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Construction of Test Road to Evaluate Engineering Properties of Polymer-Modified Asphalt Binders

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As polymers are being increasingly used for modification to enhance the properties of asphalt pavements, ASTM published its first specification for polymer-modified asphalts (PMA) in 1996. This paper reported the results of evaluating the ASTM specification of PMA mixed with styrene-butadiene-styrene (SBS) copolymers. A 4-km in-service test road was constructed in this study to monitor the performance of asphalt pavements made of two straight and two PMA binders. The rheological properties of straight and PMA binders are discussed. Laboratory and field test results indicated that blending SBS with straight asphalt brought a range of performance benefits including higher elasticity, higher viscosity and less deformation. It was found that the ASTM specification tests including penetration, viscosity and elastic recovery provided good references to separate PMA from straight binders. The ASTM specification, however, appeared inadequate to predict deformation because binder properties at test temperatures could not discriminate between different circumstances. The results of the ASTM tests did not show good agreement with rut depth measured from the test road. The SHRP parameter, $G^*/\sin\delta$, was shown to be a reliable indicator to correlate with pavement rutting. Furthermore, PMA binders in this study demonstrated relatively high aging resistance and continued elasticity after being exposed to in-situ conditions. The enhanced performance characteristics as a result of adding SBS to binders were shown to be helpful to meet the severe demands from increased traffic volumes and higher axle loadings.

Keywords: polymer-modified asphalt, rheological parameter, test road, SBS

INTRODUCTION

In the late 1980's the search for the cause of premature failures of asphalt pavements in Taiwan concluded that the dramatic increase in traffic loading and tire pressure was the major factor. A recent survey indicated that the truck loading increased from specified 35 tons to 50 tons (77 to 110 kip) while tire pressure from standard increased 550 kPa to 960 kPa (80 to 140 psi) (Chou, 1996). The profound impact of increased loading and pressure has resulted in extensive rutting and cracking. In particular, permanent deformation has been a primary concern for highway engineers because of safety problems during the monsoon season. As a result, approximately one third of flexible pavements need to be rehabilitated annually, which costs about 70 percent of the maintenance budget of Taiwan highway agencies (Ministry of

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Transportation and communication, 1998). There is an urgent need for higher performance binders both to prevent pavement distresses and to enhance greater safety. Recognition of the nature of this problem led to an effort in 1996 to investigate the modification of asphalt binders by mixing them with polymers to increase the resistance to the higher stresses.

Many types of polymers are used to mix with asphalt binders to achieve a wider performance range for asphalt pavements; the mixed products are generally called polymer-modified asphalt (PMA). There has been a proliferation of various kinds of polymers in the last 20 years for use in asphalt binder modification (Goodrich, 1998; Airey & Brown, 1998). Styrene-butadiene-styrene (SBS) block copolymers are frequently used to modify asphalt cements to address the rutting problem (Tayebali et al, Bahia et al 1998). The American Society for Testing and Materials (ASTM) first published its specification for polymer(SBS)-modified asphalts in 1996 (ASTM, 1998). The specification consists of binder properties obtained from penetration, viscosity and elastic recovery tests. The application of the ASTM specification to traffic and environmental conditions in Taiwan remains, however, unclear.

The Taiwan Area National Freeway Bureau (TANFB) began a three-year research program in 1996 to evaluate the new ASTM specification. A 4-km in-service test road was constructed to investigate the effect of PMA on pavement performance. This test road was built with a single aggregate gradation with four binders including two straight asphalts and two PMA's. Extensive laboratory tests and field surveys were conducted, and data were analyzed and compared. The intention of this paper was to answer the following questions.

- Is the ASTM specification applicable to grade PMA for traffic and environmental conditions?
- Do the improvements in the viscoelastic behavior of the asphalt due to the addition of polymer modifier imply the enhancement of the resistance to permanent deformation characteristics of asphalt pavements?
- What are the factors that may affect the determination of the PMA properties relating to the permanent deformation characteristics?

