Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 5(6):419-427

Effects of Interface Modifier on Asphalt Concrete Mixture Performance and Analysis of its Mechanism

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Abstract: A comprehensive laboratory testing program, including rotary loaded wheel rutting, four-point bending fatigue, and low-temperature bending tests, was carried out in this study to evaluate a newer type of asphalt concrete mixture modifier, termed as Interface Modifier. Unlike many of the traditional asphalt binder modifiers, such as Styrene-butadiene-styrene (SBS), Styrene-butadiene Rubber Latex (SBR), Polyethylene (PE), etc., the Interface Modifier was fed directly into the mixing chamber and mixed with heated aggregate. The electron microscope scanning combined with rheology testing was also used to analyze the mechanism of interface modifier/aggregate interactions. With the use of the Interface Modifier, improved bonding between the asphalt binder and the aggregates were observed. Test results show that the use of the Interface Modifier in the asphalt concrete mix could improve its resistance to rutting at high temperature and water stability, as well as increase its fatigue life significantly.

***Key words**: Duroflex® pavement performance; Electron microscope scan; Interface modifier; Mechanism analysis; Rheological property.*

Introduction

Because of China's rapid economic development over the last several decades, the traffic, in terms of both volume and weight, has increased significantly. The high traffic volume and heavy axle loads have caused premature failures on many asphalt pavements. Many efforts have been expended in China to improve asphalt pavement performance, such as improved mix design proportions, optimization of the aggregate gradation, use of higher quality aggregates, use of additives to improve asphalt binders, etc. Adding additives into the asphalt binder or asphalt mixture has been one of the most common and effective techniques used in improving asphalt pavement performance. The majority of the additives are blended into the asphalt binder, aiming to enhance the binder properties, which, in turn, can improve the performance of asphalt concrete mixtures. However, the addition of the additives and mixing of the modified binder require specialized equipment. The process might also lead to other issues, such as aging of asphalt binder due to repeated heating, storage stability problem, additional energy consumption, etc. To overcome these issues, this laboratory study evaluated a new type of additive to determine its effectiveness in improving the asphalt mixture performance. Unlike the traditional additives, this additive, Duroflex®, termed as Interface Modifier, was fed into the mixing chamber and mixed with the heated aggregates (direct feeding method). The aggregate/additive mixture was then mixed with heated asphalt binder. It was shown in this study that this additive enhanced the interface bonding between the asphalt binder and the aggregates. The stronger bonding resulted in improved asphalt mixture properties. Because of the elimination of the process of producing modified asphalt by heating and mixing the common asphalt binder and the additive, the direct feeding technique is considered to be more environmentally friendly by reducing energy consumption.

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Note: Submitted January 31, 2012; Revised April 19, 2012; Accepted April 24, 2012.

Background

More than 80% of China's highway pavements are constructed with asphalt concrete; the ratio is even higher in American and European countries. However, asphalt concrete is a thermoplastic material that is sensitive to temperature changes. During the summer, rutting and shoving are common distresses caused by heavy traffic and high temperatures. During winter, asphalt concrete becomes stiffer and is susceptible to the occurrence of low-temperature cracking. The demand for high performance asphalt concrete pavement becomes even greater with the increasing traffic volume and weight caused by recent economic and transportation development. The use of additives or modifiers in the asphalt binder or asphalt concrete mixture has become a commonly used technique to improve the performance of asphalt pavement and has been a topic of research for many years.

There are many types of asphalt modifiers. Polymers, such as Styrene-butadiene-styrene (SBS), Styrene-butadiene Rubber Latex (SBR), Polyethylene (PE), Ethyl vinyl acetate (EVA), etc. are the most commonly used and most studied asphalt modifiers [1,2]. Other types include mineral fillers [3], processed rubber powder [4-9], natural bitumen [10], sulfide asphalt, and Polyphosphoric acid (PPA) [11, 12]. Three methods have been used in manufacturing: modified asphalt, the Matrix Method, Industrial production in factory, and Production in the field. The Matrix Method is seldom used currently since it is generally more costly and requires a special process to prevent separation. Modified asphalt binders manufactured in the factory are heated and mixed with aggregates in the field the same way as the unmodified asphalt binders. However, the process requires the addition of several other additives to prevent the separation of the modified binder, which can increase production cost. Long-term storage can reduce the quality of the modified binders. Finally, the modified binders will need to be reheated to produce asphalt concrete mixtures that consume energy and induce additional aging to the binder. The modified asphalt binder can also be manufactured in the field, such as field produced SBS modified binder. This process requires specialized equipment in the field.

In this study, another technology, referred to as Direct Feeding Method, consists of directly feeding the modifiers, such as natural rock asphalt, Duroflex®, etc., into the mixing chamber and mixing with aggregates. The aggregates/modifiers mixtures are then mixed with asphalt binders to produce modified asphalt concrete for pavement construction. In this technology, the modifiers improve the interfaces between the asphalt binder and the aggregates, which are the weaker parts within the asphalt concrete mixtures. This type of asphalt modifier is termed as Interface Modifier in this study.

