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Evaluation of Reclaimed Polyethylene Modified Asphalt Concrete Mixtures

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Abstract: The present work is concerned with the use of reclaimed polyethylene (PE) obtained from low-density polyethylene (LDPE) carry bags, a locally available low-cost waste material collected from garbage, for modification of (80/100)-grade asphalt. Test samples were compacted using gyratory testing machine at various asphalt contents. Based on tensile strength ratio and retained stability test results, it was observed that PE-modified asphalt mixtures showed improved resistance to moisture induced damage. Beam fatigue tests were carried out on asphalt mixtures to evaluate engineering properties like fatigue life, stiffness modulus, dissipated energy and phase angle at 20, 30 and 40°C under constant strain-mode condition. At all tested temperatures, the flexural stiffness of the PE-modified mixtures were found to be comparatively higher than the conventional mixtures, whereas the dissipated energy and phase angle of the PE-modified asphalt mixtures were found to be comparatively lower than conventional mixtures. Fatigue life of the PE-modified mixtures increased by 2.5 times when compared to conventional mixtures. Charts have been developed for the design of flexible pavements using PE-modified asphalt mixtures. It was found that the thickness of the PE-modified asphalt mixture for a given traffic is substantially lower than the conventional mixture for a given practical thickness of granular bases.

Key words*: Dissipated energy; Fatigue cracking; Phase angle; Stiffness modulus; Tensile strength.*

Introduction

Fatigue is the accumulation of damage in asphalt concrete mixture under the effect of repeated loading of heavy axle loads of the commercial vehicles. Fatigue damage accumulation results in cracking in asphalt pavements, which is one of the main distresses observed on all National Highways in India. A review of literature indicated that number of efforts was made in the past to develop pavement materials that helped in attaining longer fatigue lives. Most of these efforts were directed towards improving the design of asphalt mixture and developing new modified asphalt binders [1-8].

Polymer-modified asphalt (PMA) binders are frequently and effectively used in the paving industry to improve pavement performance and to increase service life of the pavement [3-9]. PMA's are found to improve several properties of asphalt mixtures such as temperature susceptibility, fatigue life and resistance to permanent deformation [10, 11]. Research works abroad have reported that PMA may be highly suitable for special applications, where traffic is extremely heavy and or climatic variations are large [12, 13]. The type and amount of the polymer play an important role in the improvement of the mixture properties [14-17].

The polymers generally used for modification of binders for paving applications are styrene-butadiene-styrene copolymer, ethylene vinyl acetate copolymer, polypropylene, polyethylene in the form of LDPE, styrene-butadiene rubber latex, and so on [18-22]. Among these modifiers, waste reclaimed PE obtained from waste carry bags or grocery bags have drawn the attention of researchers in highway field in the recent past, mainly of its beneficial effects. Denning and Carswell [4] used NOVOPHALT binder which is Austrian asphalt (B70) modified with 7% by weight of PE. They have suggested that higher mixing and laying temperatures will be required for mixtures containing NOVOPHALT.

Jew and Woodhams [6] reported that the PE-modified AC sample retained 67.3% of the Marshall stability compared to 61.7% for the control specimen. They concluded that the wet strength of the PE-modified specimen was equal to dry strength of the control specimen. Panda and Muzumdar [19] reported that the optimum quantity of reclaimed polyethylene by weight of binder was found to be 2.5%. They concluded that at a particular temperature and stress level, polymer modification increased the resilient modulus and fatigue life of mixes. Resistance to moisture susceptibility was also improved by the modification.

Pradhan and Armijo [16] reported that modified asphalt samples were prepared in Matre-con, Inc., California, using 5% PE from NOVOPHALT America Inc., and 95% (120/150) grade asphalt. Preparation of NOVOPHALT involved high-shear blending process, which breaks down the PE into very fine particles that are blended into the asphalt at temperatures close to 171℃.

Jain *et al*. [13] reported that by adding 2% PE to asphalt cement, fatigue life of asphalt mixtures increased by 10 times that of the mixtures prepared with 80/100 asphalt binder. They also reported that by adding of 10% LDPE to asphalt cement, fatigue life of the mixture reduced to 1/5 times. Little [2] reported that binder-rich PE-modified mixtures (NOVOPHALT) are substantially more resistant to rutting than are binder-rich traditional systems.

LDPE is extensively used to produce carry bags for domestic goods. These bags become solid waste after their use for short periods and cause serious waste disposal problems [23]. In order to solve this environmental problem partly and at the same time to improve the properties of the asphalt mixture, reclaimed polyethylene in the form of LDPE carry bags were used in this

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Table 1. Aggregate Gradation Used and Test Results.

Aggregate Gradations of Asphalt Concrete Mixtures Selected	
Sieve Size	Adopted
19 mm (3/4 in.)	100
13.2 mm	87
9.50 mm (3/8 in.)	79
4.75 mm (#4)	58
2.36 mm (#8)	51
1.18 mm (#16)	41
0.60 mm (#30)	31
0.30 mm (#50)	24
0.15 mm (#100)	14
0.075 mm (#200)	7
Aggregate Test Properties	
Properties Tested	Test Results
Crushing value	33.2%
Aggregate Impact value	29.7%
Los Angeles Abrasion value	13.7%
Water Absorption value	0.89%
Specific Gravity	2.655
Combined (EI + FI) Index	20.2%

Note: EI = Elongation Index.
FI = Flakiness Index.

investigation as additive in asphalt concrete mixtures.