MATERIALS AND TEST METHODS

Binder Types

Two conventional asphalt binders and two PMA's were used in this study: pen 60/70, pen 40/50, PMA-A and PMA-B. The former two were commonly binders used for highways in Taiwan. The latter two were mixed in this study to conform to the ASTM specification D-5892, and they were also applied to the test road. Table I listed the ASTM D-5892 specification. This specification covers the requirements for asphalt primarily mixed with styrene-butadiene-styrene (SBS). SBS is an elastomer most frequently used to reduce the rutting problem on the pavement surface because it can be characteristically stretched and recover their initial shape. It should be noted that the penetration test for RTFOT residue at 4°C is not included in Table I, since it is inapplicable to environmental conditions at the subtropical areas such as Taiwan. The relatively stiff PMA types, E and F, were selected from the ASTM specification to combat deformation resulting from increasing traffic volume and axle loadings.

TABLE I ASTM D-5892 Requirements for polymer-modified asphalt

ASTM Designation	*Penetration, 25°C, dmm*	*Viscosity, 60°C, poise*	*Viscosity, 135°C, cSt*	*Solubility, %*	*Soft. pt. diff. btw top & btn, °C*	*Elastic recovery, RTFOT residue, 25°C, 10 cm, %*
E	>50	>4500	<3000	>99	Report	>60
F	>35	>8000	<3000	>99	Report	>70

TABLE II Physical properties of base binder

Properties	*Penetration, 25°C, dmm*	*Viscosity, 60°C, poise*	*Viscosity, 135°C, cSt*	*Soft. pt., °C*	*Number average, M_n*	*Molecular weight, M_n*
	91	862	246	46	650	1300

TABLE III Basic properties of SBS copolymer

Properties	*Structure*	*Styrene-butadie ne ratio*	*Specific gravity*	*Volatile matter, %*	*Number average, M_n*	*Molecular weight, M_n*
	linear	30/70	0.94	0.4	180,000	210,000

Preparation of Polymer-Modified Asphalt

The following materials were used for preparation of the polymer-modified asphalts: (1) 85/100 penetration-grade asphalt produced by the Chinese Petroleum Corporation, and (2) SBS copolymer, available as pellets 2 to 3 mm in diameter, produced by the Chie-Mei Enterprise Ltd., Taiwan. The basic properties of the base binder and SBS are described in Tables II and III respectively.

An experimental protocol was developed to mix straight asphalt with SBS. The mixer, a model of Eyel 4 produced by the Tokyo Kikakikae Corporation, can apply a constant mixing speed to ensure no voids created in the mixtures. An "X" shaped propeller was used to stir the polymer-modified asphalt. The mixing bath is a product of the Glas-Col Cooperation, and the same company produces the temperature control unit. With this device, the mixing temperature was kept constant to produce homogeneous mixtures during the mixing process. SBS was first put into a 165°C oven for 24 hours to ensure it was moisture-free. Because asphalt cements were originally stored in a one-quart can, it took two hours to preheat the whole can in a 165°C oven and to make asphalt cements liquid and ready to mix. The asphalt was then transferred to the mixing bath maintained at 165°C, and SBS was added slowly while the mechanical stirring was continued at 3500 rpm. All mixing temperatures were maintained at 165°C as determined by thermocouple measurements in the asphalt during mixing. It took ten minutes to finish the filler addition. The mixing process continued for another forty minutes after the completion of SBS additions.

Binder Tests

Binders were first aged by the Rolling Thin Film Oven Test (RTFOT) to simulate the short-term aging conditions. The Pressure Aging Vessel (PAV) was then used to simulate the changes in physical and chemical properties that occur in asphalt as a result of long term, in-service oxidative aging in the field. This method involved oxidation of asphalt in the RTFOT followed by the oxidation of the residue in the PAV. In accordance with Superpave™ test procedures, a Dynamic Shear Rheometer (DSR) measured the rheology of binders over a broad range of temperatures. The DSR, an AR500 model, is manufactured by the Carri-Med Corporation (TA Instruments). All tests were performed in the linear viscoelastic range. For tests at 40°C and higher, a 1-mm gap and a 25-mm diameter plate were used. For tests below 40°C, a 2-mm gap and an 8-mm diameter plate were used. Viscoelastic properties at difference temperatures and frequencies were obtained. The DSR frequencies corresponding to the pavement and mixture tests were based on 80 km/h that is equal to 10 rad/sec, i.e., 1.6 Hz. There is no low-temperature cracking in this region; thus, the bending beam test was not conducted.

