00			
		3	9.90			
	Wet	1	3.45	3.60	0.32	
		2	3.98			
		3	3.38			
LDPE2-PMAM	Dry	1	9.63	9.50	0.13	56.73
		2	9.36			
		3	9.50			
	Wet	1	5.99	5.39	0.96	
		2	5.92			
		3	4.28			
EVA1-PMAM	Dry	1	10.52	10.56	0.37	79.64
		2	10.22			
		3	10.96			
	Wet	1	8.12	8.41	0.36	
		2	8.82			
		3	8.31			
EVA2-PMAM	Dry	1	11.76	11.31	0.50	51.72
		2	10.77			
		3	11.40			
	Wet	1	4.85	5.85	1.12	
		2	7.07			
		3	5.63			

Table 5. Rutting coefficients

Mix type	Anti log of intercept	Slope	R^2
HMA	0.0045	0.6876	0.9957
LDPE1-PMAM	0.0082	0.5277	0.997
LDPE2-PMAM	0.0123	0.4635	0.975
EVA1-PMAM	0.037	0.2657	0.9686
EVA2-PMAM	0.0188	0.3957	0.987

are important in determining the rutting properties of PMAMs. EVA2 rutting resistance was less than EVA1. Hence, low VA content is favoured over high VA content polymers for PMAM. With the same MFI ($\sim$150), EVA1 showed less permanent deformations in comparison to LDPE1.

Most interesting behaviour was observed at higher number of repetitions. At these loads HMA failed gradually compare to PMAMs. Due to the presence of vinyl group, EVA is more rigid than LDPE. Hence, sudden failure was most likely and was found for EVA PMAM. EVA2 mix showed rapid failure compared to EVA1 mix. It is likely that high VA content makes asphalt concrete mixes stiffer. Therefore, polymer structure and the rigidness of the molecule directly are suggested to correlate with its accumulated permanent deformation. At large strains, the rheology of polymers is usually very sensitive to molecular structure (strong flow). Table 5 shows anti log of intercept and slope. Slope shows deformation at early life of pavement, which is the smallest for EVA1-PMAM and the highest for HMA. Other PMAMs show deformation in between this. Among two different polymer types, EVA-PMAM showed lower deformation at early life than that of LDPE PMAM.

Endurance limit (total number of repetitions required to complete breakdown of sample) of HMA and PMAMs as shown in Figure 4. PMAMs showed higher endurance limit compared to HMA. Endurance limit for EVA1 modified mix was the highest among all mixes. Accumulated deformation was least for EVA1 mix (Figure 3) and more than 4×10^4 cycles were needed to break a sample. This shows that EVA1 asphalt concrete mix is both strong and tough. On the other hand, EVA polymers are generally better than LDPE of similar rheological characteristics. Thus, among all the polymer modified asphalts used in this study, best mix performance was observed for EVA with low VA content polymer within performed tests and for asphalts of high asphaltene content.

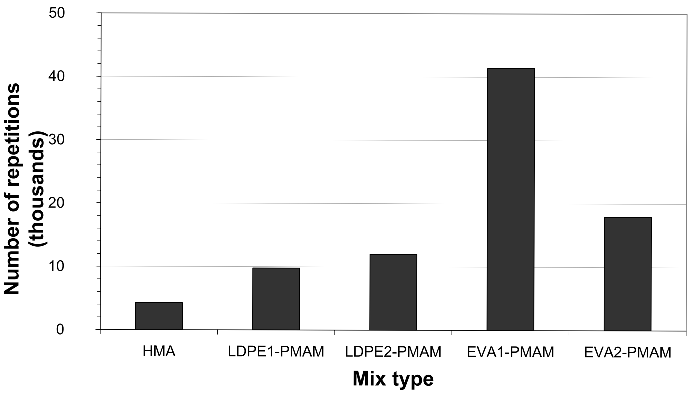

Figure 4. Endurance limit

CONCLUSION

In this study, two LDPE polymers of different MFI and two EVA polymers of different VA contents were used to modify asphalt binder. This modification was performed with 4% polymer concentration. Marshall Method of mix design was used to prepare asphalt concrete mix. Following are conclusions of this study:

1. HMA showed high initial stability, but retained stability was the lowest in comparison to PMAMs. Marshall Stability loss was the lowest for EVA1 asphalt mix (7%). In all other mixes the loss was about 30%.
2. Values of TSR indicated that PMAMs are more sensitive to water than HMA. But EVA1 PMAM showed better resistance to moisture induced damage than that of HMA.
3. Polymer modification increased the M_R of base asphalt binder. No effect for molecular weight was detected for LDPEs since their G' values were of similar magnitudes. For EVA, the resin with high elastic modulus showed a higher M_R. A correlation between M_R and G' was suggested.
4. Rutting behaviour of PMAM has improved significantly over that of base asphalt binder by a factor of 1.5–10. Accumulated deformation was very small for EVA1-PMAM. The EVA with the highest value of G′ displayed the highest value of rutting resistance and LDPEs of similar G′ showed similar rutting resistance. In general, EVA mixes showed less deformation than LDPE mixes.
5. Endurance limit was the highest for EVA1 modified asphalt mix. However, all PMAMs showed higher values than that of HMA.
6. Correlation between G' and M_R and rutting properties of asphalt concrete mix should save the time and recourses spent in screening different polymers. However, generalization of the above results to asphalts with very different compositions should be cautioned.

ACKNOWLEDGEMENT

The authors would like to thank King Fahd University of Petroleum and Minerals for performing this study. The authors are thankful to Al-Dossary Asphalt Plant for providing the aggregates and Willey Leyson of ExxonMobil, Belgium for providing polymer resins.

NOMENCLATURE

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Standard and Testing Materials
ARES	Advanced Rheometric Expansion System
EVA	ethylene vinyl acetate
G′	storage modulus
HMA	hot mix asphalt concrete
ITS	indirect tensile strength
LDPE	low-density polyethylene
M_R	resilient Modulus
M_w	weight average molecular weight
MFI	melt flow index
PG	performance grading
PMA	polymer modified asphalt
PMAM	polymer modified asphalt concrete mix
TSR	tensile strength ratio

Greek Symbols

ω	frequency

REFERENCES

Airey, G. D., B. Rahimzadeh and A. C. Collop, "Linear Rhelogical Behavior of Bituminous Paving Materials," J. Mat. Civil Eng. **16**, 212–220 (2004).

Al-Dubabe, I. A., H. I. Al-Abdul Wahhab, I. M. Asi and M. F. Ali, "Polymer Modification of Arab Asphalt," ASCE Mat. J. **10**, 161–167 (1998).

Amirkhanian, S. N. and B. Williams, "Recyclablity of Moisture Damaged Flexible Pavements," J. Mat. Civil Eng. **5**, 510–530 (1993).

Anderson, R. M., D. E. Walker and P. A. Turner, "Low-Temperature Evaluation of Kentucky Performance-Graded 70-22 Asphalt Binders," Transportation Research Record No. 1661, 69–74 (1999).

Baig, M. G. and H. I. Al-Abdul Wahhab, "Mechanistic Evaluation of Hedmanite and Lime Modified Asphalt Concrete Mixtures," J. Mat. Civil Eng. **10**, 153–160 (1998).

Berthelot, C. F., D. H. Allen and C. R. Searcy, "Method for Performing Accelerated Characterization of Viscoelastic Constitutive Behavior of Asphalt Concrete," J. Mat. Civil Eng. **15**, 496–505 (2003).

Chen, J., K. Lin and S. Young, "Effects of Crack Width and Permeability on Moisture-Induced Damage of Pavements," J. Mat. Civil Eng. **16**, 276–282 (2004).