Need for the Present Investigation

Most of the research has been concentrated on the characterization and relative comparison of conventional and PMA mixtures and little work has been done towards characterizing fatigue behavior of PE-modified asphalt mixtures. The present paper focuses on the engineering properties of PE-modified asphalt mixtures and their behavior with respect to fatigue properties like dissipated energy, stiffness modulus and phase angle. Using the fatigue characteristics, thickness charts were developed for the design of pavements with PE-modified asphalt mixtures.

The main objectives of the present study are:

- To evaluate the effect of PE content on the mechanical properties of asphalt mixtures,
- To evaluate the fatigue properties like stiffness modulus, dissipated energy and phase angle for the conventional and PE-modified asphalt mixtures, and
- To develop thickness charts for asphalt pavements with PE-modified binder.

Experimental Investigation

Asphalt Cement

80/100 grade asphalt was obtained from the Mathura Refinery, Uttar Pradesh, India, and has been widely used for paving applications in India. The penetration, softening point, ductility at 27℃, viscosity @ 60℃, and specific gravity were 86 dmm, 46℃, 98 cm, 587 Poise and 1.025, respectively.

Reclaimed Polyethylene

PE obtained from LDPE carry bags collected from domestic waste in shredded form of approximately 2mm×2mm size was used to modify 80/100 grade asphalt. The thickness, density, tensile strength at break, elongation at break, Young's Modulus, impact strength and melting point of the material were 0.20-0.30 cm, 0.95 gm/cc, 2.542 MPa, >500 percent, 0.80 MPa, 0.86 Joule, and 130℃ respectively.

Aggregates

Coarse and fine aggregates were obtained by crushing granite aggregate procured from Delhi Quarry. The crushed stone was sieved into various fractions after washing and drying. Aggregate gradings that satisfied the requirement of the Ministry of Road Transport and Highways [24] gradation was selected and is presented in Table 1. The properties of the aggregates used in the present study are given in Table 1.

Preparation of PE-Modified Asphalt

LDPE is a plastomeric polymer that is added to asphalt at 170℃ with the high-speed stirrer rotating at a speed of 3500 rpm and the blending was done for period of 25 minutes to get a homogeneous binder [11, 23]. Each binder required a different temperature of binder formation, namely, 160, 170, 180 and 190℃ for PE content of 2.5, 5.0, 7.5, and 10%, respectively. The uniformity of dispersion of PE was confirmed by passing the binder at 165℃ through an ASTM 100 sieve. It was found that the binder thus prepared can be stored for future use. It was also observed that PE content greater than 10% were difficult to blend with the unmodified asphalt.

Aging Characteristics of Asphalt Binders

Thin film oven test (TFOT) and loss on heating tests were conducted on different binders to evaluate the effect of aging on PE-modified binders developed in the present investigation [23]. Retained penetration of the modified binders ranged from 76.1% to 85.9% compared to a value of 69.7% observed for unmodified asphalt. Indian Roads Congress guidelines on modified binders recommend a minimum value of 65% [25]. The increase in the softening point of the binders after the TFOT test was in the range of 1 to 2°C, whereas for a normal binder the increase was 3.5°C.

Indian Roads Congress specifies that the increase in softening point of modified binders after TFOT should be less than 5°C [25]. All the binders tested confirmed to this specification. The PMA blend with 5% PE content had the highest retained penetration value. Results obtained from loss on heating tests [26, 27] indicated that the loss in PE-modified binders was very low (0.075–0.097%) compared to a loss of 0.90% observed in the case of unmodified asphalt. Indian Roads Congress specifies that loss on heating should be less than 1% [25]. The aging characteristics of different binders obtained from the two tests show that the effect of aging is very less on PE-modified binders compared to unmodified asphalt. Thus, PE-modified mixtures can be expected to yield longer fatigue lives due to better retention of viscosity and flexibility.

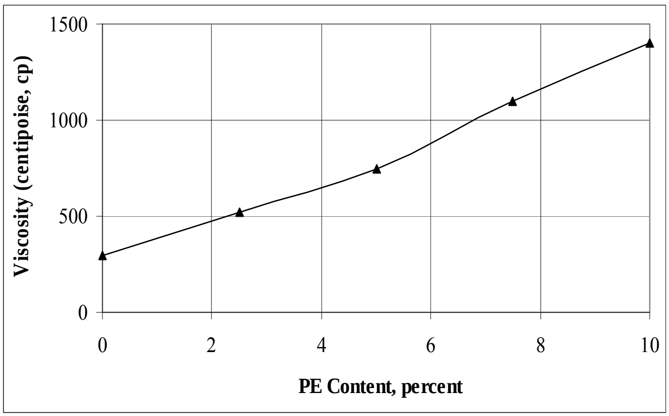

Fig. 1. Relationship between Viscosity and PE Content for Asphalt Cement.