Most of the studies of binder modifiers have focused on their effects on asphalt performance indicators and rheological characteristics. In recent years, Fluorescence Microscope [13, 14], Fourier Transform Infrared (FTIR) and Atomic Force Microscope (FAM), and Thermogravimetry (TG) Curves [15, 16] have also been used in researching polymer modified asphalt binders. In this study, using Duroflex®, the effects of the interface modifier on properties of asphalt concrete mixtures were evaluated. The mechanism of how the modifier influenced interface conditions between the asphalt binder and aggregates was also examined by Electron Microscope Scanning (SEM) and Rheology Method.

Laboratory Testing Program

A comprehensive laboratory testing program was carried out in this study to 1) evaluate the effectiveness of the interface modifier Duroflex® in improving the asphalt concrete mixture properties, and 2) examine the mechanism of the aggregate/modifier/asphalt interaction that might explain the improved performance. The goal of the project was to demonstrate that the use of Duroflex®, a type of Interface Modifier with Direct Feeding Method, can improve properties of asphalt concrete mixtures. The scope of work included:

- Rutting test for high temperature performance evaluation
- Immersion Marshall and freeze-thaw splitting tensile tests for water stability evaluation
- Four-point bending fatigue test for fatigue property evaluation
- Bending beam test for low temperature performance evaluation
- SEM and Dynamic Shear Rheometer (DSR) tests for mechanism analysis

Materials

The Modifiers

The asphalt concrete modifier used in this study was Duroflex®, a product developed and manufactured by the Rub Berlin, Germany, Limited Liability Company. It is a solid substance with irregular shapes and a dark grey color (Fig. 1). The material is composed primarily of various high molecular polymers and fibers, with other functional components. The grain size falls within 1 mm and 6 mm in diameter. Unlike most asphalt modifiers, Duroflex® was added and mixed into the aggregates and then mixed with the regular asphalt binder. For comparison, a Styrene-butadiene-styrene (SBS) was also used in this study, as it has been a widely used asphalt binder modifier in China and worldwide.

Fig. 1. Modifier used in the Study - Duroflex®

Table 1. Properties of Asphalt Binders.

Properties	Unit	A-70 Asphalt Binder	SBS Modified Asphalt Binder
Penetration 25°C, 100g, 5s	0.1mm	62	50
Penetration Index, PI	—	-1.35	0.24
Softening Point, $T_{R\&B}$	°C	48.1	70.1
Ductility 5°C, 5 cm/min	cm	—	25.2
Ductility 10°C, 5 cm/min	cm	27.5	—
Ductility 15°C, 5 cm/min	cm	>100	—
Density 15°C	g/cm³	1.043	—
Solubility (trichloroethylene)	%wt	99.9	99.8
Flash Point (COC)	°C	312	304
Wax Content	%wt	1.86	—
Dynamic Viscosity 60°C	Pa.s	233	—
Elastic Recovery, 25°C	%	—	93.7
Storage Stability*: 163°C, 48 hr	°C	—	0.4
Viscosity 135°C	Pa.s	0.39	1.78
RTFOT Residue (163°C, 85min)			
Quality Change	%wt	-0.02	-0.01
Penetration Ratio: 25°C	%	78.6	80.9
Ductility: 5°C, 5 cm/min	cm	—	15.6
Ductility: 10°C, 5 cm/min	cm	12.1	—

Asphalt Binder and Aggregates

To ensure consistency of the evaluation, the same original asphalt binder, designated as A-70, and aggregates were used in making the asphalt concrete specimens. A-70 is a Chinese standard asphalt binder grade, with the level of asphalt penetration of 70 and the quality level A. As mentioned in previous section, SBS modified asphalt binder was also used for comparison. Properties of the regular asphalt binder and the SBS modified binder are shown in Table 1.

Aggregates used in the asphalt concrete mixes, designated as AC-13C in the Chinese specifications, were comprised of crushed basalt stone of 10-15 mm and 5-10 mm; crushed limestone of 3-5 mm; and stone chips of 0-3 mm. These aggregated properties met the requirements for surface layer specified in Chinese specification. The gradation of the aggregate in the mix is shown in Table 2.

Table 2. Gradation of the AC-13C Aggregates (Percent Passing, %).

AC-13C	Sieve Size (mm)									
	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Upper Limit	100	100	85	68	50	38	28	20	15	8
Lower Limit	100	90	68	38	24	15	10	7	5	4
Target Gradation	100	91.9	79.3	51.4	36.3	26.1	21.4	14.8	10	6.1

Table 3. Effect of Interface Modifier on Dynamic Stability of Asphalt Mixtures.

Parameters	DUROFLEX® Modified Asphalt Mixture				SBS Modified
	0%	0.30%	0.55%	0.80%	
Total Deformation after 60-minute Loading, mm	6.288	3.223	1.697	1.668	2.06
Dynamic Stability, Times/mm	820	2026	5379	5918	4161
Multiply of DS at 0% Modifier	1	2.47	6.56	7.22	5.07

Fig. 2. RLWT.