Besides the Superpave™ and conventional tests, the elastic recovery of binders was conducted to evaluate the percentage of recovery strain measured after elongation during a conventional ductility test. The apparatus was manufactured according to ASTM D-5892. In this test a 3-cm long test specimen was elongated to 10 cm at 25°C and cut into two halves. Elastic recovery was measured after one hour as a percentage of the applied strain.

TABLE IV Mixture aggregate gradation

Sieve Size (mm)	*37.5*	*25*	*12.5*	*10*	*4.75*	*2.5*	*0.63*	*0.3*	*0.075*
Percent Passing	100	94.4	64.4	53.3	39.9	26.9	13.9	9.24	5.12

Hot-Mix Asphalt (HMA) Concrete

All four binders were mixed with a single mixture gradation that has a nominal maximum aggregate size of 25 mm. Limestone aggregate was used in this study. The aggregate gradation conformed to the TANFB specification and is found in Table IV. According to ASTM D 1559, the 75-blow Marshall test was carried out to determine the optimum binder content. All mixtures had Marshall stability above 6700 N, and the optimum binder content was found to be 4.8 percent by mass. Uniform gradation and binder contents were used for each type of mixture so that the effects of binder properties on performance could be studied.

Wheel Tracking Test

A wheel-tracking tester was performed to evaluate a mixture's susceptibility to permanent deformation in the Asphalt Concrete Laboratory at the National Cheng-Kung University. This equipment is similar to the Hamburg Wheel-Tracking Device. Mixture samples of different binders were carefully controlled to have the same binder content, air void content, gradation and aggregate type as used in the field. The test was conducted at the mean highest weekly average temperature as proposed by SHRP, which was set at 60 °C, under dry conditions. A smooth solid-steel wheel travelling at a speed of 1.4r km/hr was used to correlate rutting in this study. Rut depths were measured on 300mm × 300mm × 70mm samples after 200 wheel passes of a 830 kPa(120psi) tire.

CONSTRUCTION AND INSTALLATION OF IN-SERVICE TEST ROAD

Monitoring in-service pavements is one of the best methods for gaining data on how pavements perform over time under real environmental and traffic conditions. The TANFB, thus, started constructing a 4-km full-scale pavement test section on the Sun Yat-Sen National Freeway in June 1997. The researchers participating in this project and the TANFB field engineers developed the experimental design. Pavement sections from 251^K+850 to 255^K+850 in the south bound as shown in Figure 1, were selected for the field studies. The test sections on this 6-lane highway represented typical traffic and environmental conditions that pavements experience in Taiwan. These sections were constructed with asphalt mixtures having four binders and one aggregate gradation. A single pavement cross section in all of test sections ensured that the difference in pavement performance was a function of the binder types.

The test sections were constructed using typical highway materials, equipment and procedures. All the mixtures of the test sections were made of a dense-graded concrete mixture meeting the TANFB's specifications. The asphalt layer in each section consisted of a single mixture on top of a bitumen-treated base, so that pavement performance is a function of a single mixture. Each section was consisted of a 10-cm HMA concrete course over a 25-cm bitumen-treated base course. During the construction two 5-cm lifts were used to achieve smooth requirements. The mix and compaction temperatures of PMA and straight binders were decided according to ASTM D 1559.