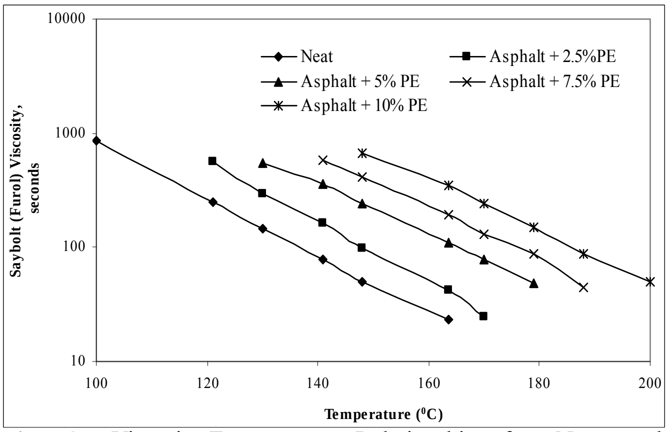

Fig. 2. Viscosity-Temperature Relationship for Neat and PE-Modified Binders.

Table 2. Gyratory Testing Machine (GTM) Mixture Compaction and Volumetric Mixture Properties for Conventional Asphalt Mixtures at $N_{design.}$

Percent Asphalt Content	% G_{mm} @ N_8	% G_{mm} @ N_{100}	% G_{mm} @ N_{160}	% Air Voids	% VMA	% VFA
5.0	86.5	95.3	96.3	4.6	14.4	67.2
5.5	87.8	96.9	97.9	4.0	13.9	77.8
6.0	87.4	97.5	98.2	3.6	14.5	81.4
6.5	88.3	97.8	98.5	3.2	15.1	85.6

Note: VMA = Voids in Mineral Aggregates.
VFA = Voids Filled with Asphalt.

Relationship between Viscosity and PE Content

The viscosity of each PE-modified asphalt blend was measured using the Brookfield viscometer at 135℃ [28]. Fig. 1 depicts the viscosity of the asphalt binder modified with PE contents. It can be seen that the viscosity of the PE modified binder increases as the PE content is increased.

Mixing and Compaction Temperatures

According to the Asphalt Institute Manual [29], the mixing and compaction temperatures for asphalt mixtures are such that

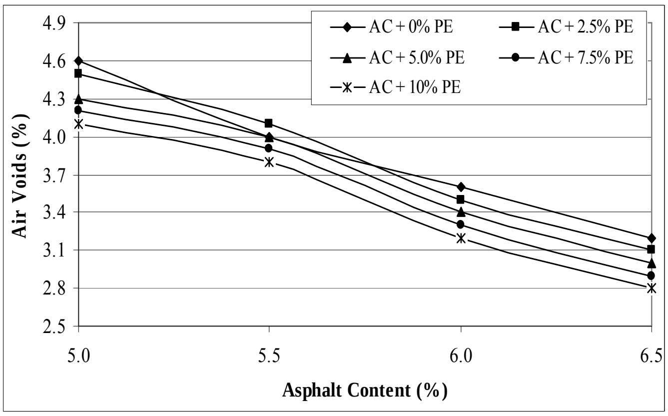

Fig. 3. Relationship Between Air Voids and Asphalt Content for Conventional and PE-Modified Asphalt Concrete Mixtures at $N_{design.}$

viscosities are 170 ± 20 mPa·s and 280 ± 30 mPa·s respectively [17, 30]. The viscosity-temperature relationships for unmodified asphalt and modified binders containing varying percentages of PE are shown in Fig. 2. It can be seen that the PE-modified binders have lower temperature susceptibility in terms of viscosity. From Fig. 2, it is observed that viscosity increases with the addition of PE content in the binder. All of the test samples were compacted using gyratory testing machine at various asphalt contents. The compaction of the mixtures were normalised to 4% air voids at the design number of gyrations using the Superpave procedures. The gyrations selected for the present study are given below.

$N_{initial}$ = 8 gyrations
N_{design} = 100 gyrations
$N_{maximum}$ = 160 gyrations

From Table 2, it was found that the design asphalt content for conventional asphalt mixture was found to be 5.5%. Samples were prepared for different PE contents at varying temperatures of 150, 160, 170, 180, 190 and 200℃ and compacting temperatures 10℃ less than the corresponding mixing temperatures [31, 32]. Higher temperatures greater than 200℃ was not considered as thermal separation, oxidation and smoking may occur at higher temperatures. It was observed that as the PE content is increased in binder, the mixing and compaction temperatures also increased. From this it was concluded that when the PE content is increased in the binder the modified asphalt mixtures require higher temperature during mixing and compaction.

After preparing a number of trial mixtures, a mixing temperature of 170 and a compaction temperature of 160 were selected for subsequent studies. From Fig. 3, it can be seen that percentage air voids decreased linearly with increasing PE contents. Further, air voids increased as asphalt binder content decreased. Test results indicated that the design asphalt content for PE-modified asphalt mixtures was found to be 5.5% (with 5% PE content).

Moisture Susceptibility of Mixtures

Moisture damage is evaluated by testing either loose mixture or compacted specimens. Stripping test is commonly done on loose mixture while compacted specimens are tested for retained-strength or tensile strength ratio.

Table 3. Tests Results of Moisture Susceptibility and Resilient Modulus Testing.