Asphalt Concrete Mix Design and Specimen Preparation

The asphalt concrete mixture used in this study was AC-13C, a standard Chinese mix type for surface layer. The recommended dosage of the modifier is from 0.30 to 0.80% by weight of the asphalt concrete mix. In this study, a regular AC-13C mix containing no modifier (0%) was used as the control mix, and three different levels of modifiers, 0.30%, 0.55%, and 0.80%, were employed to make test specimens. An asphalt concrete mix using SBS modified asphalt binder was also selected for comparison because of its extensive us in China's highway industry. The same target aggregate gradation was maintained for all mixes. Based on the Marshall Mix Design results, the optimum asphalt content was 4.1% for the control mix; 4.0% for the mixes modified by Duroflex®; and 4.2% for the SBS modified asphalt concrete mix.

A professional asphalt concrete mixer, which could simulate the conventional asphalt concrete batching in a batching plant, was utilized in producing the mixes. The batching procedures are summarized as follows:

1. The mixing chamber was heated to around 180°C in advance and the aggregates were heated to 190–200°C;
2. The heated aggregates were fed into mixing chamber and were mixed for 3–5 seconds;
3. The asphalt concrete interface modifier Duroflex® was fed directly into the mixing chamber and was mixed with the aggregates for about 120 seconds. It was dispersed among the aggregates and coated the aggregate particle surface during the mixing;
4. Asphat binder was injected into mixing chamber and mixed for another 60-90 seconds;
5. Finally, the mineral filler was added to the chamber and mixed for final 90 seconds.

To ensure consistent and uniform mixes, the first two (2) batches of mixtures were discarded. Normally, the weight of each batch of asphalt concrete mix was around 10-18 kg.

Results and Analysis

Effects of the Modifier on High Temperature Performance

A wheel rutting tester was used to evaluate high temperature performance of the various asphalt concrete specimens, in accordance with Chinese Standard Test Method T0719-1993. The test was performed at a temperature of 60°C; loading speed of 42 times per minute; and with a tire pressure of 0.7 MPa. Total deformations were measured on the specimen surface after it was subjected to 60 minutes of wheel loading. The Dynamic Stability was also recorded. Dynamic Stability is defined as the number of wheel loadings required to induce a 1-mm deformation during the testing time frame from 45 minutes to 60 minutes. The rutting test results are shown in Table 3.

Table 3 shows that the total deformation decreased, from 6.288 mm to 1.668 mm, as the dosage of the Interface Modifier increased from 0% to 0.80%, indicating that the use of this modifier significantly improved the mix's high temperature performance. Similarly, the Dynamic Stability increased from 820 to 5,918 as the modifier dosage increased from 0% to 0.80%. Also, the Dynamic Stability increased at a faster rate at the lower dosage level, and leveled off as the dosage reached 0.55% and higher. Therefore, the optimum level of the modifier is probably around 0.55%. Based on the data presented in this table, it can also be observed that the SBS modified asphalt concrete had similar performance to the DUROFLEX® modified asphalt containing between 0.30% and 0.55% of modifiers.

High temperature performance was also evaluated using the Rotary Loaded Wheel Tester (RLWT), as shown in Fig. 2. The repeated wheel loads were applied on the Marshall specimen by rotating 10 rubber wheels at a test temperature of 60°C. The axle load of each wheel is 125 N, which resulted in a contact pressure of 0.69 MPa. The test results are shown in Table 4.

RLWT results indicate that the deformation on the unmodified AC-13C asphalt concrete mixture specimen was much larger than

Table 4. Test Results of RLWT.

Loading Cycle	Deformation（mm）				
	Various Percentage of Modified Asphalt Mixture				SBS Modified Asphalt Mixture
	0%	0.30%	0.55%	0.80%	
4,000	1.22	0.27	0.23	0.22	0.28
8,000	1.57	0.38	0.29	0.3	0.34
12,000	1.87	0.49	0.35	0.34	0.37
16,000	2.08	0.58	0.39	0.37	0.41

those on modified asphalt at all loading cycles. For example, at 4,000 cycles, the deformation was 1.22 mm for the unmodified control sample, and were 0.27 mm, 0.23 mm, and 0.22 mm for mixtures containing 0.30%, 0.55% and 0.80% Interface Modifier, respectively. At all loading cycles, the rate of decrease in deformation was the highest at the lower dosage, and the rate decreased as the percentage of modifier increased. The increase eventually leveled off when the dosage was above 0.55%. The deformation for the SBS modified asphalt samples was again comparable to that for the specimens with Interface Modifier between 0.30% and 0.55%.

Effects of Interface Modifier on Water Stability of Asphalt Concrete Mixture

The effects of interface modifier on water stability of asphalt mixtures were studied using the Immersion Marshall Test and Freeze-Thaw Splitting Test (Chinese Standard Test Methods T0709-2000 and T0729-2000, corresponding to AASHTO T245 and T283, respectively). The test results are shown in Figs. 3 and 4. Fig. 3 shows that the Marshall Stability, both before and after the immersion, increased as the Duroflex® content increased; furthermore, the residual stability after immersion increased with the increasing modifier content. Similar to the observation made under the high-temperature performance in the previous section, the SBS modified asphalt concrete performed similarly to the mixtures containing between 0.30% and 0.55% of Duroflex® modifier. From Fig. 4, the splitting tensile strength results showed identical trends. Therefore, it can be concluded that the use of the interface modifier can improve the asphalt concrete performance related to water stability. It should also be noted that all specimens met the Chinese specification requirements for asphalt concrete water stability.