After the construction, traffic was monitored by the weight-in-motion (WIM) system installed along the highway to measure the tire forces of moving vehicles. Six cores were taken from each section to extract asphalts for further binder testing. Table V presented the pavement geometry and mixture properties of test sections. Distress surveys were conducted every three months on each section during trafficking. The surveys including transverse profiles, longitudinal profiles and the number and severity of cracks were

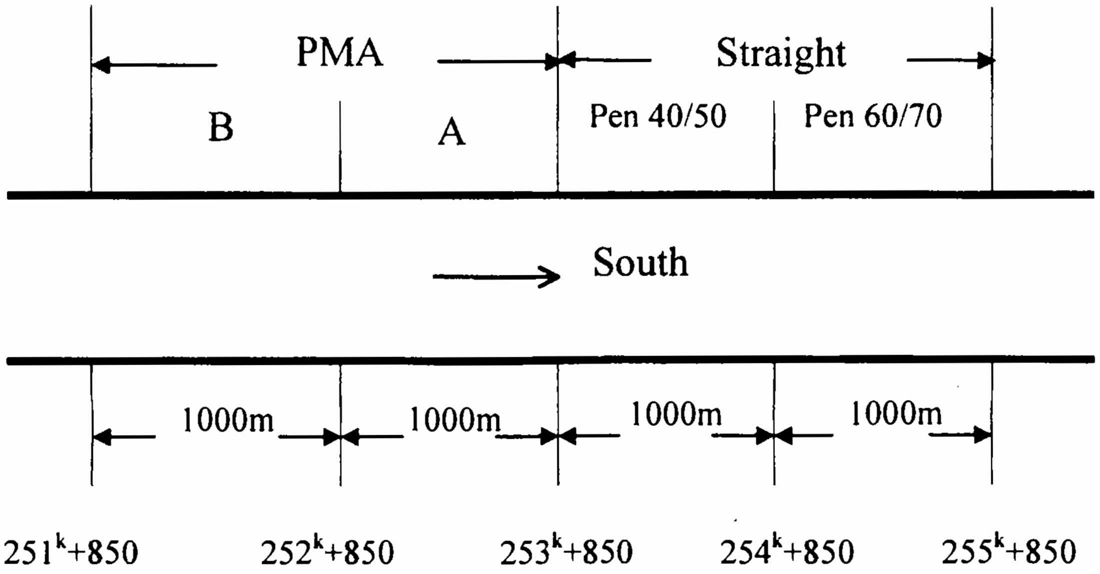

FIGURE 1 Layout for in-service test road

performed every three months. Profiles were obtained with a semiautomatic device. Longitudinal profiles were collected at the centerline of the wheel path. Three transverse profiles were collected for each section. Data were collected from pavement survey reports that were carefully documented by the engineer on the field, and, later on, double checked for any ambiguity or error. Traffic volume and loading, environment conditions and material properties were closely monitored.

TABLE V Pavement geometry and mixture design

Section	*Binder Type*	*Surface Thickness (cm)*	*Asphalt Content*	*Air Void (%)*
1	40/50	10	4.8	4.9
2	60/70	10	4.7	4.8
3	PMA A	10	4.8	4.7
4	PMA-B	10	4.9	4.9

TABLE VI Physical properties of binders

Binder Type	*Penetration, 25°C, 100g, 5s, 0.1mm*	*Viscosity, 60°C, poise*	*Viscosity, 135°C, cSt*	*Solubility, %*	*Soft. pt. diff., °C*	*Elastic recovery, after RTFOT, 25°C, 10 cm, %*
PMA-A	56	4900	880	99.8	0.4	87.6
PMA-B	45	8500	1500	99.9	0.5	89.5
Pen 85/100	92	970	350	99.9	–	3.1
Pen 60/70	62	1820	480	99.9	–	4.5
Pen 40/50	50	2900	560	99.9	–	5.2

A database administered by the TANFB was employed in this study for the pavement performance. Database containing traditional properties of asphalt binders (penetration, viscosity, softening point, etc.), pavement distresses and temperatures was maintained. These sections representing typical of traffic and environment conditions were aged differently in this study to assist in validating binder properties.

RESULTS AND DISCUSSIONS

Binder Properties

Test results related to the ASTM D-5892 specification are presented in Table VI. The physical properties of PMA-A and PMA-B met the requirements of ASTM D-5892 as listed in Table I for types E and F respectively. PMA's showed higher viscosity values than conventional asphalts. It was, however, difficult from the penetration data to tell the differences between PMA and conventional binders. SBS tended to increase the viscosity of asphalt at 60°C. However, PMA's caused no difficulties in making mixtures that were as easy to handle as those made with straight asphalts.