Tests	Properties		Asphalt Type Used				
			AC	AC + 2.5% PE	AC + 5.0% PE	AC + 7.5% PE	AC + 10.0%PE
Stripping Test	Stripping (%)	Static Immersion Test	8	0	0	0	0
		Boiling Test	10	5	0	0	0
Tensile Strength Ratio Test	Indirect Tensile Strength at 25℃, MPa	Unconditioned	0.55	0.75	0.90	0.83	0.73
		Conditioned at 60 ℃ for 24 hr	0.42	0.65	0.86	0.76	0.65
		Tensile Strength Ratio (%)	75.5	86.8	95.9	91.0	89.5
Retained Stability Test	Stability (kg) at 60℃	Dry	1227	1530	1717	1823	1820
		Wet	1050	1362	1596	1703	1701
		Retained Stability (Wet/Dry)×100	85.5	89.0	92.9	93.4	93.5
Resilient Modulus (M_R) Test	Resilient Modulus at 25℃, MPa		2040	2470	2630	2450	2410
	Percentage Increase in M_R		-	21	28	20	18.1

Stripping

The adhesion properties of neat and PE-modified binders with aggregates were studied using static immersion test [33] and boiling test [34]. Results are presented in Table 3. As can be seen from the table, mixtures containing unmodified asphalt showed 8% stripping in static immersion tests while the stripping was negligible for mixtures prepared with PE-modified binders. In boiling tests, PE-modified mixtures displayed lower stripping compared to conventional asphalt mixtures.

Retained Stability

Retained stability of compacted specimens was determined after conditioning them by keeping in water maintained at 60°C for 24 hr prior to testing [17, 30]. This stability, expressed as percentage of the stability of prepared specimens determined under standard conditions, is the retained stability of the mixture. From Table 3, it can be seen that PE-modified mixtures performed better than conventional asphalt mixtures.

Tensile Strength Ratio

Moisture susceptibility of the mixtures was evaluated in terms of tensile strength ratio. Tensile strength ratio is the average static indirect tensile strength of the conditioned specimens expressed as percentage of the average static indirect tensile strength of unconditioned specimens [30]. Conditioning was done by keeping the specimens in water maintained at 60°C for 24 hr and by curing at 25°C for 2 hr before commencing the test. The test was conducted at 25°C. The results are presented in Table 3. PE-modified mixtures were observed to have better indirect tensile strength characteristics. Tensile strength ratio values of modified mixtures are more than that of conventional mixtures indicating that PE-modified mixtures are less susceptible to moisture damage. Mixtures with 5% PE content showed the least moisture susceptibility.

Indirect Tensile Cyclic Load Test

In the indirect tensile cyclic load test (ITCLT), the 101.6 mm diameter, 63.5 mm thick sample was placed on its die on the 12.5 mm wide loading strip located on the indirect tensile test device and a sustained load of 130 N was applied. When the specimen came to rest, a cyclic load of 750 N was applied and the deformation of the sample was measured using linear variable differential transducers (LVDT's). The gyratory samples to be tested were conditioned for 24 hours in an environmental chamber at the specified test temperature prior to testing. Prior to testing, the LVDT's were zeroed. Then the constant dynamic load was applied through the pneumatic unit. Each loading cycle consisted of a 0.1 s load-unload time and a 0.4 s rest period [23]. The resilient modulus (M_R) of asphalt mixtures was calculated using the following equation:

$$M_R = (\mu + 0.273) * P / \delta * h \quad (1)$$

where
μ = Poisson ratio
P = The magnitude of the dynamic load
δ = Total recoverable deformation
h = Specimen thickness

The test results (Table 3) indicated that the M_R of PE-modified asphalt mixtures increased by greater than 18% with respect to unmodified asphalt binders.

Flexural Fatigue Characteristics of Asphalt Mixtures

Beam Sample Preparation

Laboratory testing of fatigue was performed on several asphalt mixtures at Central Road Research Institute, New Delhi, India. The mixtures were heated and then compacted using a rolling wheel compactor (RWC) to compact the specimens into asphalt concrete beams measuring 375mm × 125mm × 75mm. The RWC applies vertical pressure to the specimens by means of a rolling wheel with a moving table. After compaction, volumetrics were checked for every compacted beam to determine the air voids. The beam samples were prepared at optimum asphalt content of 5.5% (with 5% PE content).

Table 4. Dynamic Flexural Beam Fatigue Test Results at 20℃, 30℃, and 40℃, 10 Hz Frequency.

Test Temperature (℃)	Initial Tensile Strain, microstrains	Tensile Stress (MPa)	Stiffness Modulus (MPa)	Fatigue Life, cycles	Cumulative Dissipated Energy (MPa)	Phase Angle (degrees)
Asphalt Concrete Mixtures						
20	1000	2037.37	2097.35	52789	9.471	46.9
20	900	2151.75	2369.12	68193	12.16	45.6
20	700	1309.79	2847.16	184892	16.32	44.1
20	600	1699.17	3277.11	248943	49.34	43.2
20	400	713.123	3351.83	283548	57.15	45.4
30	1000	1416.58	1565.42	31475	35.32	49.6
30	700	949.441	1682.42	47139	44.83	47.3
30	650	996.982	1706.72	129341	53.49	46.4
30	600	1073.46	1853.03	137849	58.27	47.1
40	950	1010.76	1003.84	15789	76.82	60.7
40	900	949.442	1164.02	18483	85.35	55.3
40	650	775.813	1173.84	21368	98.96	56.4
40	600	760.674	1202.73	26864	119.4	57.5
PE-Modified Asphalt Concrete Mixtures						
20	700	2121.2	2895.79	136865	3.73	41.1
20	650	2062.4	2853.21	175848	5.08	40.2
20	500	727.61	3426.08	335308	10.11	38.2
20	400	685.13	3624.34	374627	14.31	37.8
20	400	886.54	3767.10	398346	27.72	37.3
30	1000	1485.2	2163.32	69587	19.14	49.1
30	620	915.16	2497.02	279341	24.12	44.3
30	650	983.28	2602.42	241895	26.06	45.4
30	600	1059.7	2679.83	282946	28.17	43.8
40	950	969.42	1162.31	35789	31.56	55.7
40	900	956.34	1232.92	56783	34.57	54.8
40	700	798.92	1290.97	77368	41.92	53.4
40	600	790.13	1340.53	90874	40.84	53.2