Goodrich, J. L., "Asphalt and Polymer Modified Asphalt Properties Related to the Performance of Asphalt Concrete Mixes," Asphalt Paving Technol. **57**, 116–175 (1988).

Hansen, K. R. and G. Anderton, "A Laboratory Evaluation of Recycled Tire Rubber in Hot-Mix Asphalt Paving Systems," ASTM Special Tech. Pub. STP 1193, 69–83 (1993).

Hınıslıoğlu, S. and E. Ağar, "Use of Waste High Density Polyethylene as Bitumen Modifier in Asphalt Concrete Mix," Mat. Letter **58**, 267–271 (2004).

Hussein, I. A., M. H. Iqbal and H. I. Al-Abdul Wahhab, "Influence of M_w of LDPE and Vinyl Acetate Content of EVA on the Rheology of Polymer Modified Asphlat," Rheol. Acta **45**, 92–104 (2005).

Hussein, I. A., T. Hameed, B. F. Abu Sharkh and K. Mezghani, "Miscibility of hexene-LLDPE and LDPE Blends: Rheological Study of the Influence of Branch Content and Composition Distribution," Polymer **44**, 4665–4672 (2003).

Hussein, I. A., K. Ho, S. K. Goyal, E. Karbashewski and M. C. Williams, "Thermomechanical Degradation in the Preparation of Polyethylene Blends," Polym. Degrad. Stab. **68**, 381–392 (2000).
Iqbal, M. H., I. A. Hussein, H. I. Al-Abdul Wahhab and M. B. Amin, "Rheological Investigation of the Influence of Acrylate Polymers on the Modification of Asphalt," J. Appl. Polym. Sci., in press.
Jew, P., J. A. Shimizu, M. Svazic and R. T. Woodhams, "Polyethylene-Modified Bitumen for Paving Applications," J. Appl. Polym. Sci. **31**, 2685–2704 (1986).
Krishnan, J. M. and C. L. Rao, "Permeability and Bleeding of Asphalt Mixture using Theory," Int. J. Eng. Sci. **39**, 611–627 (2001).
Metcalf, J. B., K. Gopalakrishnan and M. D. Waters, "An Initial Investigation of the Rubber Waste (EPDM) in Asphalt Concrete Mixtures," Waste Management Series, Waste Materials in Construction, 940–952 (2000).
Murphy, M., M. O'Mahony, C. Lycett and I. Jamieson, "Recycled Polymers for Use as Bitumen Modifiers," J. Mat. Civil Eng. **13**, 306–314 (2001).
Panda, M. and M. Mazumder, "Utilization of Reclaimed Polyethylene in Bituminous Paving Mixes," J. Mat. Civil Eng. **14**, 527–530 (2002).
Parker, F. and E. R. Brown, "Effects of Aggregate Properties on Flexible Pavement Rutting in Alabama," ASTM Special Tech. Publ. STP 1147, 68–89 (1992).
Perdomo, C., J. W. Button and R. L. Lytton, "A New Approach for Prediction of Permanent Deformation," ASTM Special Tech. Publ. STP 1147, 295–309 (1992).
Srivastava, A., P. C. Hopman and A. A. A. Molenaar, "SBS Polymer Modified Asphalt Binder and its Implication on Overlay Design," ASTM Special Tech. Pub. STP 1147, 309–329 (1992).
Zhou, H., S. E. Nodes and J. E. Nichols, "Evaluation of Three Polymer Modified Asphalt Concretes," Transp. Research Record No.1454, 181–192 (1997).
Zoorob, S. E. and L. B. Suparma, "Laboratory Design and Investigation of the Properties of Continuously Graded Asphaltic Concrete Containign Recycled Plastics Aggregate Replacement (Plastiphalt)," Cem. Concr. Compos. **22**, 233–242 (2000).

Manuscript received February 14, 2006; revised manuscript received April 24, 2006; accepted for publication April 25, 2006.