Table 5. Effect of Additive X on Adhesion.

	Adhesion Grade between Binder and Aggregates	
Aggregate Type	A-70 Asphalt Concrete Mix	Modified Asphalt Concrete
Granite	3	4
Basalt	4	5

It is a well known fact that water stability of the asphalt concrete mixes will be directly influenced by the adhesion between the asphalt binder and the aggregates. To verify this phenomenon, two straight-run A-70 asphalt concrete mixes and two asphalt concrete mixes with about 0.20% to 0.25% of the interface modifier were prepared in the laboratory. Two types of aggregates were used, including granite and basalt. Adhesion tests (Chinese Standard Test Method T0616-1993) were conducted on the four mixes, and the results are shown in Table 5. These results show that the interface modifier can improve the adhesion grade of asphalt to aggregate.

Effects of Interface Modifier on Fatigue Property of Asphalt Mixture

There are many test methods that can be used to evaluate asphalt mixture fatigue performance, such as four-point bending test, trapezoidal cantilever bending test, indirect tensile test, etc. From a comparison study documented in the SHRP A-003A research report, the four-point bending fatigue testing was considered to be superior to others. The modified four-point bending fatigue test was used to evaluate the fatigue performance at 15°C [17]. Fig. 5 shows the Cooper NU-14 four-point bending tester used in this study, and test results are shown in Table 6.

Test data in Table 6 indicate that the interface modifier Duroflex® could significantly improve the fatigue life of asphalt mixture. With

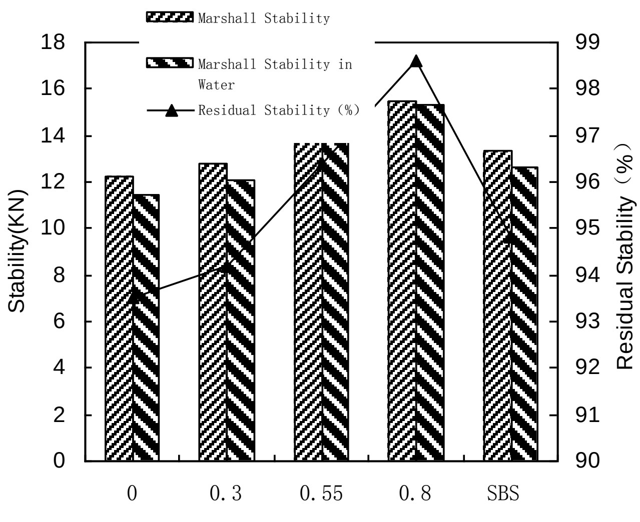


Fig. 3. Effects of Modifier on Residual Stability.

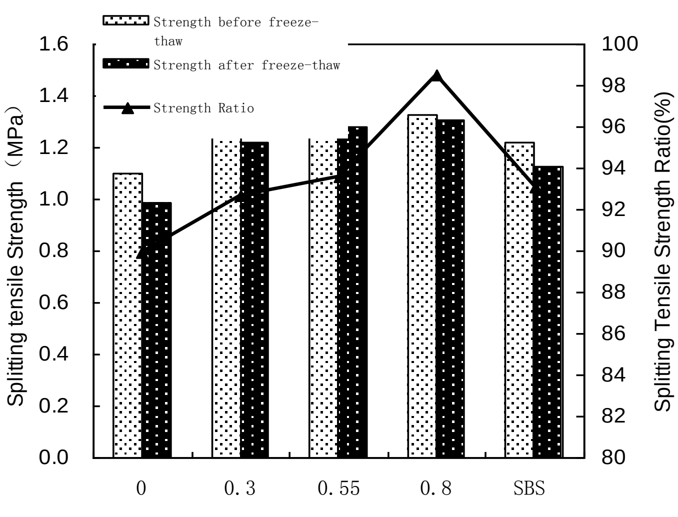


Fig. 4. Effects of Modifier on Splitting Tensile Strength on**.**

Fig. 5. Cooper NU-14 Foure-Point Bending Tester.

the increase of modifier content, the fatigue life of asphalt mixtures increased. As shown in the table, at all strain levels, the initial asphalt mixture stiffness increased slightly with the increase of the interface modifier content. Similarly, at each of the four strain levels, as the modifier content increased, the cumulative dissipated energy increased gradually, indicating that more energy would be required to reach the fatigue damage point for asphalt mixtures containing the interface modifier. In research conducted by Van Dijk in 1977 [18], an exponential correlation existed between accumulated dissipated energy and fatigue life for asphalt concrete; the greater the cumulative dissipated energy, the longer fatigue life.