Beam Fatigue Equipment

Digitally controlled pneumatic beam fatigue equipment was used to test the asphalt concrete beam specimens. The equipment consists of three main components: the testing frame, the environmental chamber, and the control data and acquisition system (CDAS). The environmental chamber holds the testing frame and specimens inside it. All the tests were conducted as specified by Strategic Highway Research Program (SHRP) standards at 20, 30, and 40℃ respectively. Temperature transducers measured the temperature at both skin and core of the specimen. The testing frame is a completely self-contained, digital closed-loop servo pneumatic controlled third point loading frame that satisfies AASHTO TP8-94 for sample positioning. The loading system operates under position feedback control. This control system automatically adjusts the output waveform to match the input waveform, producing very precise control. The CDAS with a personal computer controls the load-deformation during testing and collects the data at the same time.

Test Conditions

The beam specimens were kept for 60 minutes to bring them to the test temperature in a time prior to the testing. For each temperature and strain level, 4 beams were tested and test results are tabulated in Table 4. The test was done under controlled strain mode and the failure of the specimens was defined as the number of cycles required until the flexural stiffness value reduced to half (50%) its initial value [35, 36]. The following parameters were used in the flexural fatigue equipment:

- Mode of loading: controlled strain;
- Wave shape: haversine;
- Load pulse width: 100 ms (10 Hz); and
- Temperature: 20, 30, and 40℃;

Testing was conducted at varying strain levels to generate a fatigue curve for the material. Test data were analyzed using a fatigue testing computer program to compute the stress, strain, stiffness, phase angle, and dissipated energy per cycle as functions of the number of cycles, and the cumulative dissipated energy to a given load cycle [36]. In the present study, fatigue tests were performed over range of strain levels (so that fatigue life varies between approximately 3000 cycles and 300,000 cycles). The specific testing consisted of carrying out a test at a fairly high strain so that the life of the specimen is between 30,000 and 10,000 cycles. As a starting point, a strain level between 800 and 1000 microstrains were used. If the fatigue life at this strain level is more than

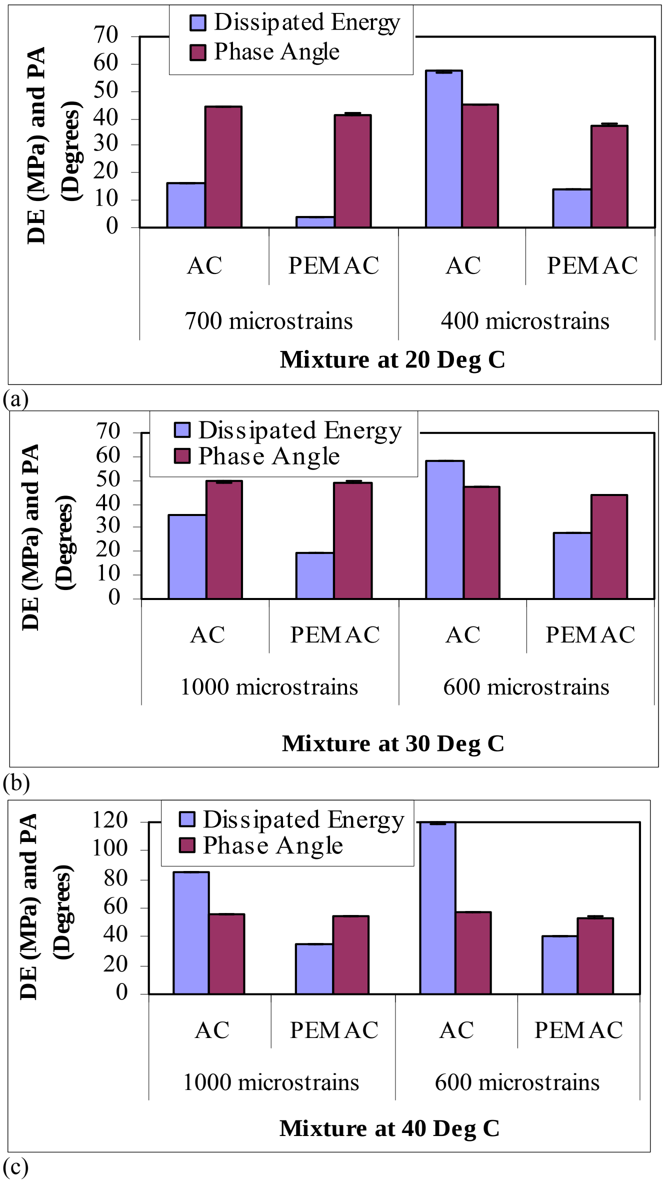

Fig. 4. Dissipated Energy and Phase Angles for Unmodified and PE-Modified Asphalt Mixtures at Temperatures (a) 20℃ (b) 30℃ and (c) 40℃.