Since PMA consists of two distinct phases, they are subjected to the same physical principle as those governing separation or sedimentation of asphalt emulsions. The separation test of polymer and asphalt during storage was evaluated by comparing the ring and ball softening point of the top and bottom samples. The softening point differences for PMA-A and PMA-B were 0.4°C and 0.5°C respectively as shown in Table VI. These values were less than 1% of their original softening points, i.e., 54°C and 57°C respectively. Although no particular value is given in the specification, the difference indicated that the separation within PMA was not significant. Making PMA with low softening point difference therefore implied that SBS was to dissolve in hot asphalt and would not separate on prolonged storage.

As shown in Table VI, improvements of adding SBS to straight asphalts were clearly demonstrated in the elastic recovery test as compared to pen 60/70 and pen 40/50. The recovery values showed that PMA elastically deformed a large amount when a force was applied to them, and almost returned to their original shape when the force was released.

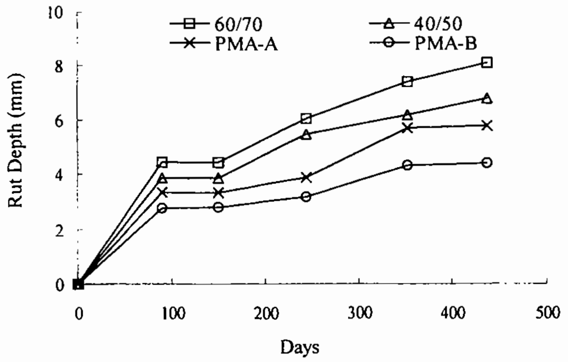

FIGURE 2 Rutting depth for four test sections

Evaluation of Rutting Occurring in Field and Laboratory

Pavement rutting occurred rapidly in the first three months for all four sections as shown in Figure 2. Afterwards asphalt concrete mixtures seemed to adjust internal structures for about three months before picking up rutting again. After open to traffic for one year, the rutting rate of PMA sections were, however, kept relatively unchanged. Traffic flow at the sections was estimated to be were estimated to be about 5x10^6 ESAL annually with an average truck factor 1.35 according to the WIM. Test sections made of PMA showed lower rutting rates than of straight binders. Thus, under this heavily trafficked highway, PMA sections were more resistant to permanent deformation. Deformation was in part of a result of viscous flow of the binder. By introducing high level of SBS elasticity into straight binders, high levels of viscosity were then imparted to the polymer-modified asphalt.

The results of the rheological testing are shown in Figure 3 for three binder systems. With binder types

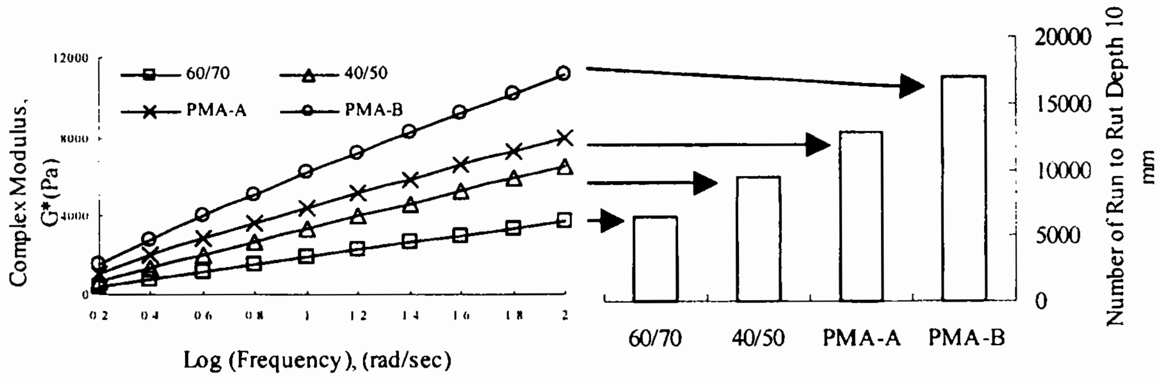

FIGURE 3 Relationship between viscoelastic properties of binders at 60°C and wheel tracking performance of their respective mixes at 60°C

changing from pen 60/70 to PMA-B, the complex modulus, G^*, increased. The SBS concentration for PMA-A and PMA-B was 3.5% and 5.5% respectively. Hence with increasing polymer content, PMA's were more resistant to deformation and exhibited enhanced elastic recover. Figure 3 showed that the rheological properties of PMA's correlated well with deformation measured on a laboratory test track and in a dynamic shear rheometer. Both viscoelastic properties and wheel tracking experiments confirmed the contribution of SBS to the fundamental rheological properties of the binders.