The modified four-point bending test was also conducted on the SBS modified asphalt concrete mix. Since the SBS modified asphalt had much longer fatigue life, tests were performed at strain levels of 400 μm, 600 μm, and 800 μm, and the results are presented in Table 7.

Table 7. Fatigue life of SBS Modified Asphalt Mixture.

Index	Strain Level		
	400 μm	600 μm	800 μm
Initial Stiffness (MPa)	8733	8184	7819
Cumulative Dissipated Energy (J/m^3)	1005916	959124	61178
Fatigue Life (times)	1520492	280714	24845

From Tables 6 and 7, it is observed that the fatigue life of SBS modified asphalt mixture was much longer than the unmodified AC-13C asphalt concrete and the Duroflex® modified asphalt mixtures. At the strain level of 400 μm, the fatigue life of the SBS modified asphalt mixture was 23 times of that of asphalt mix with 0.80% of interface modifier and about 96 times of the fatigue life of the unmodified asphalt mix. Test results of the fatigue life for all asphalt mixtures are also plotted in Fig. 5. Fig. 5 clearly shows that SBS modified asphalt concrete had the longest fatigue life among all asphalt mixes. The incorporation of the interface modifier in the asphalt concrete mixtures also improved their fatigue lives. Fig. 5 also shows that the fatigue life continued to decrease with the increasing strain levels, indicating that strain level is an important factor influencing fatigue performance.

The classical fatigue life prediction model for asphalt mixture developed by Carl L. Monismith in the 1970s, as shown in Eq. (1), was applied to establish relationships between fatigue life and strain level in this study.

$$N_f = A(1/\varepsilon_t)^B \tag{1}$$

where N_f = fatigue life; ε_t = strain level; *A, B* = test parameter.

The data in Tables 6 and 7 were used to fit into Eq. (1) and the fatigue equations of asphalt mixtures are listed in Table 8. The correlations of fatigue life and strain level are very good, as evidenced by the high coefficients of correlation.

Table 6. Effects of Interface Modifier on Fatigue Property of Asphalt Mixture.

Strain Levels	Index	Percent of Interface Modifier Content			
		0	0.3	0.55	0.8
200 μm	Initial Stiffness (MPa)	14919	15121	15343	16028
	Cumulative Dissipated Energy (J/m^3)	99441	124158	160540	224056
	Fatigue Life (Cycles）	468352	612041	867142	1052689
	Relative Fatigue Life (Times)	1	1.31	1.85	2.25
300 μm	Initial Stiffness (MPa)	14995	15097	15824	16236
	Cumulative Dissipated Energy (J/m^3)	36956	47210	69694	95381
	Fatigue life (Cycles)	76402	97810	138997	191564
	Relative Fatigue Life (Times)	1	1.28	1.82	2.51
400 μm	Initial Stiffness (MPa)	14934	15482	16031	16452
	Cumulative Dissipated Energy (J/m^3)	17137	27364	45940	66212
	Fatigue Life (Cycles)	15715	28120	48025	62148
	Relative Fatigue Life (Times)	1	1.79	3.06	3.95
500 μm	Initial Stiffness (MPa)	14346	15375	16283	16683
	Cumulative Dissipated Energy (J/m^3)	15160	16405	18158	31025
	Fatigue Life (Cycles)	9887	11421	14107	16542
	Relative Fatigue Life (Times)	1	1.16	1.43	1.67

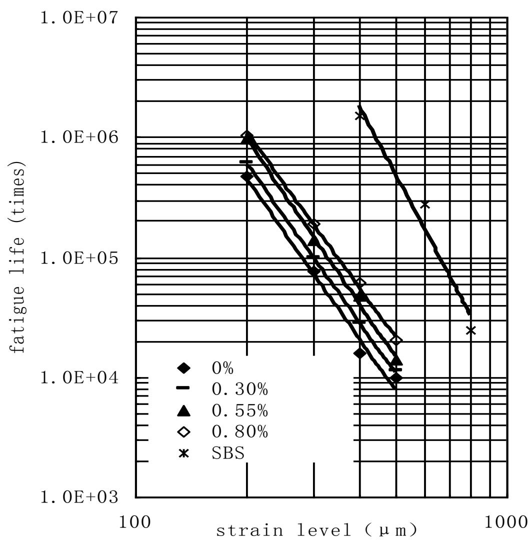


Fig. 6. Fatigue Curves.

Table 8. Fatigue Equations of Asphalt Mixtures.

Additives	Fatigue Equation	Correlation Coefficient
0%	N_p=5.2954×10^{15} $\varepsilon^{-4.3804}$	0.9847
0.30%DUROFLEX	N_p=6.3295×10^{15} $\varepsilon^{-4.3577}$	0.9995
0.55% DUROFLEX	N_p=2.4030×10^{16} $\varepsilon^{-4.5206}$	0.9964
0.80% DUROFLEX	N_p=6.2756×10^{15} $\varepsilon^{-4.2444}$	0.9984
SBS	N_p=2.5682×10^{21} $\varepsilon^{-5.8193}$	0.9603

Table 9. The Effects of Interfacial Modifier on Low Temperature Performance.