10,000 cycles, then the strain was increased for the second fatigue test; otherwise, the strain level was decreased. In the second set of testing, strain levels were varied between 500 to 600 microstrains to get fatigue life in the range of approximately 100,000 cycles. In the final set of testing, strain levels were varied between 200 to 300 microstrains to get the fatigue life of approximately 200,000 to 400,000 cycles.

Test Results

Test results indicated that increase in initial tensile strain resulted in the decrease in the fatigue life of asphalt mixtures. It was also observed that with the increase in the test temperature, the fatigue life of the asphalt mixtures decreased. For the temperature range between 30℃ and 40℃, the fatigue life of the PE-modified asphalt mixtures was found to increase by 2.5 times when compared

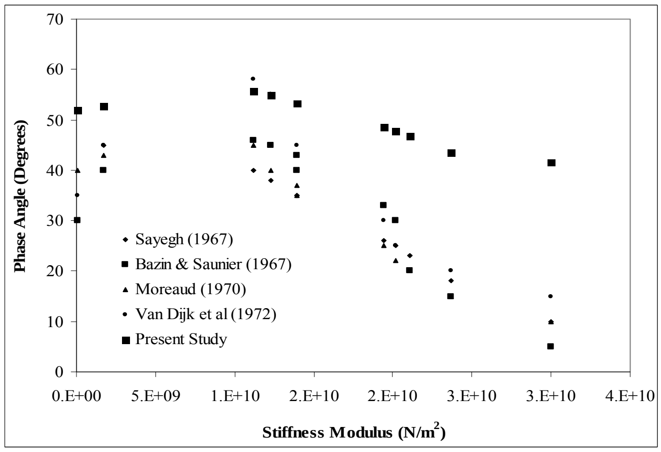

Fig. 5. Relationship Between Phase Angle versus Stiffness Modulus for PE-Modified Asphalt Concrete Mixtures at Different Temperatures.

to conventional asphalt mixtures. Test results also indicated that the number of repetitions to failure for PE-modified asphalt mixtures is comparatively higher than the conventional mixtures tested at 20, 30, and 40℃.

The dissipated energy per cycle decreases with an increasing number of load repetitions in the controlled-strain test. The cumulative dissipated energy to failure for a flexural beam fatigue test is the area under the curve between dissipated energy and number of cycles. Research has shown that the dissipated energy approach will make it possible to predict the fatigue behaviour of mixtures in the laboratory over a wide range of conditions from the results of a few simple fatigue tests. From Table 4, it was observed that at the same strain level, for all tested temperature, as cumulative dissipated energy increased, the fatigue life of both conventional and PE modified mixtures decreased. At all tested temperatures and at the given strain levels, it was observed that the dissipated energy for the PE modified mixtures is comparatively less when compared to unmodified mixtures.

From Table 4, it can be seen that, the smaller is the phase angle, the higher is the fatigue life of the asphalt mixture. Fig. 4 represents the cumulative dissipated energy and phase angles for unmodified and PE modified mixtures at 20, 30 and 40℃. From Fig. 4, it can be seen that the dissipated energy observed for PE modified mixtures (for a given strain level) was found to be lower than observed for unmodified mixtures.

A comparison of phase angles with the other studies reported in literature [37, 38] is shown in Fig. 5. It can be seen that phase angle, too, depends on the asphalt mixture stiffness as reported by various researchers [38, 39]. Several researchers [39, 40] showed a parabolic type of relation to exist between phase angle and stiffness (Fig. 5). Latest observations have also shown that the behavior is dependent on the asphalt mixture composition (in this case, PE-modified asphalt concrete mixture).

Test results of the stiffness modulus, fatigue life, cumulative dissipated energy and phase angle values were statistically analyzed as reported in Table 5 at the 5% level of significance (0.05 probability of a Type I error) with respect to the tested temperature and initial tensile strain for the mixtures studied. Statistical analysis test results indicated that in most cases it was observed that tested