TABLE VII Aging index from laboratory and field tests

Binder Type	*Properties*	*Field Aging Index 438 days/Unaged*	*Laboratory Aging Index*	
			RTFOT/Unaged	*PAV/Unaged*
Pen 60/70	Pen. (dmm)	0.65	0.61	0.35
	Vis.$_{60°C}$ (Pa.s)	1.96	1.95	7.89
	Soft. Pt. (°C)	1.06	1.08	1.23
Pen 40/50	Pen. (dmm)	0.60	0.56	0.38
	Vis.$_{60°C}$ (Pa.s)	1.96	1.94	7.57
	Soft. Pt. (°C)	1.08	1.10	1.22
PMA-A	Pen. (dmm)	0.75	0.77	0.38
	Vis.$_{60°C}$ (Pa.s)	1.78	1.71	6.81
	Soft. Pt. (°C)	1.04	1.05	1.17
	Ela. Recov. (%)	0.98	0.99	0.95
PMA-B	Pen. (dmm)	0.82	0.79	0.39
	Vis.$_{60°C}$ (Pa.s)	1.75	1.79	6.67
	Soft. Pt. (°C)	1.03	1.04	1.16
	Ela. Recov. (%)	0.99	0.98	0.95

Comparison of Binder Properties after Exposed to Traffic

The changes in asphalt rheology caused by aging and determined by conventional testing methods were presented in Table VII. The expected results of a decrease in penetration and elastic recovery, and an increase in softening point and viscosity were recorded for the binders tested. The field aging indices showed a general trend that binders aged after 438 in-service days were similar to ones aged by RTFOT. The average air temperature in the hottest month was 33.7°C with the maximum 7-day pavement temperatures at 62.5°C. Data in Table VII indicated that the RTFOT could properly simulate the short-term aging effect on binders.

Based upon laboratory and field test results, aging effects appeared to be higher on straight binders than on PMA binders. After 438 days the binder penetration fell by about 40% for straight asphalts and about 20% for PMA's. Overall viscosity increased by 70–90% while softening point rose by 2–7°C. The elastic recovery of PMA's, however, remained relatively unchanged. Binders became hardened in this study largely due to oxidation. Oxidation of PMA both increased the viscosity of the base asphalt cement as indicated in Table VII. It is believed that oxidation caused chain scission of the SBS polymer. Chain scission produced a reduction in viscosity that would balance the hardening of the base asphalt. The net result was that PMA binders became less hardened than straight binders; thus, appeared to be comparatively less oxidation. It was shown in Table VII that SBS modification yields significantly reduced temperature susceptibility. These results might be attributed to the network forming capability of the SBS block copolymer.

The complex modulus versus phase angle was plotted in Figure 4 for PMA A, indicating a continuous shift of the curves towards lower phase angles after aging. The shift in the curves was caused by the dual actions of an increase in complex modulus, indicating the hardening of the PMA, and a decrease in phase angle, indicating an increase in the elastic behavior of the bitumen. The different magnitudes of these two actions resulted in shifting the curves towards lower phase angle values for a given complex modulus. The result of aging was therefore an increase in G* and a decrease in δ.