Parameters at -10°C	Percent of DUROFLEX® by Weight of Asphalt Mixture			
	0	0.3	0.55	0.8
Flexural Tensile Strength (MPa)	6.11	6.6	6.85	7.02
Bending Stiffness Modulus (MPa)	2042	2198	2230	2133
Failure Strain (με)	2993	3001	3069	3290

Effects of Interface Modifier on Low Temperature Performance of Asphalt Mixture

A bending beam test at -10˚C was selected to evaluate the low temperature performance of the asphalt mixtures with various levels of interface modifiers amounts, and the test results are shown in Table 9. It is noted from Table 9 that all indicators—the low temperature flexural strength, stiffness, and failure strain—showed slight increases with increasing modifier content.

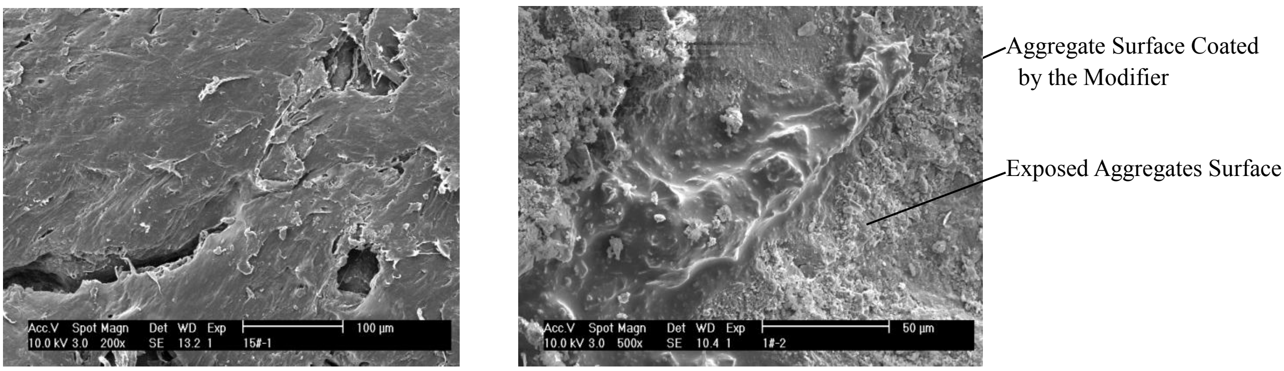
Analysis of Interaction Mechanism among Asphalt Binder, Aggregate, and Interface Modifier

In this study, the interaction among the asphalt binder, aggregate and interface modifier were evaluated using the scanning electron microscopy (SEM) technique and dynamic shear rheometer (DSR) testing.

It was hypothesized that, while mixing with the heated aggregates, the interface modifier adhered and covered the aggregate surfaces that enhanced the bonding between the aggregate and the asphalt binder. To verify that the interface modifier did adhere to aggregate surface during the high temperature mixing process, the SEM technique was used to examine both the modifier Duroflex® and the modifier/aggregate mixture, and the results are displayed in Fig. 7(a) and 7(b), respectively. Fig. 7(b) shows that the modifier formed a thin film and covered part of the aggregate surfaces.

Analysis of the chemical element of the interface modifier showed that the interface modifier is a type of macromolecule polymer, composed primarily of carbon, oxygen and silicon (Fig. 8). The atomic ratios are 97.0%, 1.5%, and 0.7%, and the ratios by weight are 93.9%, 1.9%, and 1.5% for carbon, oxygen and silicon, respectively. The chemical compositions of the modifier are similar to that of asphalt binder. It was also discovered in this study that, when mixed with the asphalt binder at a high temperature of 170˚C, the modifier melted gradually into asphalt binder, which indicates that it is compatible with asphalt binder. The modifier can be dissolved, infiltrated, and diffused into asphalt binder at a high temperature.

Element analyses by SEM were also performed on the aggregate and modifier coated aggregate, and the results are shown in Fig. 9 and Fig. 10. The aggregate mainly consists of Si, O, Ca, K, AI, and other elements, as shown in Fig. 9. The atomic ratios of carbon, oxygen, silicon atoms are 9.9%, 35.1%, and 30.5%, and the ratios by weight are 5.2%, 24.2%, and 36.9%, respectively. As presented in Fig. 7(b), part of the aggregate surfaces was coated by a thin film of the interface modifier after the mixing of the modifier and the



(a) Microstructure of the Interface Modifier

(b) Microstructure of the Modifier/Aggregate Mixture

Fig. 7. SEM Images of the Modifier and the Modifier/Aggregate Mixture.

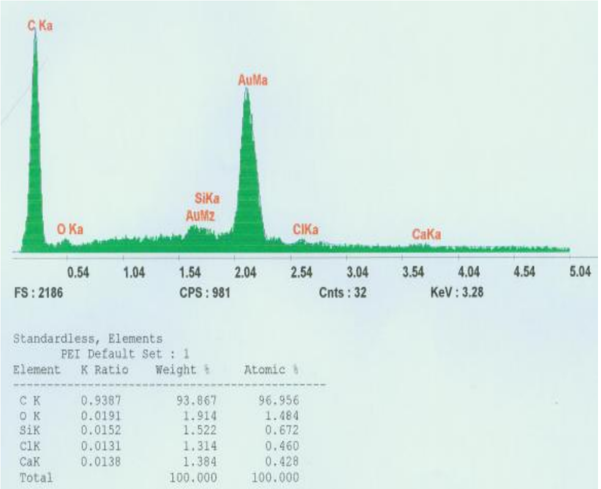


Fig. 8. Chemical Elements of Modifier.