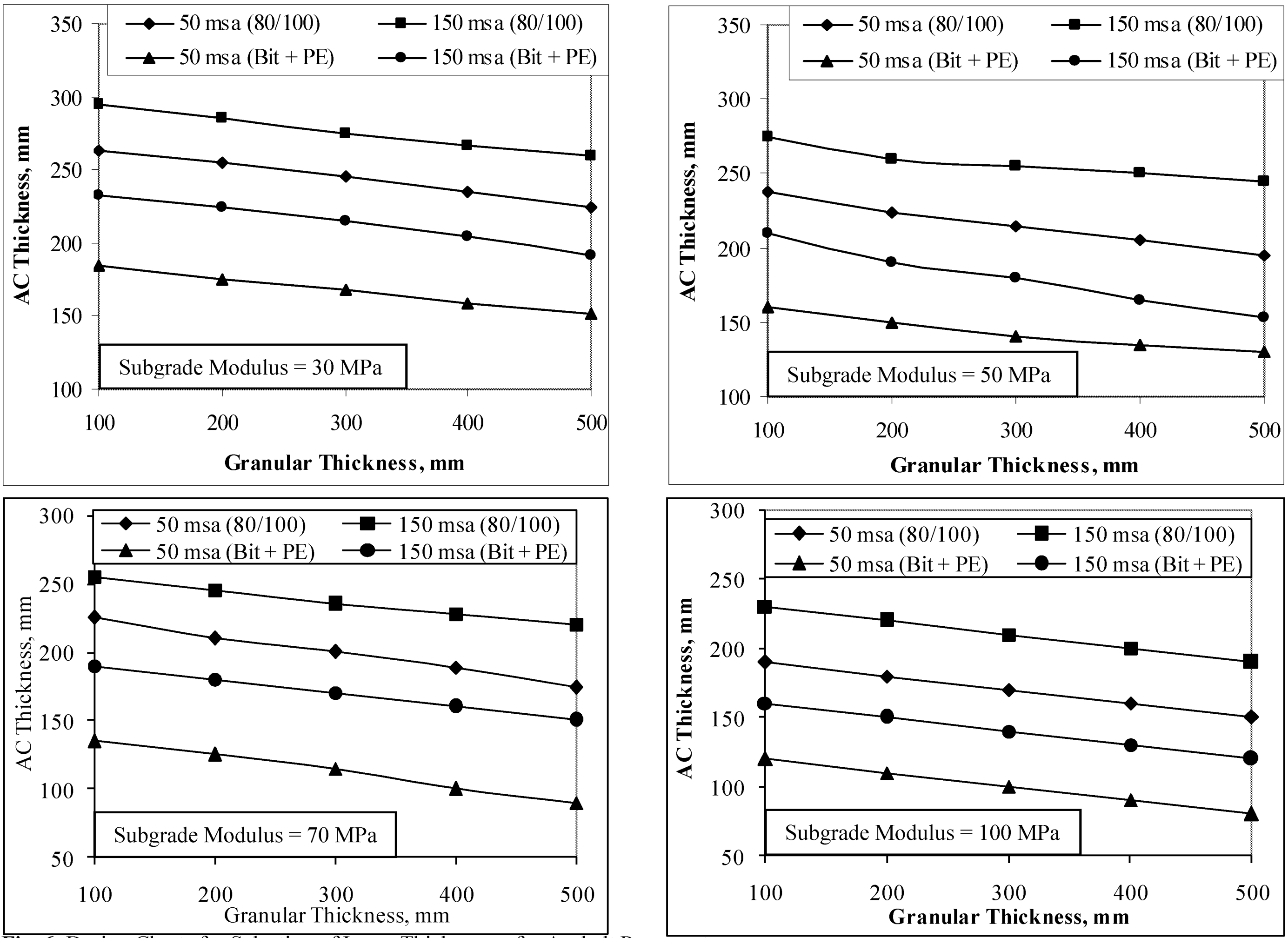

Fig. 6. Design Charts for Selection of Layer Thicknesses for Asphalt Pavements.

Table 5. Statistical Analysis for Fatigue Test Results Between PEMAC and AC Mixtures (α = 0.05).

Temperature (℃)	Initial Tensile Strain (microstrains)	Fatigue Life	Stiffness Modulus	Cumulative Dissipated Energy	Phase Angle
20	700	S	S	S	S
	400	S	S	S	S
30	1000	S	S	S	NS
	600	S	S	S	S
40	900	S	S	S	S
	600	S	S	S	S

Note: S: P-value < α = 0.05 (significant difference) and NS: P-value > α = 0.05 (No significant difference).

Table 6. Tensile Strains for Mixtures at Varying Traffic Levels.

Mixtures	Allowable Tensile Strain (microstrains) for a Traffic Level (msa)				
	20	50	100	150	200
80/100	298	235	197	177	165
Bit + PE	363	287	240	216	201

Note: msa = million standard axles

properties like fatigue life, stiffness modulus, cumulative dissipated energy, and phase angle for PE-modified asphalt mixtures were found to be significantly different compared to conventional asphalt concrete mixtures tested at 20, 30 and 40℃ respectively. Also results showed that at 1000 microstrains, no significant difference was observed between the mixtures with respect to the phase angle values tested at 30℃.

Development of Thickness Charts for Asphalt Pavements with PE-Modified Binder

Fatigue and rutting are the two major modes of failures occurring in the case of asphalt pavements in India. Efforts were made in the past by researchers to develop asphalt mixtures showing improved performance with respect to resistance to permanent deformation and fatigue cracking. In their earlier study authors have reported that

PE-modified asphalt mixtures were found to have lesser strain values compared to conventional asphalt concrete mixtures. Creep test results indicated that the accumulated strain for asphalt mixtures decreases with increase in PE additive content. It was also reported that the creep strain rate at high temperatures can be reduced by the inclusion of PE into asphalt cement [23].

As seen from the present investigations, it is observed that the fatigue life of the PE-modified mixtures is almost two and half times longer than the conventional asphalt mixtures. Tensile strength ratio test results indicated that PE-modified mixtures showed maximum strength and lower susceptibility to moisture damage when compared to conventional mixtures. Considering all these aspects, fatigue lives of PE-modified mixtures has been taken as two and half times that of conventional asphalt mixtures, similar to earlier published work by Sibal *et al.* [41]. The fatigue performance criterion developed earlier [42] for flexible pavements are given below.

$$N_f = 2.21 \times 10^{-4} (1/\epsilon_t)^{3.89} \quad (1/E)^{0.854} \tag{2}$$

where
N_f = Number of Load Applications,
ϵ_t = Initial Tensile Strain, and
E = Resilient Modulus.