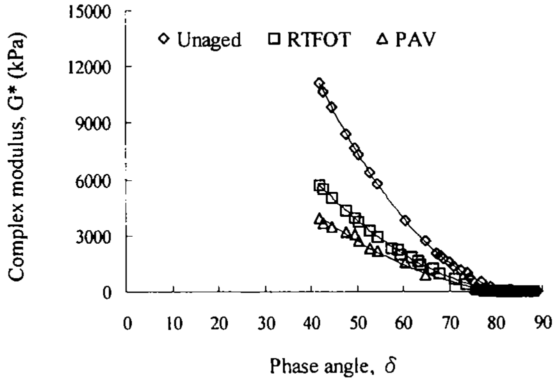

FIGURE 4 Complex modulus vs. phase angle for PMA-A

Figure 4 showed that the major effect of aging on asphalt is a reduction in phase angle across the range of loading frequencies. The oxidized binders of Pen 60/70 and 40/50 showed fairly large changes in phase angle with loading frequency while PMA showed smaller change. It was implied that, at long loading time/high temperatures (i.e., the critical condition for rutting), the PMA binders were more elastic and less likely to flow than the straight binders. The PMA's enhancement to rutting has been confirmed in Figures. 1 and 2. At short loading time/low temperatures (i.e., the critical condition for cracking), the PMA binders were less elastic. Concerns have been raised that PMA binders may be easier to dissipate stresses that might cause cracking. Field surveys in this study did not, however, support this speculation since all test sections showed little cracking.

Relationship between Binder Properties and Rutting

Figures. 5 and 6 showed rutting rate measured at test sections as a function of penetration and viscosity at 60°C. The decrease in penetration and the increase in

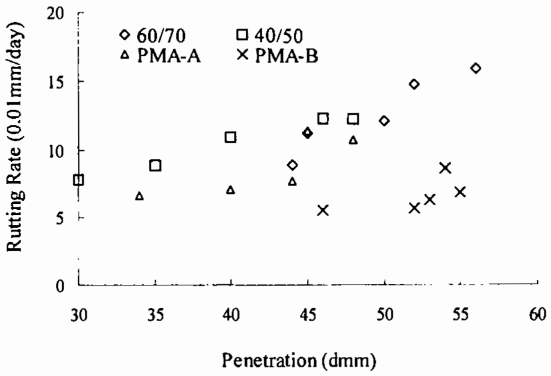

FIGURE 5 Rutting rate as a function of penetration

viscosity were gained by adding SBS to straight asphalt. The first point to note was that both measurements gave a reasonable explanation of rutting for the binders tested in this study. In general a low penetration or a high viscosity was a good indicative of rut resistance for both straight and polymer-modified asphalts. However, points between penetration 40 and 55 indicated the possible danger in using such relationships for PMA. Viscosity at 60°C may be expected to provide a better indicator of performance, since it is a fundamental rheological measurement. However, it is clearly not a reliable indicator of rut resistance for all binders as shown Figure 6. The same was true of softening point.

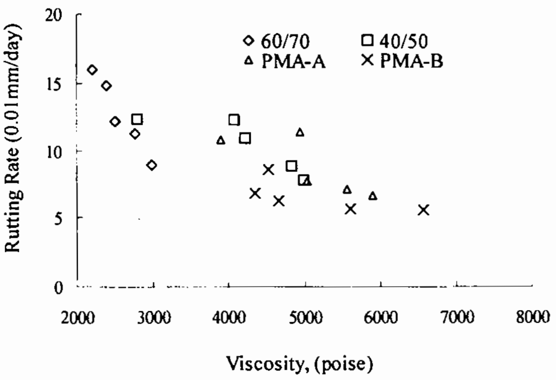

FIGURE 6 Rutting rate as a function of viscosity at 60C

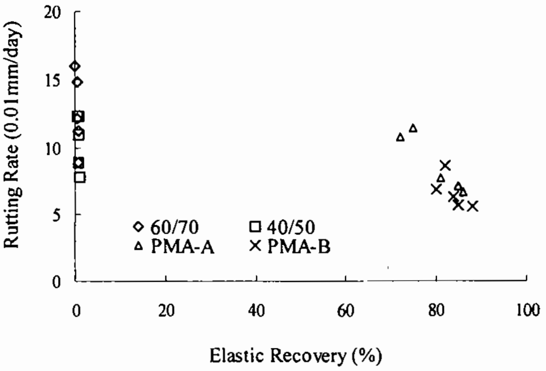

FIGURE 7 Rutting rate as a function of elastic recovery at 25°C

Figure 7 showed rut resistance as a function of binder elastic recovery at 25°C. When elongated to 10 cm the addition of SBS improved elastic recovery of straight binders. This test is a relatively new empirical method that has been developed to characterize PMA. The elastic recovery test was, however, conducted under considerably different temperature and loading conditions from field situations. Figure 7 confirmed that, while elastic recovery is an excellent indicator of the presence of an elastomeric polymer, there is no correlation with performance at high temperatures.