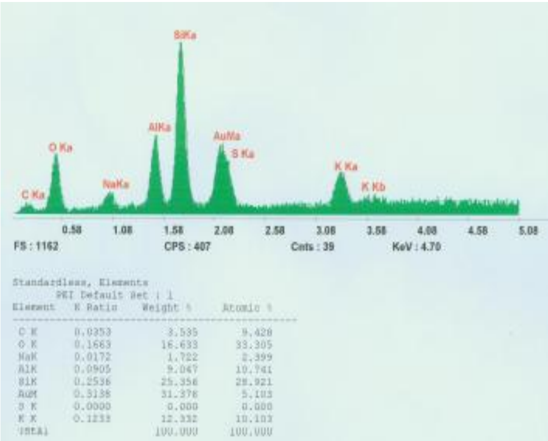


Fig. 9. Chemical Composition of Aggregate.

aggregates. Fig. 10 illustrates the chemical compositions of the aggregate coated by the interface modifier film. In this study, the laser used had incident energy of 10KV and penetration depth of 4-5μm. Since the film thickness might be less than the penetration depth of the laser at some places, the element analysis results represented chemical compositions of the mixture of the interface modifier and the aggregate. From Fig. 10, it is deduced that the atomic ratios of carbon, oxygen, silicon atoms are 69.4%, 9.6%, and 14.6%, and the ratios by weight are 53.2%, 16.1%, and 13.9%,

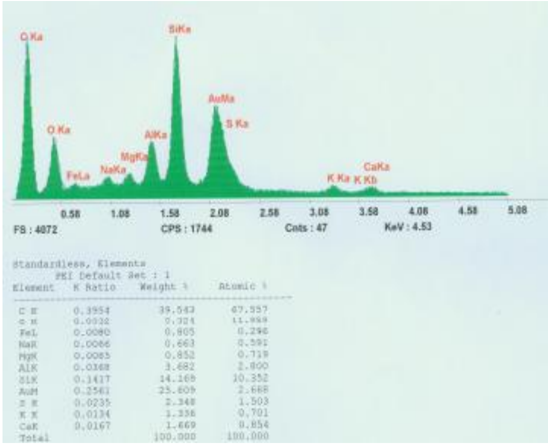


Fig. 10. Chemical Composition of Aggregate Coated by the Modifier.

respectively. The ratios are between those ratios observed from the Duroflex® and the aggregates. Therefore, it can be deduced that the interface modifier formed a thin film (thickness less than 4μm) and adhered to aggregate surface.

The thin film of the interface modifier wrapped on the aggregate surfaces changed the two-phase aggregate-asphalt interface into a three-phase interface of aggregate-interface modifier film-asphalt. A schematic presentation of the three-phase interface is presented in Fig. 11. As shown in the figure, the physical-chemical interactions occurred between the aggregate-modifier and the modifier-asphalt binder. Through infiltration, interaction, and divergence at a high temperature, a transition layer was formed between the modifier and the asphalt binder. The transition layer was a viscous film consisting of layers without clear boundaries. From the asphalt binder side, the polarity increased from weak to strong, and the viscosity increased from low to high. Compared to the unmodified asphalt binder, the transition layer had more polar surfactants and stronger adsorption force to the aggregates. Therefore, the bonding between asphalt and aggregate can be significantly improved by the addition of the interface modifier.

It was also observed during the laboratory study that part of the modifier did not coat the aggregates and was dispersed into the asphalt binder. Therefore, efforts were expended to evaluate the effects of the interface modifier on the rheological properties of asphalt binder used. Samples of unmodified A-70 asphalt binder and the A-70 containing 5% and 10% of the interface modifier, by

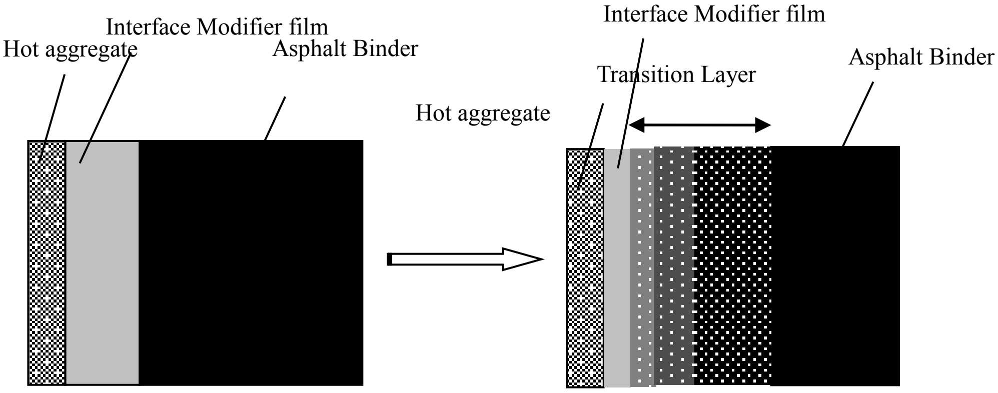


Fig. 11. Schematic Presentation of the Three-Phase Interface.