This criterion has been modified in the present study for PE-modified asphalt concrete mixtures using a shift factor of 2.5. The modified criterion is given below.

$$N_f = 2.5 \times 2.21 \times 10^{-4} (1/\epsilon_t)^{3.89} \quad (1/E)^{0.854} \tag{3}$$

Using this performance criterion, thickness charts have been developed for the selection of different layer thickness for pavements constructed with PE-modified asphalt concrete surfacings. The charts have been developed for an average annual pavement temperature of 35℃ as reported by MOST [42]. For design purpose, the pavements have been considered to be three-layer systems with subgrade, granular base and bituminous surfacing.

Standard axle load of 80 kN for dual wheel set up and a tire pressure of 560 kPa was considered for the design purpose. Various combinations of pavements with different subgrade strength, granular and asphalt layer thickness were analyzed using FPAVE software, a program developed for the solution for the elastic-layered systems [41]. Each layer in the pavement is represented by its thickness and elastic properties (E-value and Poisson's ratio). Subgrade moduli of 30, 50, 70 and 100 MPa and the granular layer moduli of 100, 200, 300, 400, and 500 MPa have been considered in the present study. Poisson's ratios (μ) of the bituminous layer, granular layer and subgrade were taken as 0.5, 0.4 and 0.4 respectively. From Table 4, at 30℃, the stiffness modulus values obtained for conventional and PE-modified asphalt mixtures was found to be 1706 MPa and 2497 MPa respectively and the same has been used for the design purpose. The elastic modulus of granular base (E_2) was estimated using the relation:

$$E_2 = 0.2 \times E_3 (h_2)^{0.45} \tag{4}$$

where E_3 = Elastic modulus of subgrade, MPa = 10 × (CBR), CBR in %, h_2 = Granular base thickness, mm.

Limiting strain value, allowable in the bituminous layer for a given life is computed by Eqs. (2) and (3) by substituting the appropriate stiffness modulus value of the asphalt mixture. Limiting strain values determined for different traffic levels for the two types of mixtures are given in Table 6. Tensile strain at the bottom of bituminous layer was computed for all pavement sections analyzed. For a given subgrade strength (E_3), granular layer thickness (h_2), and the corresponding granular layer elastic modulus (E_2) (estimated from E_3 and h_2 from Eq. (4)), the asphalt layer thickness to satisfy the limiting strain criterion given by Eqs. (2) and (3) was determined.

Thickness charts have been developed for mixtures containing conventional and PE-modified asphalt mixtures and the results are presented in Fig. 6. It is observed that for subgrade strength of 30 MPa, for 50 million standard axles (msa), the thickness required for conventional and PE-modified mixtures were found to be 255 mm and 175 mm respectively for granular layer thickness of 200 mm. Whereas for a strong subgrade of 100 MPa, for 50 msa, the thickness required for conventional and PE-modified mixtures were found to be 180 mm and 110 mm respectively for granular layer thickness of 400 mm. From the design charts it was observed that, the PE-modified asphalt mixtures require lower design thickness when compared to conventional asphalt mixtures for a given practical thickness of granular bases.

Conclusions

The viscosity of the PE-modified asphalt blend is found to be higher than the unmodified asphalt. PE-modified asphalt binders showed lower temperature susceptibility compared to unmodified asphalt. The test results from GTM indicated that the percentage air voids decreases almost linearly with increasing PE contents in the asphalt mixture. PE-modified asphalt mixtures were found to be less susceptible to moisture induced damage compared to conventional mixtures as indicated by higher retained stability, higher tensile strength ratio, and improved stripping characteristics. The resilient modulus values for 5% PE-modified mixtures increased by 28% when compared to conventional mixtures. The increase in M_R values is due to the fact that, increase in the viscosities of the binders with the addition of PE content.

Based on the statistical analysis it was observed that the fatigue life of PE-modified mixtures was found to be significantly higher than conventional asphalt mixtures. At 40℃, the cycles to failure were approximately 90874 and 26864 at 600 microstrain for PE-modified and conventional asphalt mixtures respectively. Test results indicated that as the cumulative dissipated energy increased the fatigue life of conventional and PE-modified asphalt mixtures decreased at all tested temperatures. Results indicated PE-modified mixtures showed lower cumulative dissipated energy and phase angle values when compared to conventional mixtures at all tested temperatures. At 30℃, the stiffness modulus values for PE-modified and conventional asphalt mixtures were found to be 2497 and 1706 MPa respectively. Statistical analyses results showed that the fatigue properties like dissipated energy, phase angle and stiffness modulus for the PE-modified mixtures were found to be significantly different than compared to conventional asphalt mixtures at the similar tested temperatures and strain levels.

Considering the improvement in other mixture parameters such as better aging characteristics, lower temperature susceptibility, lower susceptibility to moisture damage, etc., field fatigue lives of the PE-modified mixtures can be expected to be at least 2.5 times longer than that of conventional asphalt mixtures. From pavement design charts, it was observed that the thickness of PE-modified asphalt concrete mixture for a given traffic is substantially lower than the corresponding asphalt concrete mixture for practical thickness of granular bases.

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