Examining the results from these three tests showed that the ASTM specification provided a reference to specify PMA and reflected the relative properties of PMA. The penetration was, however, unreliable for some binders, because neither temperature nor loading conditions corresponded with those of binders testing. The same was true of elastic recovery, a modern empirical measurement. Viscosity measures fundamental binder properties, but loading time is significantly larger than what experiences in pavements. The use of these three measurements for selecting binders to predict performance at high temperatures may give misleading results. Therefore the penetration, viscosity and elastic recovery tests cannot be used as predictive tools for PMA.

Rheological measurements on the binders may provide a measure of how the binder behaved at different loading times, which may be more relevant to traffic

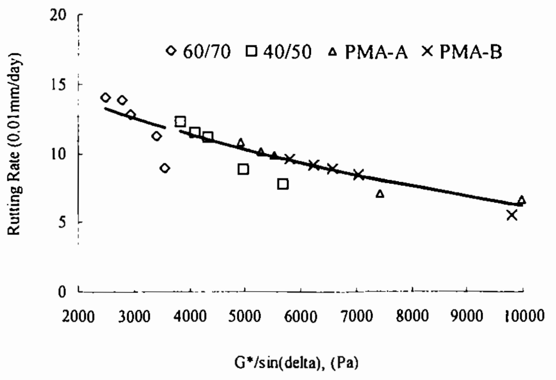

FIGURE 8 Rutting Rate as a Function of complex modulus G*/sinδ at 60°C, 1.6 Hz

speeds. The binder complex modulus, G^*, measured at 60°C and 1.6 Hz was found to give a reasonable correlation of rutting resistance. As expected, a stiffer binder provided a more rut resistant mix. A better correlation was identified using the parameter recommended by the SHRP as a high-temperature binder specification, $G^*/\sin\delta$. Figure 8 shows rutting rate versus $G^*/\sin\delta$ at at 60°C and 1.6 Hz. For this range of binders, the SHRP parameter gave the most reliable correlation of rut resistance. The SHRP recommended frequency (1.6 Hz) was found to correspond closely to the frequency of pavement sections investigated by this study. It appeared that the SHRP parameter, $G^*/\sin\delta$, could adequately predict mix performance at high temperatures. This parameter included not just the binder stiffness (G^*), but also a measure of its ability to recover the deformation when traffic load was passed ($\sin\delta$). The following functions was found to provide the best fit: rutting rate = $16.93 \cdot \exp(-0.001(G^*/\sin\delta))$ The associated correlation coefficient, $R^2=0.83$, confirmed a good correlation between the binder rheological parameter and rutting rate. However, cautions should be paid when one uses this relation to predict rutting. The study controlled a number factors such as gradation and mineral type that are applicable to this aggregate mixture combination.

CONCLUSIONS

Based upon the analyses of the test results, the following conclusions were drawn:

- The ASTM specification tests including penetration, viscosity and elastic recovery provided good reference points to differentiate between straight and polymer-modified asphalts. They are not, however, reliable indicators to predict pavement performance.
- Blending SBS with straight asphalt brought a range of performance benefits including higher elasticity, higher viscosity and less deformation.
- PMA binders showed higher aging resistance as compared to straight asphalts.
- At pavement temperatures located in subtropical areas such as Taiwan, the rheological parameter, $G^*/\sin\delta$, measured at the same frequency and temperature conditions as the binders tested has found to be a reliable indicator of rutting rate. However, this parameter may not be directly applicable if the aggregate system is not properly designed and the construction is not adequately conducted.
- The enhanced performance characteristics as a result of adding SBS to binders were shown to be beneficial to meet the severe demands from ever-increasing axle loadings and tire pressures.

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