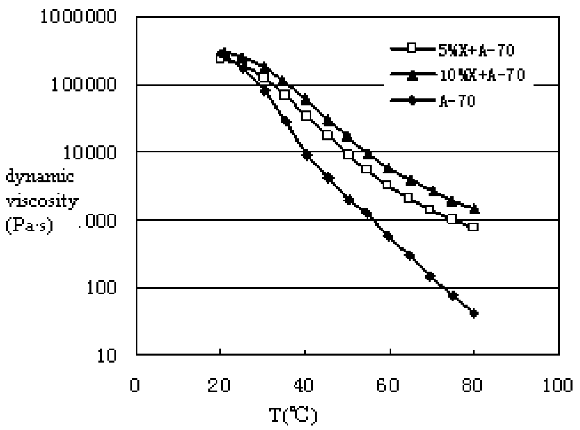


Fig. 12. Effect of Modifier on Dynamic Viscosity.

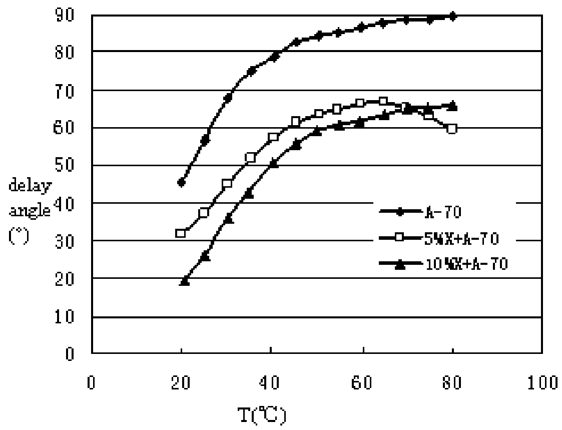


Fig. 13. Effect of Modifier on Phase Angle.

weight of the binder, were subjected to the DSR testing and the test results are shown in Fig. 12. Fig. 12 shows that, at the lower temperature of 20˚C, the interface modifier had virtually no effects on the dynamic viscosity of the binders. As the temperature became higher, the effects became more profound. It can be deduced that the use of interface modifier can improve the high-temperature of asphalt binders.

Usually, for viscoelastic materials, the strain response lags behind the stress. The phase angle of an ideal fluid is 90°, and the phase angle of an ideal solid is 0° [19, 20]. The DSR results of phase angle at various temperatures are shown in Fig. 13. It is clear from the figure that the interface modifier had significant effects on viscoelastic properties of asphalt binder. The phase angle of unmodified A-70 asphalt binder increased rapidly with the increase of test temperature, reaching 90° at about 70°C, indicating that the unmodified binder would lose the elastic property and became viscous at a high temperature, and would easily accumulate plastic deformation in asphalt pavement structure. In Fig. 13, the modified asphalt binder had much smaller phase angles at high temperature region, which indicated that the modified binder would be more resistant to permanent deformation.

Summary and Conclusions

A comprehensive laboratory testing program was performed in this study to evaluate the effects of a new type of asphalt mix modifier, Duroflex®, on the performance of the asphalt concrete mixtures. Unlike many modifiers, Duroflex® was directly fed into the chamber and mixed with the heated aggregate, thus eliminating the additional heating of manufacturing the modified binder. The following observations and conclusions can be drawn from this study:

- The interface modifier can significantly improve high temperature performance of the asphalt concrete mixtures. The rate of increase on dynamic stability was higher at lower modifier content and leveled off at about 0.55%, indicating an optimum content of about 0.55%. The SBS modified asphalt concrete mixture had a similar performance to mixtures containing between 0.30% and 0.55% of Duroflex®.
- The results of Immersion Marshall Test and Freeze-Thaw Splitting Test show that the interface modifier had positive effects on the water stability of asphalt mixture. Also, test results showed that the adhesion between the asphalt binder and the aggregate could be enhanced by incorporating the interface modifier in the asphalt mixture.
- The interface modifier can extend the fatigue life of an asphalt mixture significantly. With the increase of modifier content, the fatigue life of asphalt mixtures increased.
- From the Bending Beam test results at -10˚C, the interface modifier had a slightly positive effect on low temperature performance.
- Using the SEM technique, it was observed that, after mixing, a thin film of the interface modifier (less than 4μm) was formed and coated on the surface of the aggregate. The SEM technique was also used to identify the chemical compositions of the mixed materials.
- The DSR test results showed that the interface modifier could improve the elastic property of the asphalt binder.

Acknowledgements

The authors gratefully acknowledge the financial support of the project by the National Natural Science Foundation of China (50878090 / 51008132).

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